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The Development and Demonstration of an Underwater Oil Harvesting Technique

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April 1973

THE DEVELOPMENT AND DEMONSTRATION OF AN UNDERWATER OIL HARVESTING TECHNIQUE

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ABSTRACT

Analytical studies and harbor tests were conducted to determine the feasibility of harvesting oil beneath the surface of the water with the use of inclined planes.

The analytical and laboratory investigations provided sufficient basic information to design and build operational units and showed that this kind of device could harvest both light and heavy oils between 3/4 knot and 2 knots. Information was obtained regarding angle of incline, length of collection well, and the design of a baffle grid. Tests, which were performed in waves, showed that a platform could be designed so that oil could be collected in waves and chop without seriously affecting efficiency.

A 22-foot-long unit was designed, built, and demonstrated in Boston Harbor. The results showed that the fixed-plane concept is highly effective in areas where the vessel can travel through the slick. Recovered oil is virtually water free and, under representative conditions of wind, waves, and current, and in one pass through an oil slick, the unit recovered between 70% and 86% of the oil presented to it. The quantities of oil collected in one pass could be greatly increased if sweeping arms were used to increase the active area and concentrate the oil.

Although the fixed inclined plane (SHOC) demonstrator unit works well between 3/4 knot and 2 knots, in the interest of extending the velocity range to from zero knots to over 2 knots, it is recommended that a modified operational unit employing a new principle of a moving inclined plane be designed and built to work in actual spill situations. It is also recommended that a set of effective sweeps to be directly attached to the unit be investigated and developed.

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SECTION I

CONCLUSIONS

1. The method of collecting oil beneath the surface of the water using an inclined plane is feasible and practical.

2. The fixed inclined plane (SHOC) unit operates effectively at vessel or water velocities of from 3/4 knot to 2 knots.

3. For effective oil recovery, the inclined plane angle with respect to the horizontal should not be greater than 30°.

4. Baffle grids between 3 and 4 inches square and 9 inches high will capture both the high and low viscosity oils.

5. Baffle sections greater than 7 feet long will capture between 70% and 90% of the oil presented to the skimmer in one pass at the operating velocities.

6. Vessels employing the fixed inclined plane principle can be made as small or as large as desired. Size will be determined by cost, use, and handling considerations.

7. Vessels employing the SHOC concept can harvest thin or thick oil slicks over a very wide range of viscosities without any serious effect on efficiency or performance.

8. The tow basin and harbor tests show that SHOC units can be built that will collect oil effectively under severe wave conditions.

SECTION II

RECOMMENDATIONS

This program was limited to the investigation and harbor demonstration of the fixed inclined plane (SHOC) concept. It was not within the scope of the program to design and build an operational unit. It is recommended, however, that a full-sized, self-propelled operational unit employing a new principle of a moving inclined plane be designed and built to work in actual spills. The first part of this recommendation, namely the design of an operational unit employing the new principle, has been supported by the Environmental Protection Agency.

Effective sweeps for sweeping oil to the oil skimmer that are integrated with the skimmer do not exist. The use of simple flat plates has been unsuccessful because of their behavior in waves and their high drag characteristics. It is recommended that a program be supported to investigate and develop a set of integral sweeps to increase the effectiveness of oil skimmers.

Conditions created by extreme operating maneuvers, such as rapid changes in direction or sharp turns, may interfere with efficient removal of oil from the collection well. Laboratory and harbor tests should be performed to determine what alterations should be made in and around the collection well to improve the efficiency of collection during various maneuvers.

SECTION III

INTRODUCTION

In 1970, JBF Scientific Corporation was awarded a contract to (1) perform an investigation of the engineering principles involved in collecting oil below the surface of the water by means of an inclined plane, and (2) design and fabricate a demonstration unit for evaluation in a realistic environment.

The development and demonstration of the concept was accomplished in two phases. In the first phase, investigations were performed with laboratory tests to develop design information for building the demonstration model. In the second phase, a demonstration unit was designed, fabricated, and evaluated in Boston Harbor. A more detailed breakdown of the program is outlined below.

PHASE I - THE DEVELOPMENT OF DESIGN INFORMATION USING LABORATORY MODELS

1. The Performance of Literature Review
2. The Design and Construction of a Circulating Tank
3. The Design and Construction of Models for the Circulating Tank Tests
4. The Performance of Circulating Tank Tests
5. The Design and Construction of Models for Tow Basin Tests
6. The Performance of Tests in the Tow Basin
7. The Development and Preparation of Design Data

PHASE II - THE DESIGN, CONSTRUCTION, AND DEMONSTRATION OF A UNIT IN BOSTON HARBOR

1. The Design of the Demonstration Unit
2. The Fabrication of the Demonstration Unit
3. The Design and Preparation of a Harbor Test Plan
4. The Evaluation of the Demonstration Unit

The oil recovery technique developed under the contract is directed at hydrodynamically funneling the oil slick down into the submerged inlet of a collecting chamber. The principle involves forcing the surface oil to follow the submerged contour of an inclined plane so that the oil film is thickened and so that the thickened film is then trapped in a well at the end of the inclined plane. The concept is called, "The Submerged Hydrodynamic Oil Concentrator (SHOC)."

The behavior of the SHOC concept from the hydrodynamic viewpoint is a complex phenomenon involving laminar and turbulent flow and two fluids of different densities and viscosities. There are several possible non-dimensional groups involved in describing the process so that a completely analytical approach is not possible. That is, none of the dimensionless expressions occur in such a way as to be the principle phenomenon that explains the entire collection process. They are all involved and there are transition zones. The approach which was used to develop design data was to present a theoretical framework to define the processes and to generate sufficient empirical information to explain these processes and to make predictions of the oil collection effectiveness for various size units. Based on these predictions, several models were designed and a 22-foot-long SHOC unit was built and demonstrated in Boston Harbor.

SECTION IV

ANALYTICAL AND EXPERIMENTAL PROGRAM

SHOC Concept

The principle of the SHOC concept involves forcing the oil on the surface of the water to follow the contour of an inclined plane to a collection well located beneath the surface of the water.

Figure 1 is a schematic of the concept. Two side plates extend into the water so that as the vessel moves forward, oil and water must follow the contour of the incline without escaping to the side. The principle is the same whether the vessel moves relative to the water or the water relative to the vessel (i.e., water current).

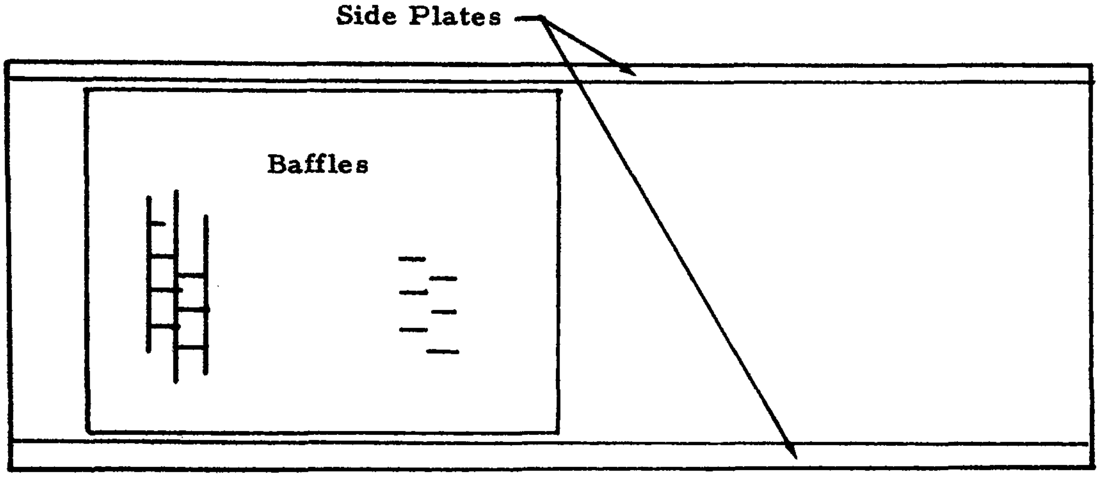
Basically, there are two different zones of importance. In the first, the concentration zone, the oil slick is concentrated as it flows along the incline of the vessel. The oil is buoyant and has a higher viscosity than water and, therefore, its flow is in sheets and globules along much of the length of the concentration zone. This results in a stable layer of oil flowing along the incline. As the oil flows down to the second zone, the collection zone, the sheets and globules coalesce and are trapped in a baffled well. In the collection zone, the oil which has been flowing along the bottom of the vessel rises due to buoyant forces into the baffles and the collection tank. The oil then concentrates into a thick layer at the top of the well where it can be pumped off practically free of any water.

Literature Search

Prior to performing the theoretical and experimental work a search was made to obtain pertinent information on the oil-on-water behavior and on the practical aspects of oil recovery processes. For the behavior of oil on water particular attention was paid to analyses that has been performed concerning the instabilities of oil-water interfaces, the way that oil breaks up beneath the water surface, and the trajectories of submerged oil globules. This information is referred to in the text. The investigation of the practical aspects of oil recovery processes was limited to readily available information on the physical and chemical removal of oil slicks. This work provided insights into the practical problems of recovering oil, such as the amounts of oil spilled, the number of spills, film thicknesses, the spreading characteristics, and the sweep and containment difficulties. This literature is listed in Appendix A.

Theoretical Investigations

The behavior of the SHOC concept from the hydrodynamic viewpoint is a complex phenomenon involving laminar and turbulent flow regimes



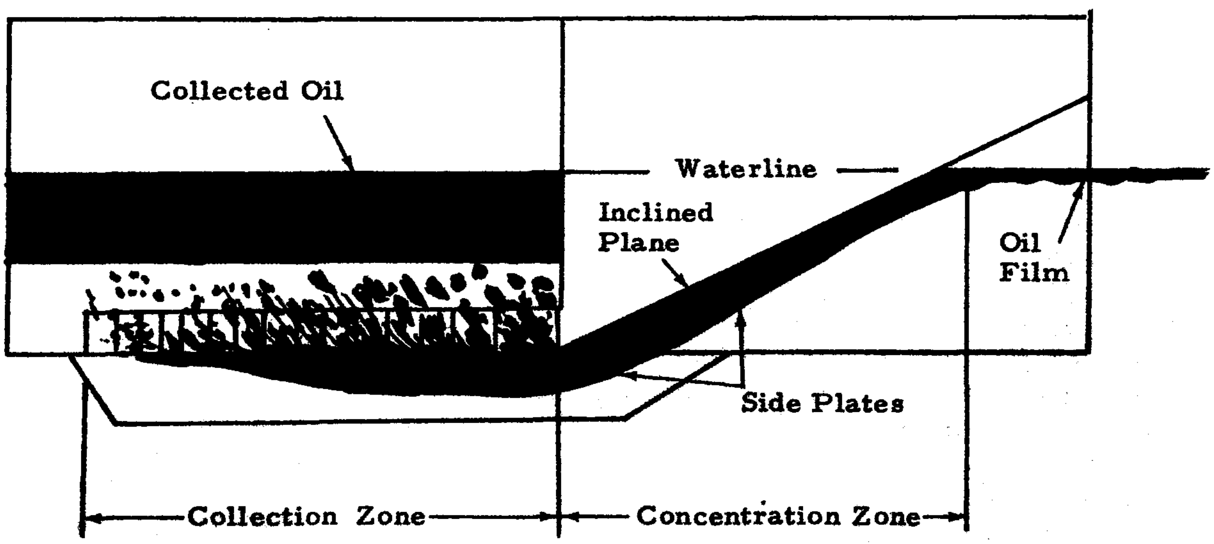


Figure 1. The SHOC Concept

and boundary layers, coupled with wave interactions. There are five different non-dimensional groups which appear in the equations describing the flow processes, and each of these has a different structure in relation to the modelling parameters of characteristic length and velocity. The Densimetric Froude Number relates inertial to buoyant effects, the Reynolds Number relates inertial to viscous effects, the Euler Number relates pressure or acceleration to inertial effects, the Strouhal Number relates vortex spacing to a diameter, and the Weber Number relates inertial to surface-tension effects. Unfortunately none of these dimensionless expressions occurs in such a way as to be the principal phenomenon that governs the entire oil collection process. They are all involved, and there are transition zones so that a completely rational expression for the collection process is not possible. However, a combination of the analyses and the empirical information developed is sufficient to quantify the process and make predictions of the oil collection effectiveness for various size units.

Appendix B presents the development of the theoretical framework of the SHOC concept and only a brief synopsis will be presented here. Basically, there are three possible modes of collection for a device employing the SHOC concept (see Figure 2). These modes are (a) the oil-layer buildup extends sufficiently far in front of the plane to cause the depth of oil to exceed the draft of the vessel; (b) the oil-water interfacial waves cause oil to shear off in sheets and globules that are transported to the incline down to the collection zone; and (c) the oil shears at the buildup region adjacent to the incline in sheets that travel with a wave-like action.

The modes of prime concern in the design of SHOC units are shown in Figure 2 (b and c), where the oil-water interfacial wave causes oil to shear off in sheets, globules and droplets. The parts of Appendix B that are useful in design are the critical Weber Number (which establishes the velocity at which oil begins to move down the incline) and the governing relations for the globule size and collection well length as a function of oil-water relative velocity.

The critical Weber Number is given by

$$W_c = \frac{P_o d V_c^2}{\sigma}$$

where P_o = oil density

d = diameter of globules

V_c = critical relative oil-water velocity

σ = interfacial tension between oil and water

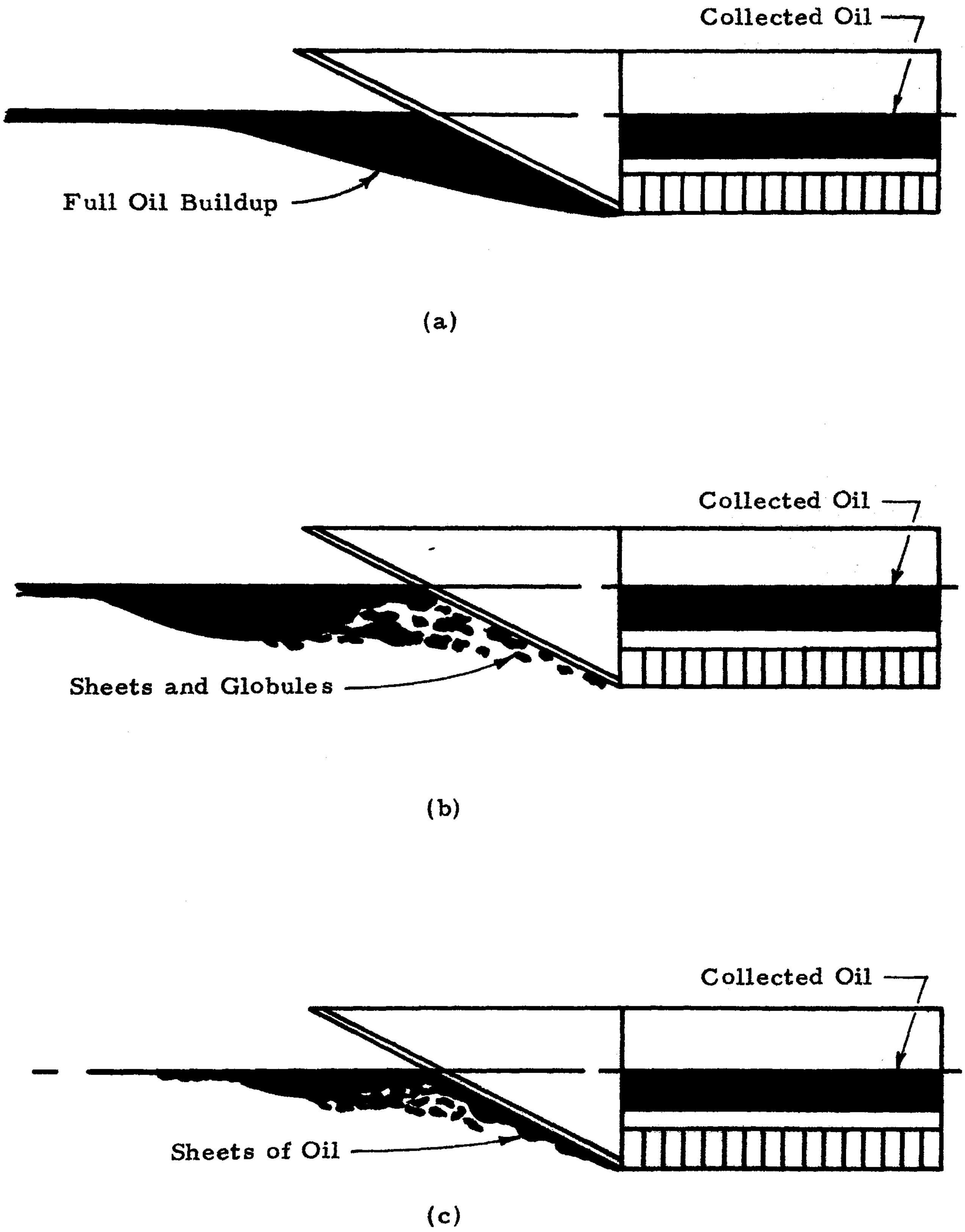


Figure 2. Three Modes of Oil Collection

A W_c approximately equal to 22 has been found by Wicks [1] to give good agreement with tests. It is used to determine the critical velocity for effective oil collection where oil moves relative to the plane.

Figure 3 shows oil droplet size for limiting values of surface tensions and specific gravities plotted as a function of relative velocity between the oil and water particles. It is used to determine the mean size of oil globules which travel down the incline.

Figure 4 is a plot of collection well length versus water or vessel operating velocity. It was obtained from calculations substantiated in reference [1] and is used to determine the length of baffle section required to collect the oil particles, whose size has been determined above.

The cross-section and baffle height were determined on the following basis. It is most desirable to have as small a cross-sectional area as possible to minimize the size of the eddy within a baffle. The smaller eddies or vortices do not tend to push oil out of the baffle and back into the water stream. In theory the height of the baffle should be at least twice the dimension of the cross-section width so that there is a minimum of disturbance in the well above the top of the baffles. The design values obtained using these rules have to be modified to consider the size openings required to capture the more viscous oils, and final design dimensions, therefore, were optimized experimentally.

Experimental Program

The literature search and the theoretical work discussed in the previous section provided the guidance for the experimental program. A very important part of the tests was the recording of experimental results on motion picture films for subsequent analysis. This visual information was correlated with measurements of oil collection rates for making many important decisions in the actual design of SHOC units.

Two major test programs were carried out in the laboratory. The first involved the use of a circulating tank and the second a tow basin.

Circulating Tank Facility

The circulating tank designed and built under this program is 15 feet long, 5 feet wide, and 3 feet deep. Figure 5 is a photograph of the tank without accessories. Water was circulated by the air-driven propeller shown in Figure 6. The circulator provided the water velocities from 0 to 3 feet per second. Figure 7 shows the circulating tank facility with all of the accessories. Oil was presented to the water by means of a splash plate at controlled rates to provide variations in average oil film thickness. The oil harvested was pumped

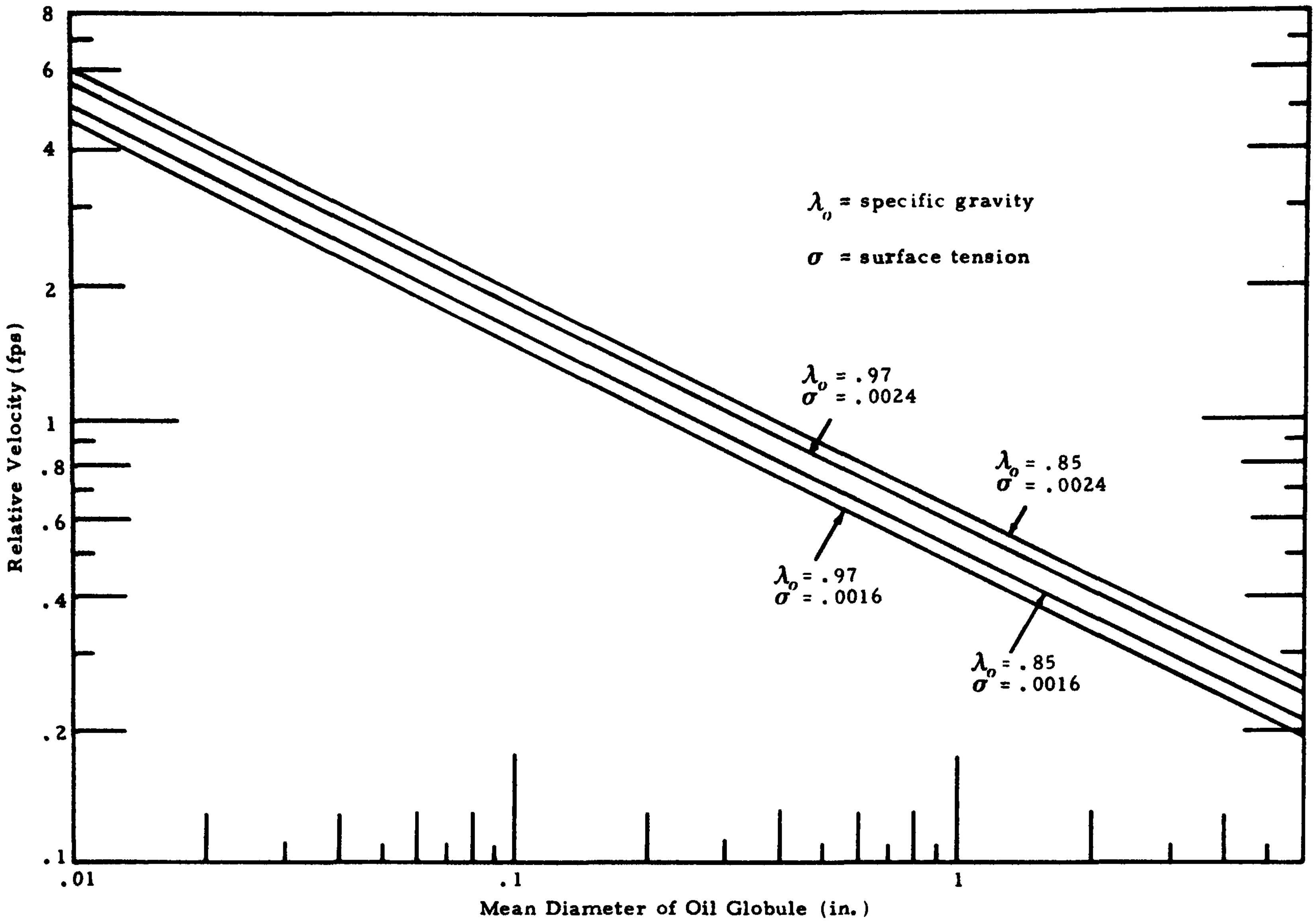


Figure 3. Oil Globule Size vs Oil-Water Relative Velocity

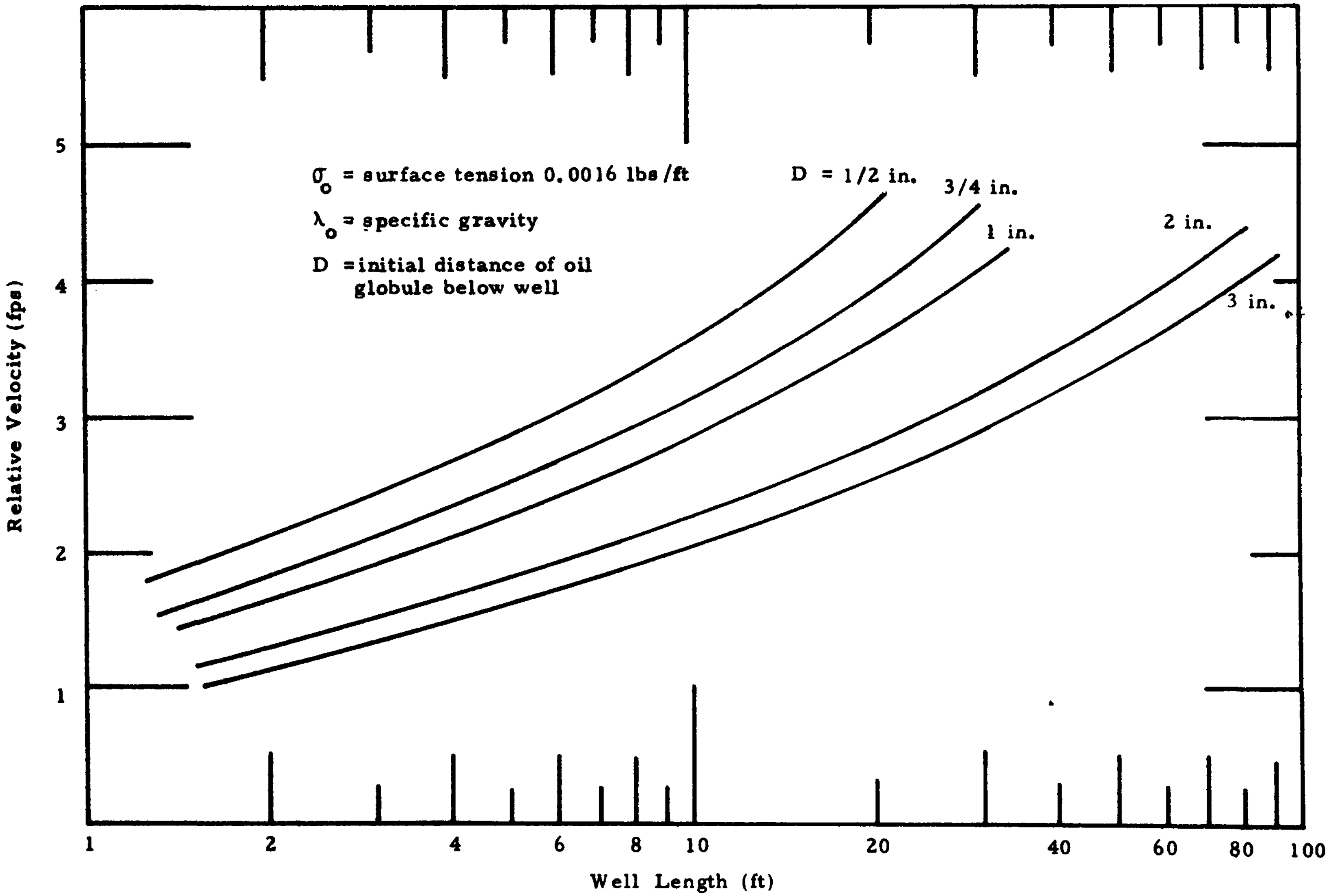


Figure 4. Well Length vs Oil-Water Relative Velocity

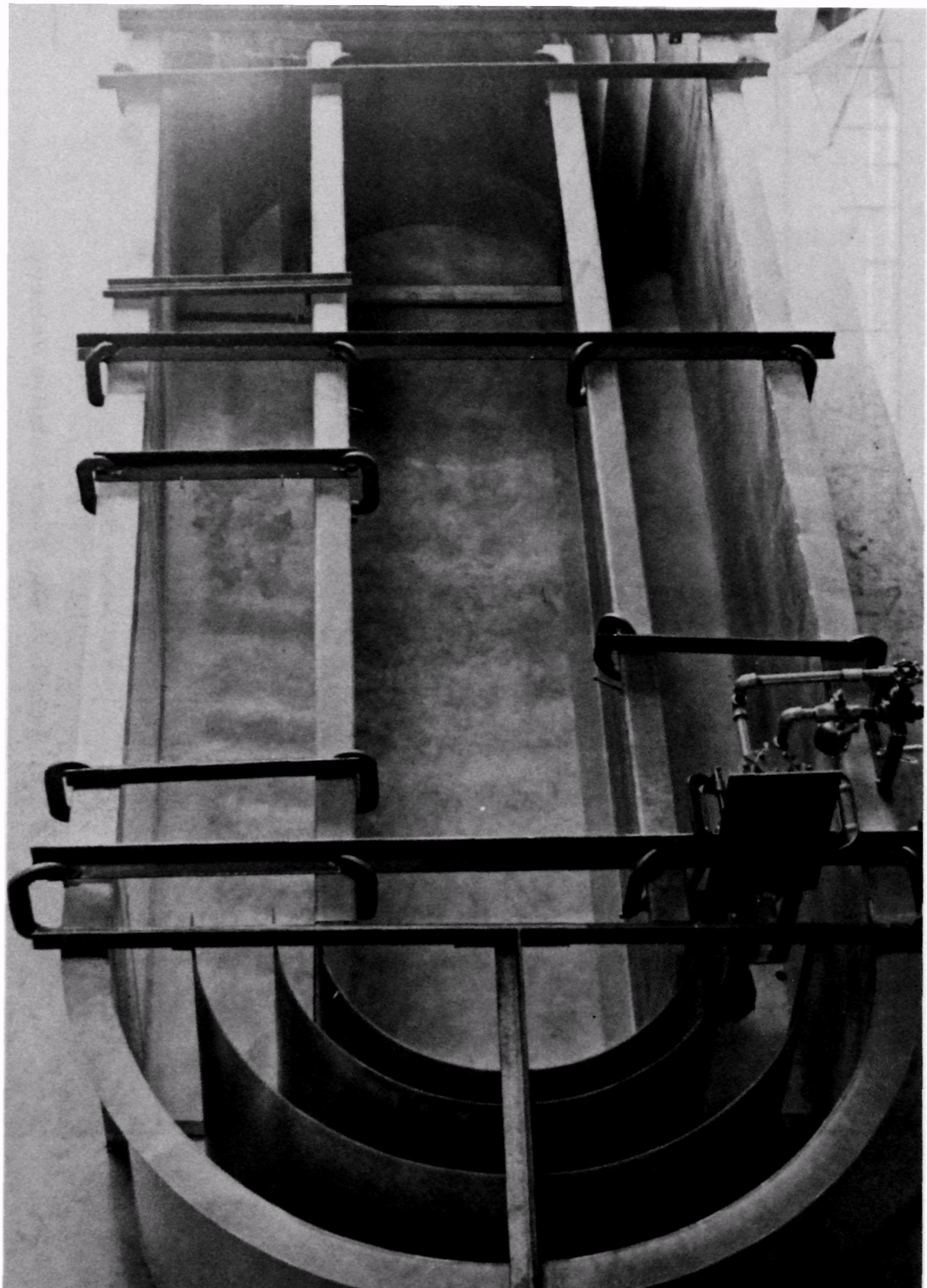


Figure 5. Circulating Tank Without Accessories

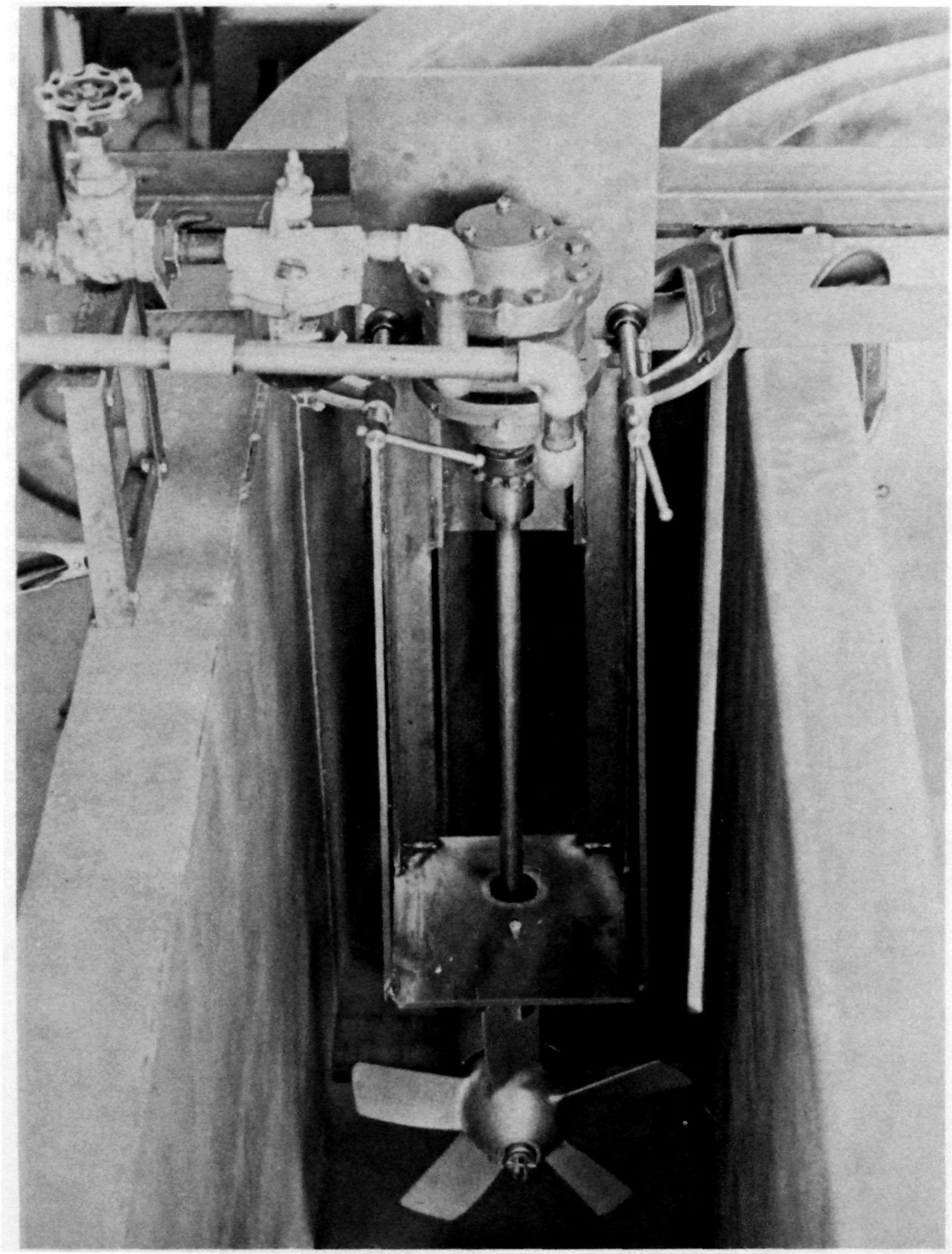


Figure 6. Circulating Tank Air-Driven Water Circulator

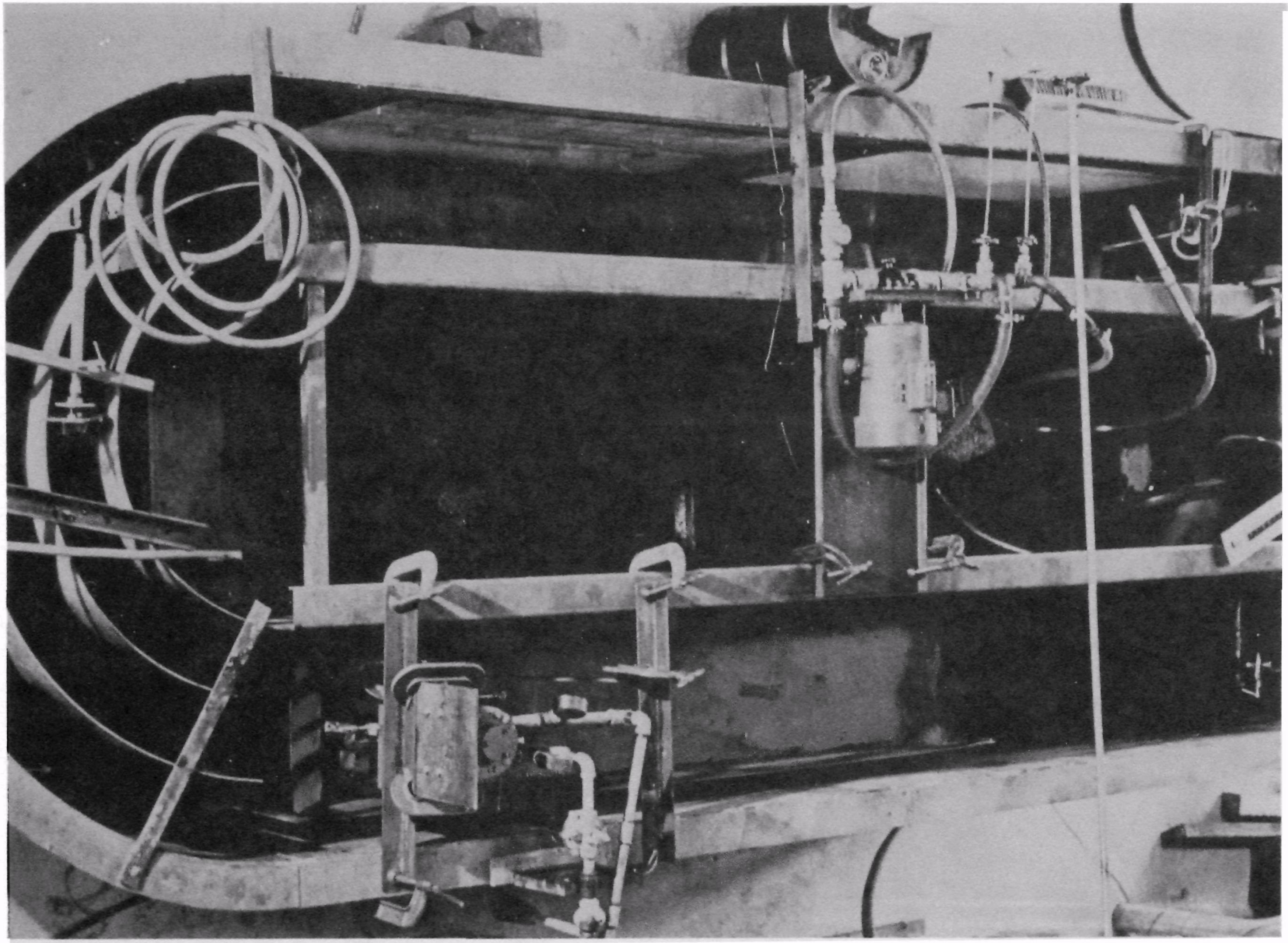


Figure 7. Circulating Tank Facility With Accessories

from the collection wells of the models to a separate oil storage container, so that quantities of oil collected could be compared directly with the quantities presented. Turning vanes were used to prevent excessive turbulence in the straight test section, and plexiglas sections provided the means of obtaining motion pictures of the underwater oil collection process.

Free stream velocity in the circulating tank was determined by inserting a calibrated water U-Toube manometer upstream of the test model.

Tow Basin Facility

The towing facility to test the SHOC models is shown in Figures 8 and 9. Figure 8 contains photographs of the building and an overall view of the tow basin. Figure 9 shows an underwater traveling light source, which was used for taking still and motion pictures; the towing cable and motor; and the wave generator. The tow basin is 5 feet wide, 5 feet deep, and over 100 feet long. The wave generator is a hinged paddle, driven through an electric cam by a variable-speed electric drive. Models were towed at velocities up to 5 feet per second and traveling waves up to 12 feet long and 6 inches high were attenuated at both ends by means of inclined beaches. A known quantity of oil was placed on the water and allowed to spread over the surface to provide an average film thickness of 0. 5 mm to 1. 0 mm, and models were towed between 1 and 4 feet per second. Measurements were made of the amount of oil collected by removing the oil and some water from the well and placing the mixture into a graduated cylinder. The oil level alone was a measure of the amount collected.

Test Oils

Petroleum oils (No. 2 and No. 6), silicone fluids, and castor oils were tested. The silicone fluids and castor oils were used with controlled amounts of dye, so that clear motion pictures could be taken of the oil flowdown and the collection processes.

Table 1 shows the densities and viscosities of the test oils.

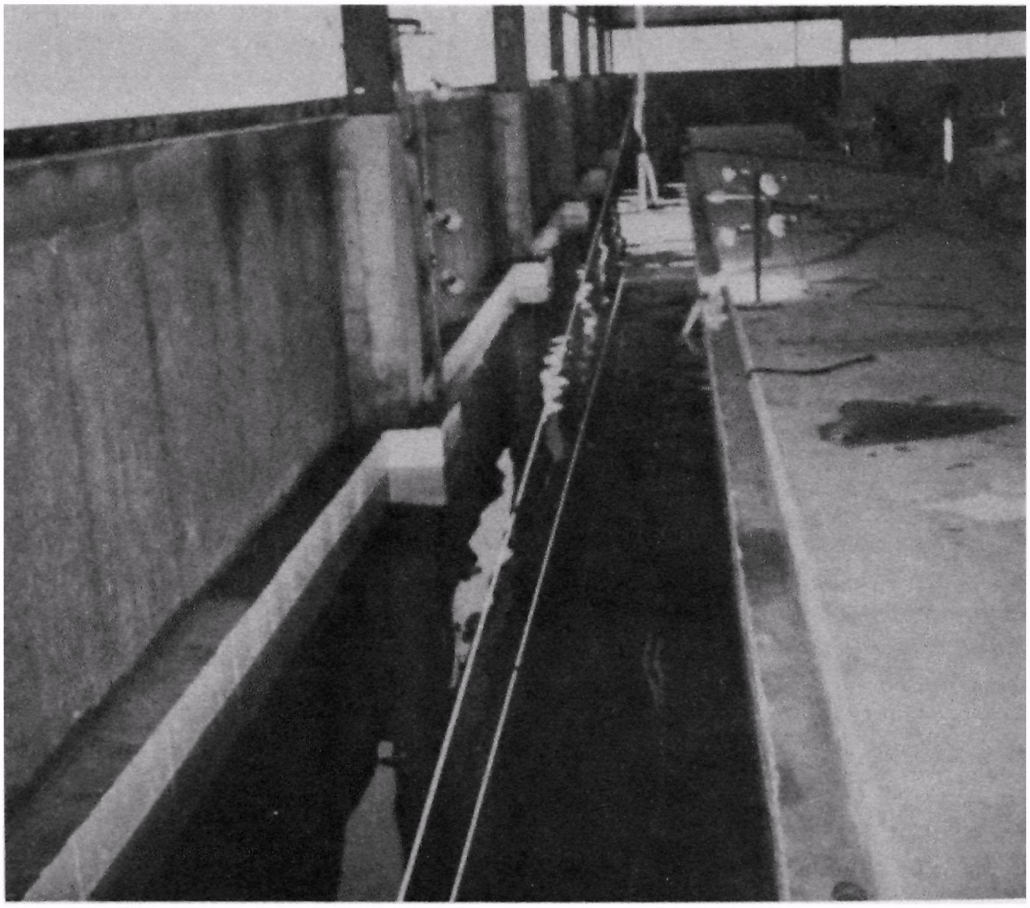


Figure 8. Tow Facility Building and Basin

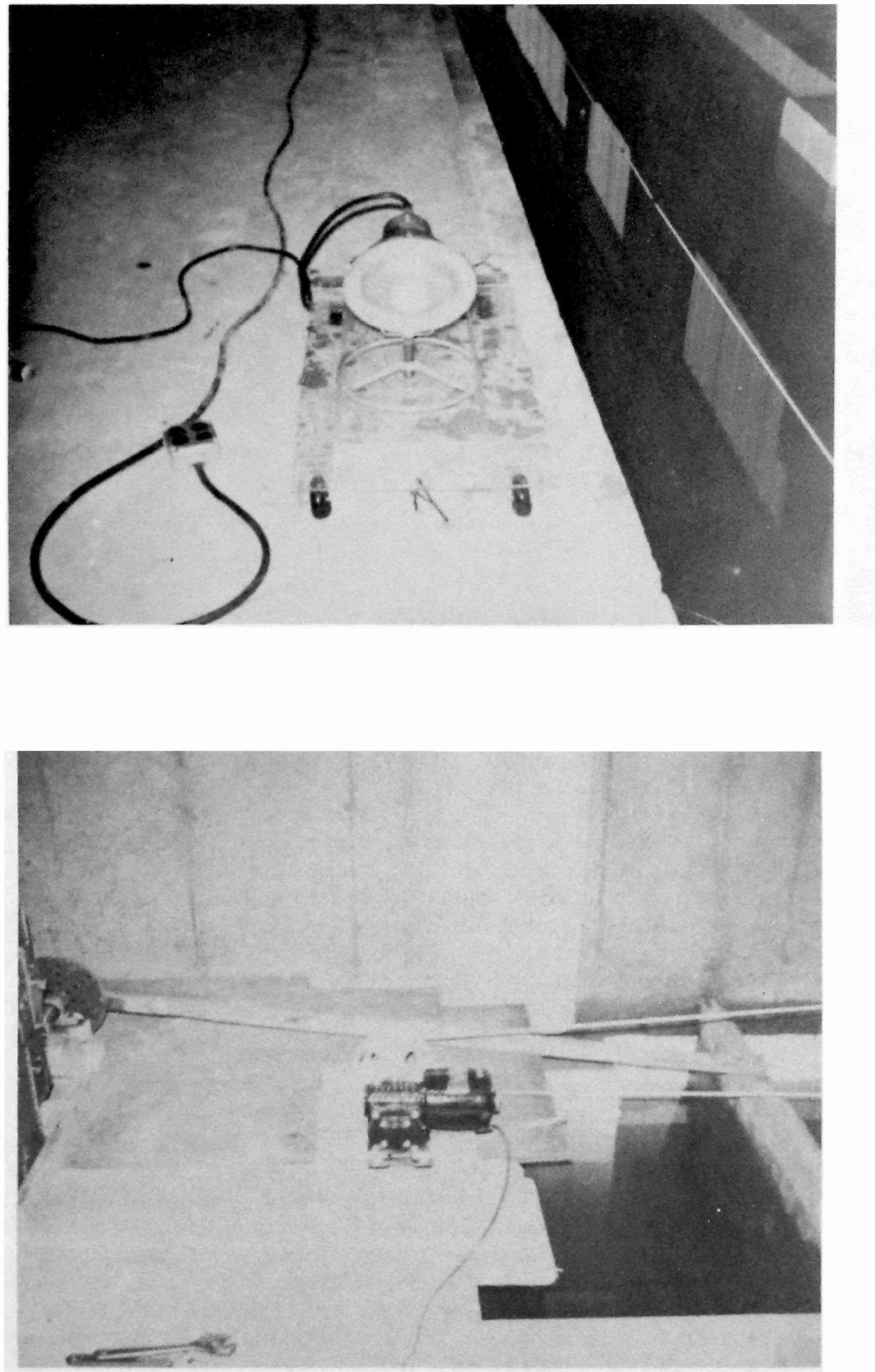


Figure 9. Underwater Light and Wave Generator for Tow Basin

TABLE 1

Properties of Test Oils

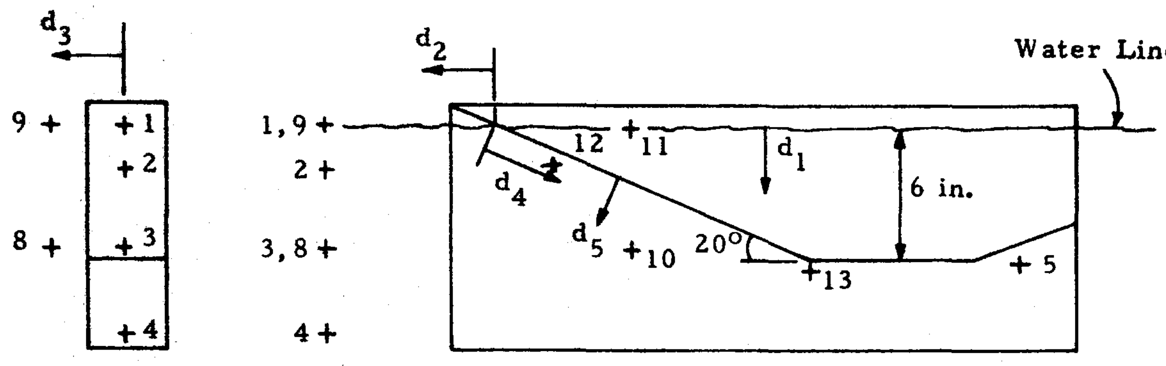
Type of Oil	Viscosity (centistokes)	Specific Gravity
Castor	2,000	0.98
Soybean	65	0.92
Silicone Fluid	10,000	0.98
No. 2 Oil	10	0.85
No. 6 Oil	10,000	0.98

Circulating Tank Tests and Results

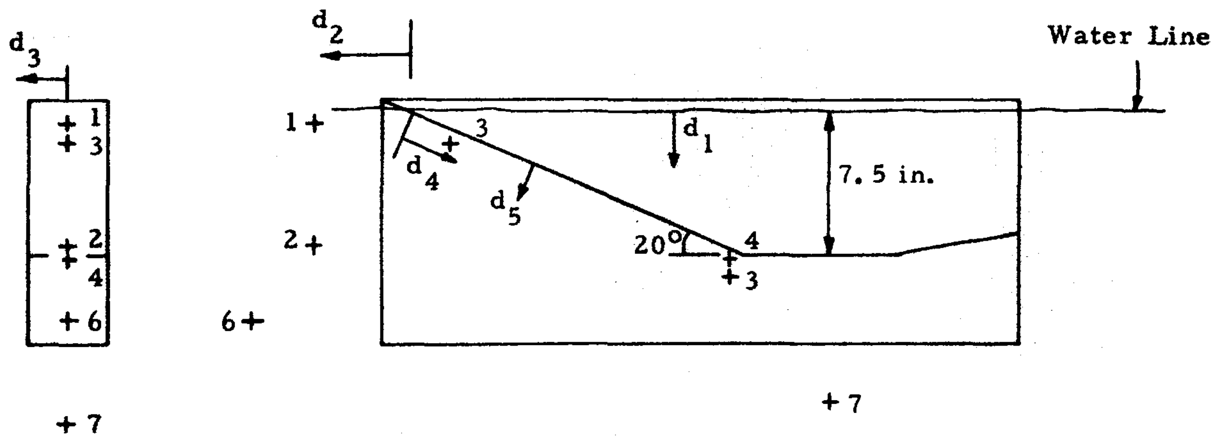
Before testing with oil in the circulating tank, it was important to establish the relevance of two-dimensional testing. This test technique greatly simplified the oil collection and efficiency measurements as well as the methods of observing and filming the tests. The first tests, therefore, were performed using a 4-inch wide model in the 12-inch wide test section. Figure 10 is a photograph of the plexiglas model used. There were non-oil tests to determine the relative velocities down the incline between the side plates around the model. Figure 11 is a schematic showing the test point locations, and Tables 2 and 3 contain velocity variations in a 1-1/4 feet per second and 3 feet per second free-stream circulating velocity. The results showed that testing models that were the full width of the circulating annulus was justified since the flow velocities down the inclined plane and under the baffles would be substantially the same as they would be if flow were permitted around the sides of the model.

The first series of oil tests was designed to determine the effect of incline angle on the oil buildup and flowdown. A flat plate was placed in the test section and inclined at angles between 10° and 40°, and a wide range of tests were performed using No. 2 and No. 6 oil at free-stream circulating velocities of 0.5 feet per second to 3 feet per second. These tests were visually monitored and filmed, so that the results could be repeatedly reviewed. Figure 12 is a photograph which shows the buildup at the interface in front of the incline and one of the flow patterns observed on the incline. Several critical observations were drawn from the results of these tests.

Figure 10. Plexiglas Model for Determining Velocity Profiles



(a) Positions for 1-1/4 fps Free Stream Velocity



(b) Positions for 3 fps Free Stream Velocity

Figure 11. Test Positions for Determining Velocity Variations

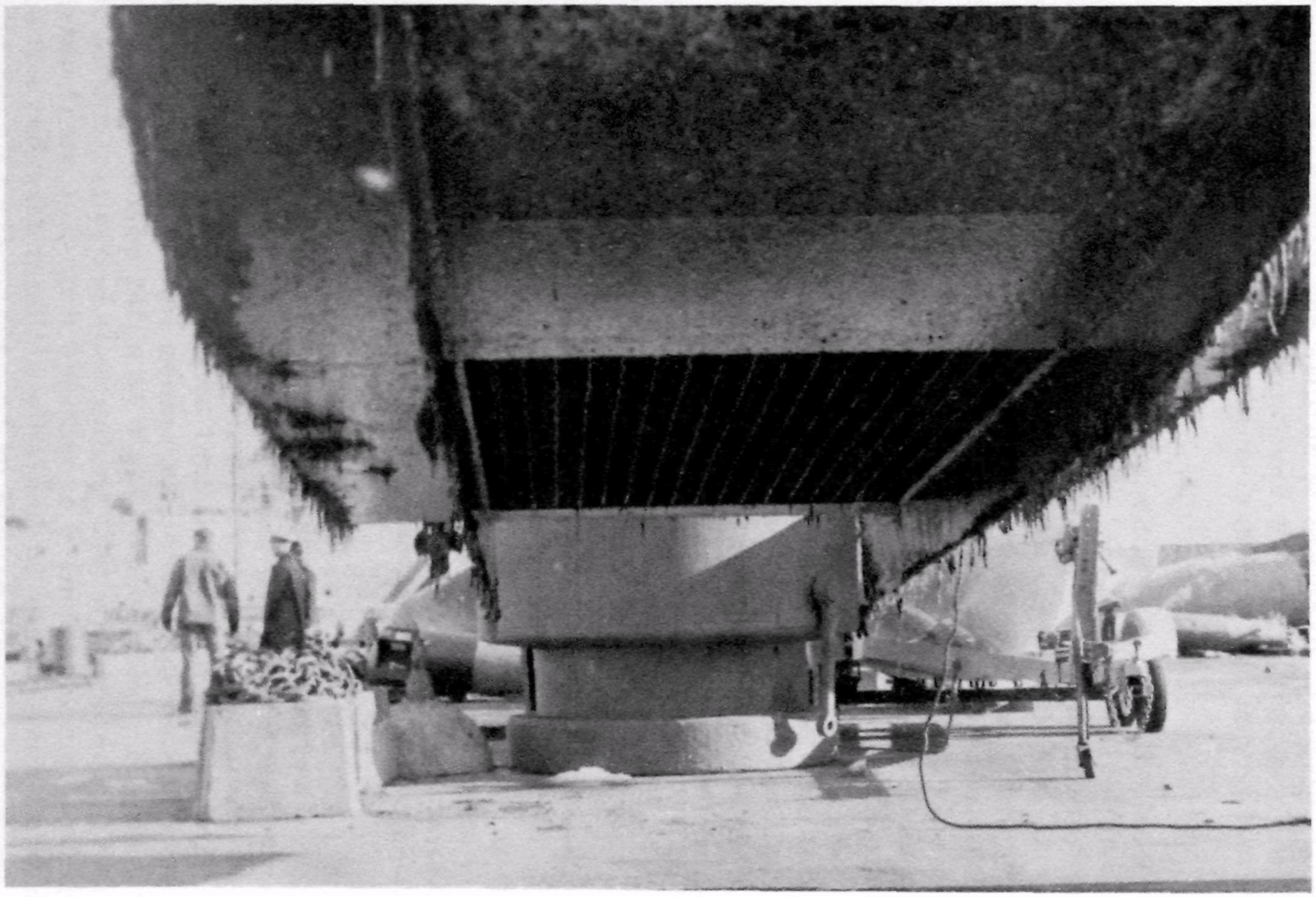


Figure 12. View Loking up at the Action of Hydrodynamic Forces on the Interfacial Wave

Table 2. Horizontal Velocity Variations Around Narrow Model (1-1/4 ft/sec Free-Stream Velocity)

Test Position	Distances (in inches) d_1	d_2	d_3	Horizontal Velocity (ft/sec)
1	1.0	+14.5	0	1.1
2	3.0	+14.5	0	1.2
3	5.5	+14.5	0	1.2
4	9.5	+14.5	0	1.15
5	5.4	-35.0	0	1.25
6				
7				
8	5.5	+14.5	4.0	1.25
9	1.0			
10	5.5			
11	1.0			
14	(see below)		0	1.4
	-----------			
	d_4	d_5	d_6	Slant Velocity
12	4.0	1.0	0	.7
13	21.0	.35	0	.9

Table 3. Horizontal and Slant Velocity Variations Around Narrow Model (3 ft/sec Free-Stream Velocity)

Position	d_1 (in)	d_2 (in)	d_3 (in)	d_4 (in)	d_5 (in)	Velocity (ft/sec)
1	1	7	0	-	-	2.8
2	5	7	0	-	-	2.8
3	-	-	0	4	1	3.1 (slant)
4	-	-	0	21	.25	3.35 (slant)
5	-	-	0	21	1.25	3.35
6	15	12	0	-	-	2.75
7	20	center/tank	0	-	-	3.0
8	1.25	0	4	-	-	3.15
9	5.5	0	4	-	-	3.3

- Below about 1 foot per second oil will not tear off the interfacial wave and flow down the incline.

- At angles less than 25° and at velocities approaching 1 foot per second all oils tend to travel down the incline in large sheets and globules. At velocities between 2 and 3 feet per second oil tends to break up into finer particles and droplets.

- Gradually curving the incline at the base of incline to the horizontal greatly improved the trajectories of oil globules and particles, which is important for minimizing collection well length.

From the results of the tests, the literature review, and the analyses an engineering test model was designed and fabricated out of plexiglas. It consisted of a curved inclined surface with a nominal angle of 23° and a collection well 34 inches long with the provision for inserting a variety of baffle cross sections and spacings. The plexiglas model is shown in Figures 13 and 14. The particular model shown has 1-inch square by 1-1/2 inch high baffle sections. It is free-floating, twelve inches wide, and has a 7-inch draft. It also has a reverse incline surface rising in the collection well to provide a concentration zone for pumping out the collected oil. Two-inch, three-inch, and four-inch square cross sections of baffles were also fabricated and inserted in the collection well. The tests of the flow of oil through these cross sections were made using the dyed silicone fluid which closely simulates a typical No. 6 fuel oil. The heights of these latter baffles were twice the dimension of the cross-section width to minimize the disturbance in the well above the top of the baffles.

A series of tests were run at various water velocities with No. 2, No. 4, and No. 6 type fuel oils. Figure 15 is a plot of the data. The straight line represents the theoretical limit of rate of oil that can be collected. Points to the left of the line are due to experimental error. Tests were run below 1.5-mm film thickness because of the EPA contract requirement. All data was normalized to 1-mm film thickness for comparison purposes.

In addition to the data plotted in Figure 15 a series of motion pictures was taken and reviewed in considerable detail. The observations of the No. 2 oil tests led to the idea of using a series of parallel flow guides on the incline. It was reasoned that these flow guides would provide a better control of the oil geometry on the incline and would result in higher oil collection rates at higher velocities. Figure 16 is a photograph of the full set of flow guides that was tested. These guides were tested from 1/2-inch spacing to 6-inch spacing, and the results were compared with the data obtained on the 12-inch-model-width tests. The results are presented in Figure 17.

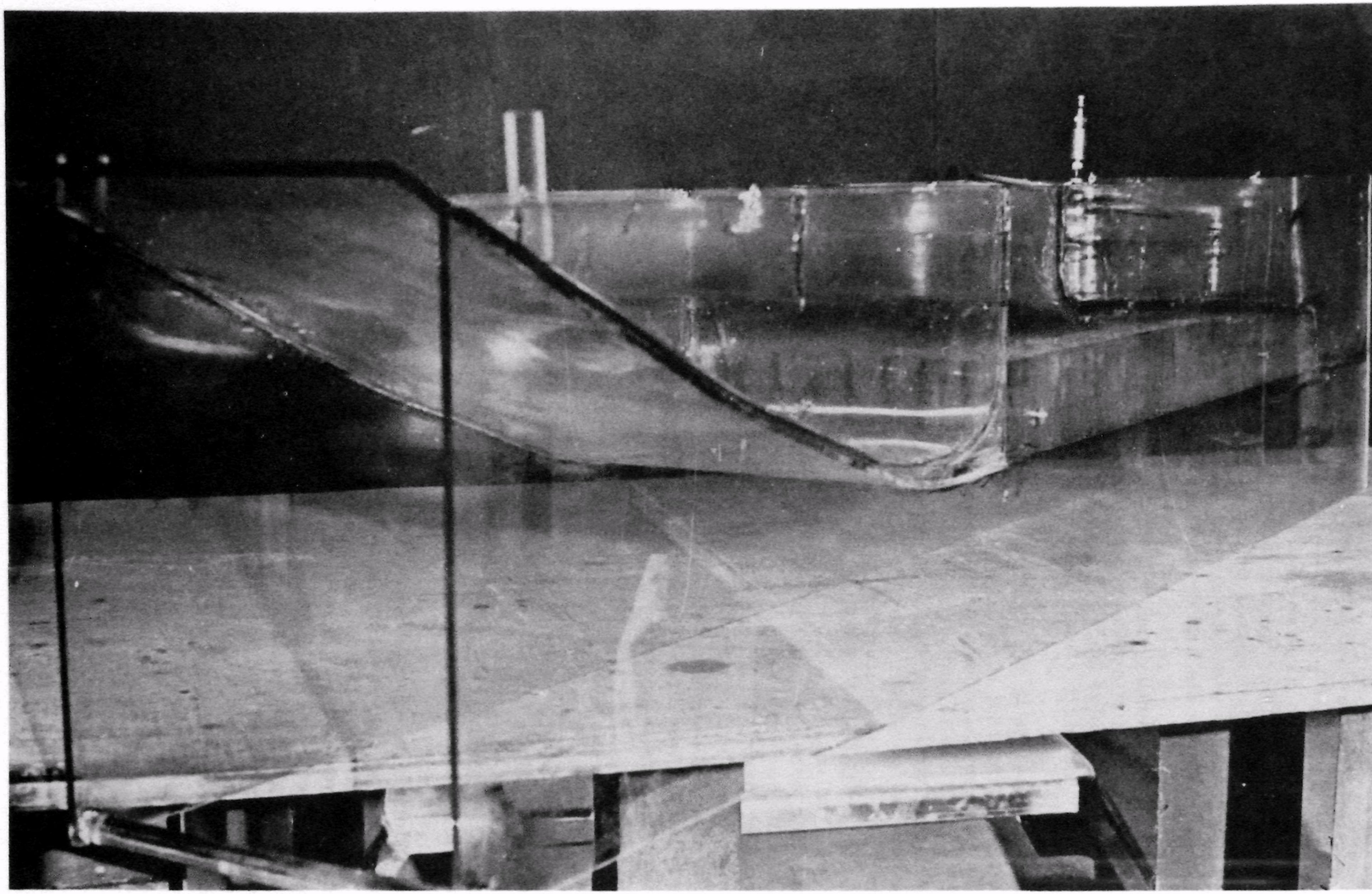


Figure 13. Plexiglas Model of SHOC with Curved Incline and Baffle Section

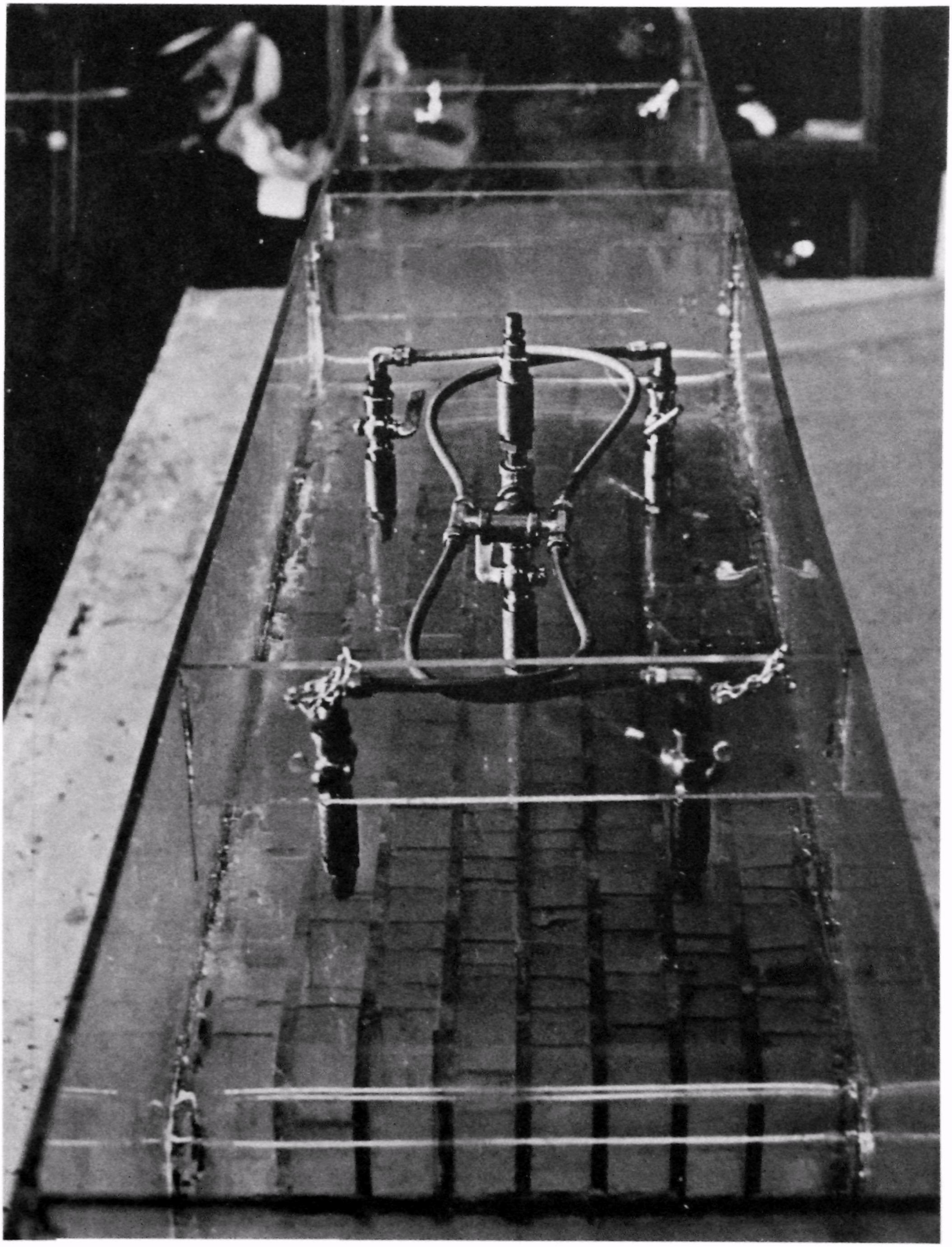


Figure 14. Baffle Section of Plexiglas SHOC Model

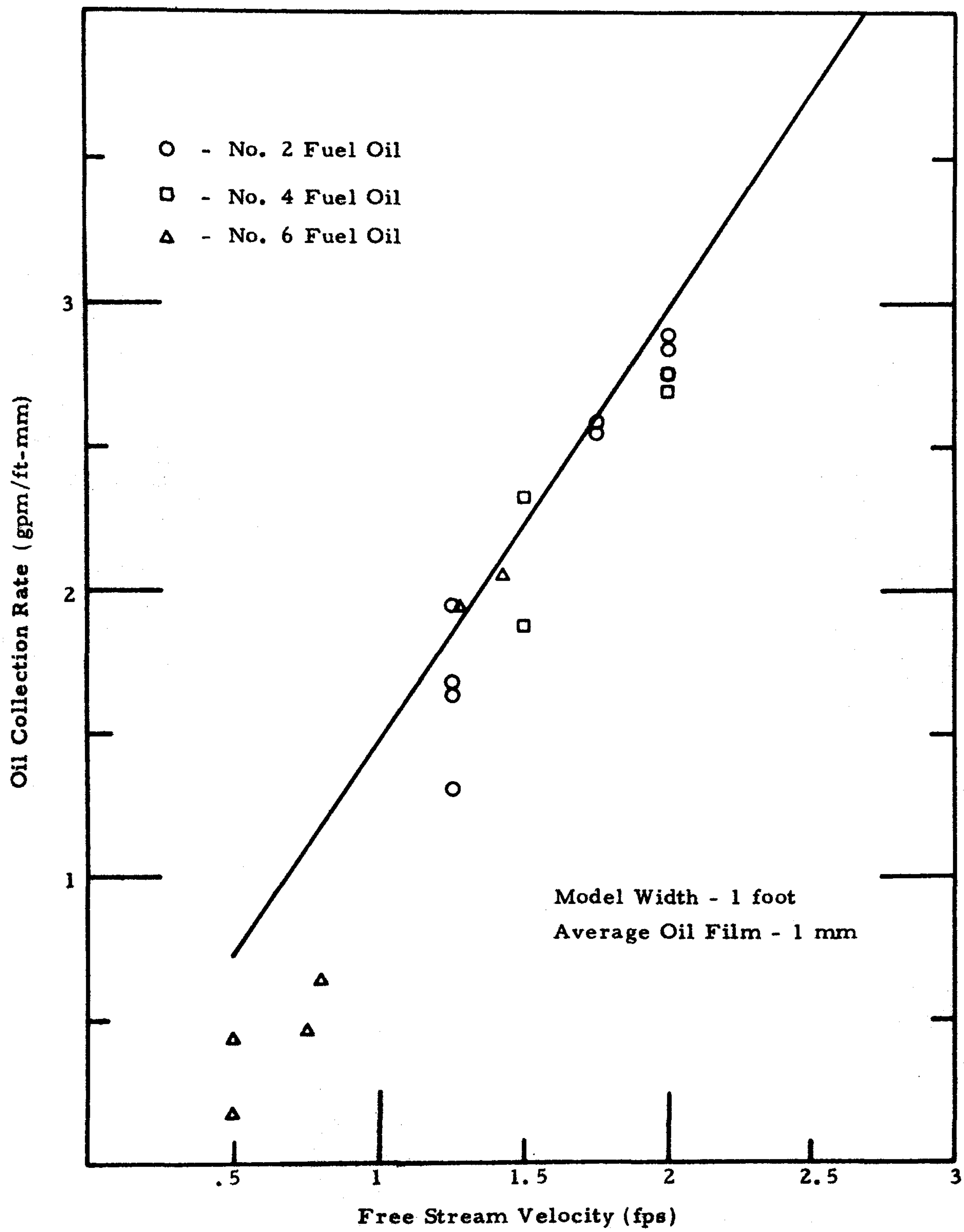


Figure 15. Circulating Tank Data for Various Oils

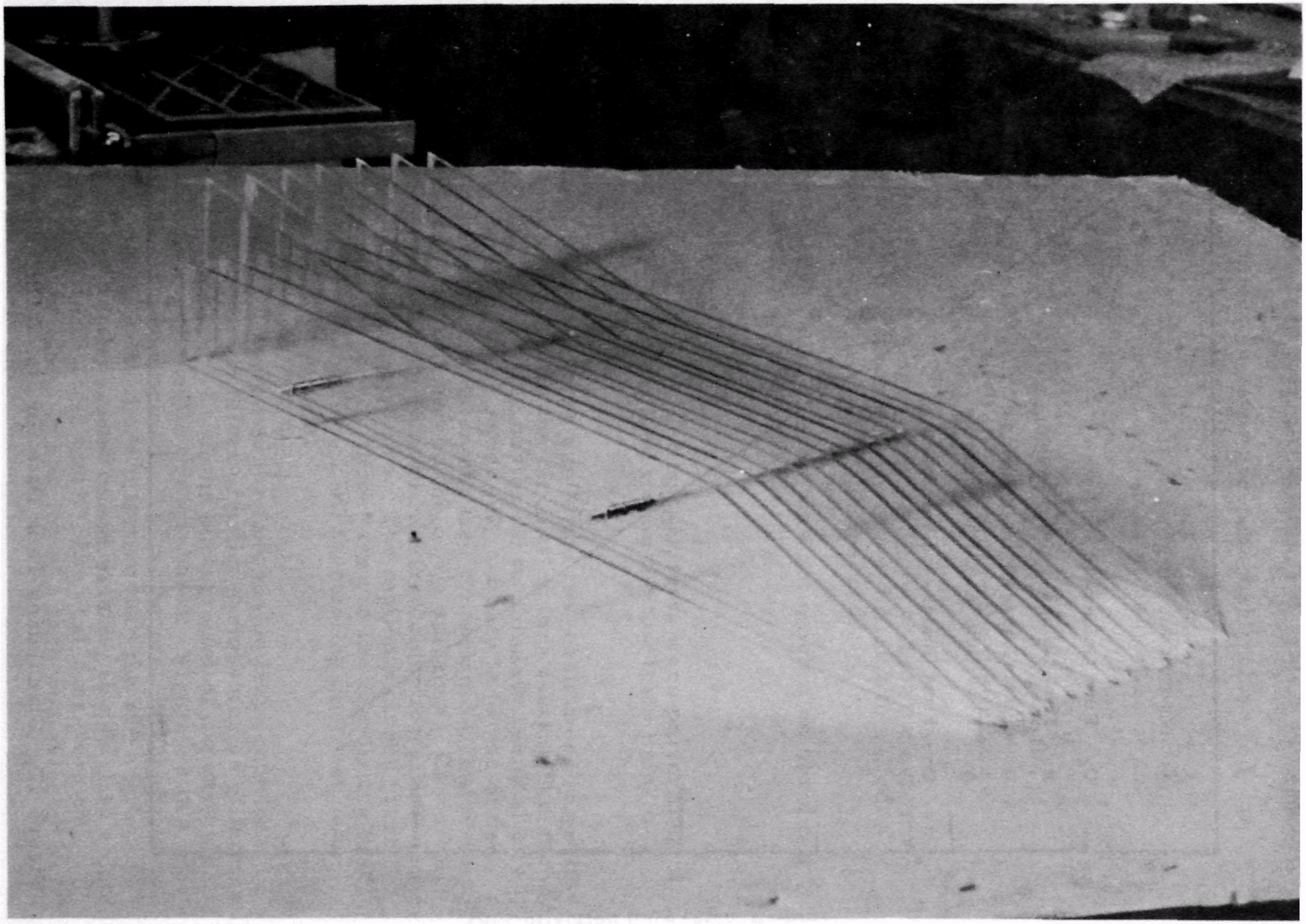


Figure 16. Flow Guides for Test Model

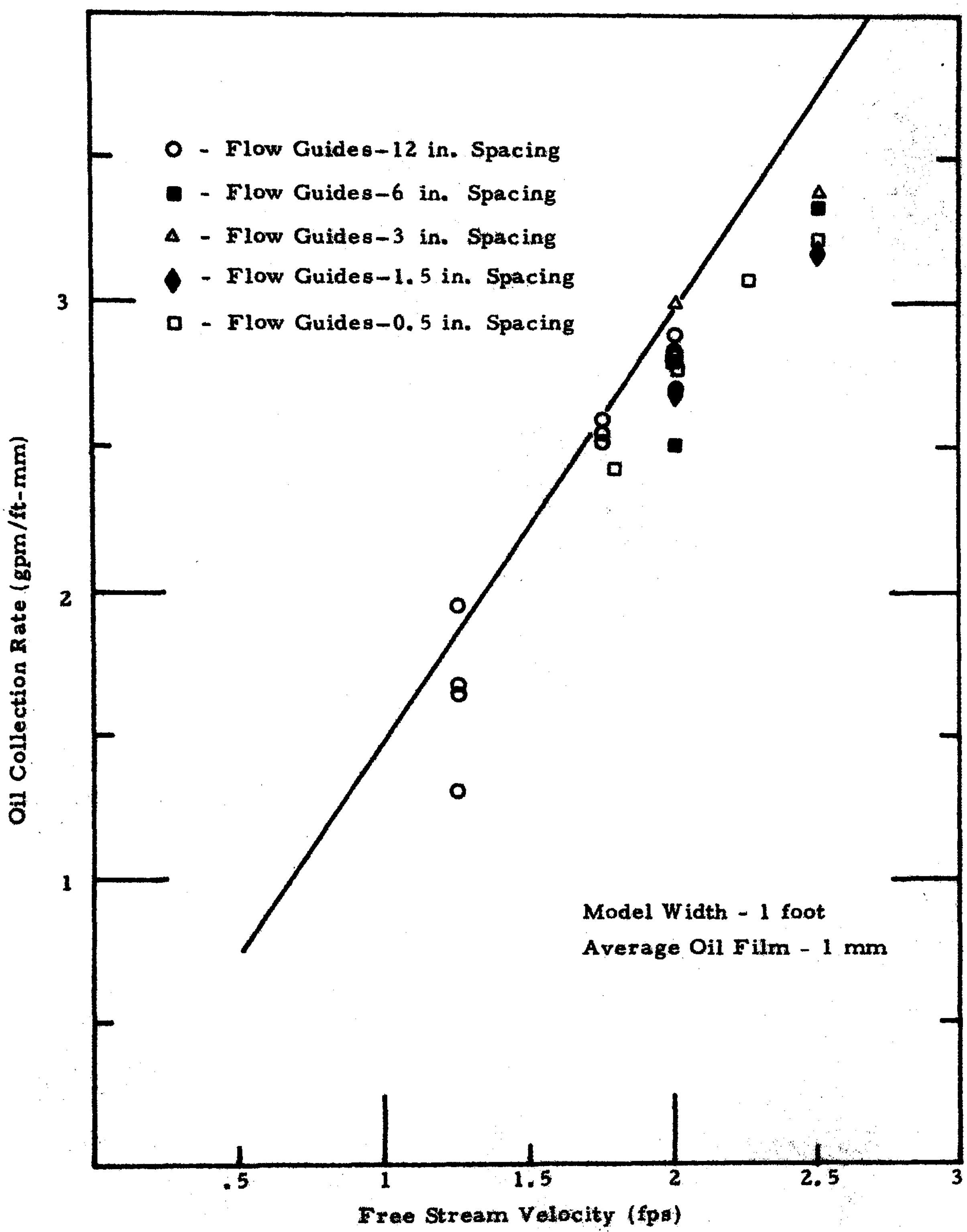


Figure 17. Circulating Tank Data for No. 2 Oil, Flow Guide Model

The conclusions drawn from our circulating tank tests were as follows:

(a) The oil collection rates are reasonably close to what was predicted theoretically.

(b) The oil collection rate is not significantly affected by introducing various flow guides at velocities up to 2.5 feet per second.

(c) The baffle cross sections must be at least 3" x 3" in order to pass the heavier fuel oils, and twice the dimension of the cross section (6") area ample for the height of the baffle to minimize the disturbances in the well above the baffles.

(d) The towing tests should be designed to test the heavier oils which are theoretically more difficult to collect at velocities over 1-1/2 feet per second.

We also observed that the oil collected was not emulsified nor did it contain any significant quantities of water.

Tow Basin Test Results

Because the majority of the circulating tank tests were performed using the lighter oils, it was decided to run the tow tests using a heavy, high-viscosity oil.

The first series of tests that were run in the tow-basin were to verify the No. 2 oil results obtained in the circulating tank tests. The second set of tests were conducted using castor oil to simulate residual oils like No. 6. The simulation was excellent, not only in terms of density, viscosity, and surface tension but also its tackiness, wettability, and its behavior on the incline and on the baffle surfaces. Castor oil was used because it could be dyed to the desired color for visual observations and for taking motion pictures. The motion pictures taken with No. 2 oil were compared with those taken in the circulating tank. These observations showed that No. 2 oil circulating tank test data would be the same as tow tank data.

Oil recovery rates were determined for four major test conditions. The first was to determine the effect of using various angles of incline on the collection rate. Figure 18 shows photographs of the variable incline angle model being placed in the tow basin. Figure 19 is a plot of the results of the tests performed. As can be seen in Figure 19, the 12° angle was significantly more effective than the 23° angle incline. A 16° angle was also tested at one velocity to establish a data point between the 12 and 23° angle tests. The next runs were to evaluate the use of flow guides. A spacing of 1 inch was selected as

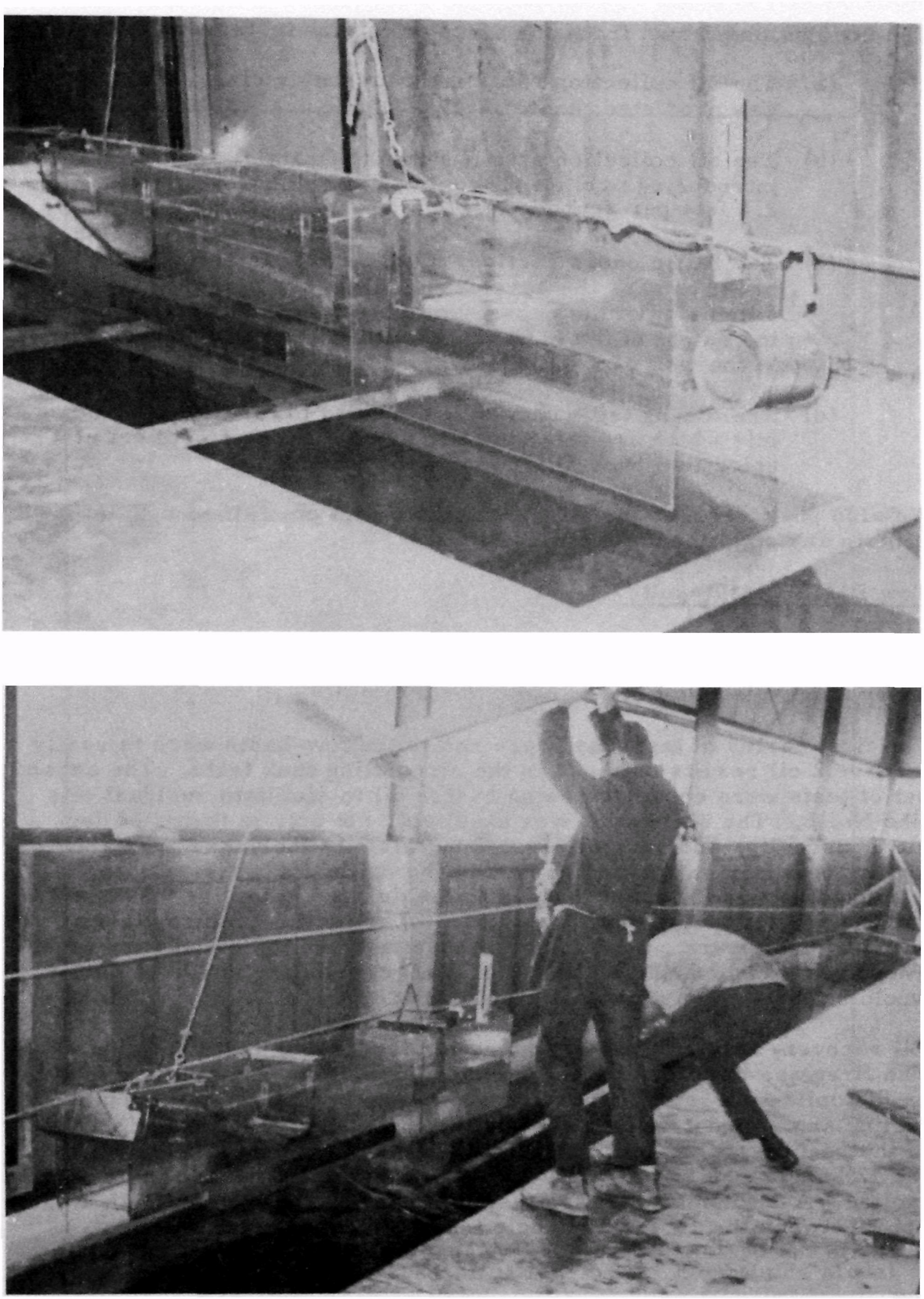


Figure 18. The Variable-Incline-Angle Model Being Prepared for Testing

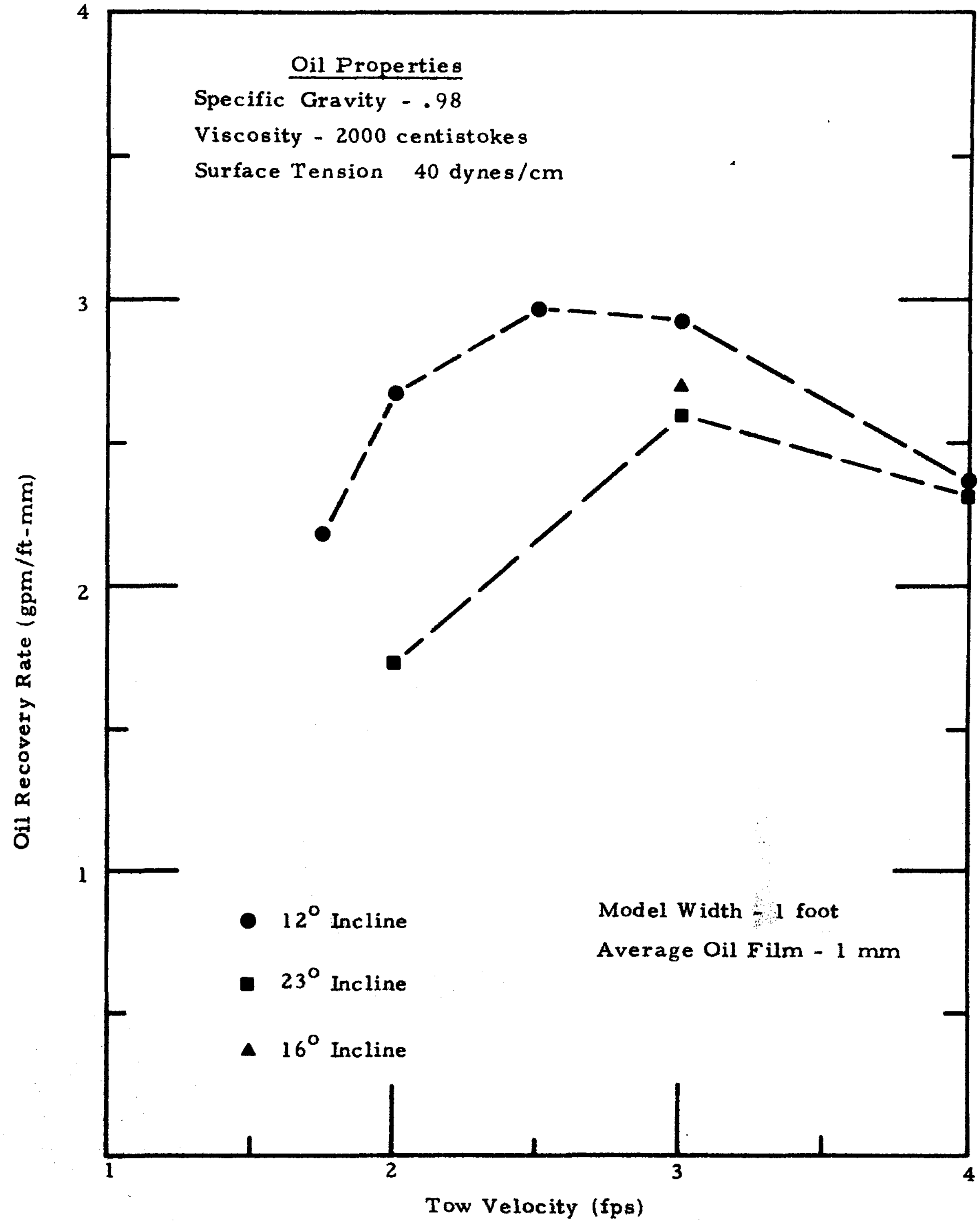


Figure 19. Tow Basin Data for Various Incline Angles

optimum for the viscosity of 2000 centistokes. Figure 20 shows the flow guides attached to the model at the tow basin. The results are shown in Figure 21. The collection rate was actually much less with the flow guides. A close examination of the motion pictures taken revealed that the increase in resistance caused a significant buildup of oil in front of the model, which was directed around the sides, resulting in much lower recovery rates.

Another series of tests compared results with waves to results in calm conditions. Since wave response models have an entirely different scaling relation from those associated with oil recovery, it was not possible to simply scale the wave lengths and amplitudes with the inclined plane model. Based on the advice of naval architects, it was reasoned that if we could generate a combination of wave lengths, wave amplitudes, and vessel velocity such that the model heaved and pitched severely, then the simulation to full scale units in relatively heavy seas would be realistic. The wave conditions selected caused the model to heave and pitch at amplitudes of 50% of the vessel draft. Vessels can and should be designed to meet this requirement in 3- to 5-foot seas if they are to survive in anticipated harbor environments. Figure 22 shows the models being tested in waves. The results of the tests are plotted in Figure 23. The performance in waves of this severity only caused a small percentage change in the recovery performance. There is an anomaly at 4 feet per second but this was caused by the test technician inadvertently leaving the wave damper plate out of the baffled collection well at this speed. This was not realized until after the test series was completed. We later verified that this decrease in performance does occur when the wave damper is removed, at the higher speed, in calm water.

The last test runs were to obtain design information on the length of the collection well. Baffle length was varied by attaching additional baffle sections to the model. This can be seen by referring again to Figure 20. Figure 24 shows the effect of doubling the baffle length. This data was particularly useful, because the oil recovery rate was higher than was predicted from calculations using the information in Appendix B. For a test oil of a viscosity of 2000 centistokes the mean size of the globules was larger than predicted. As can be seen, the increased baffle length increased the pick up rate at velocities above 1-1/2 feet per second by approximately 25%.

Some General Design Considerations

Figure 25 contains a family of curves with collection well length as the running parameter and was developed from the experimental data and the information in Appendix B. The collection rates are normalized to a unit (per foot) width of skimmer.

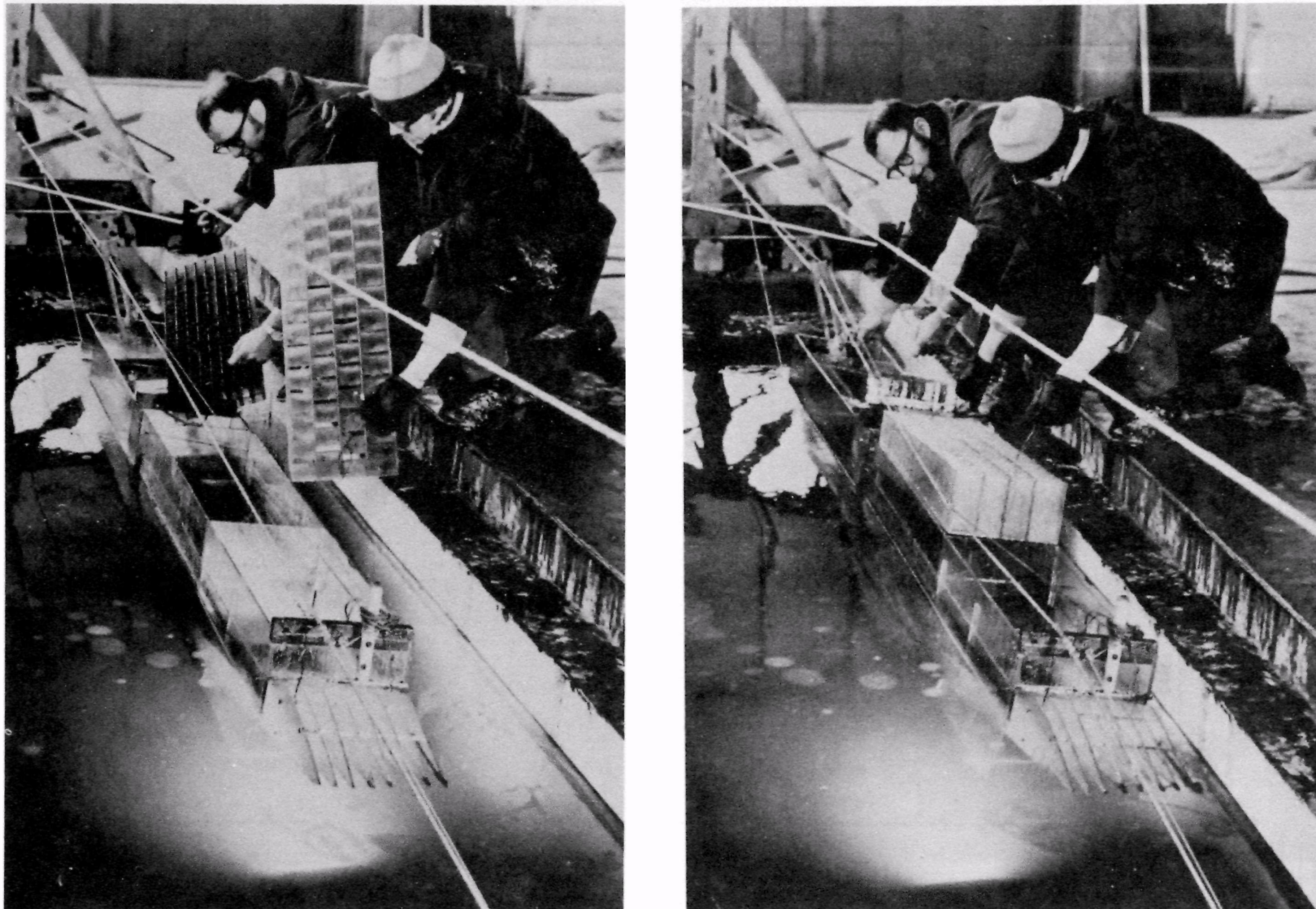


Figure 20. Tow Basin Model with Flow Guides and Baffle Sections

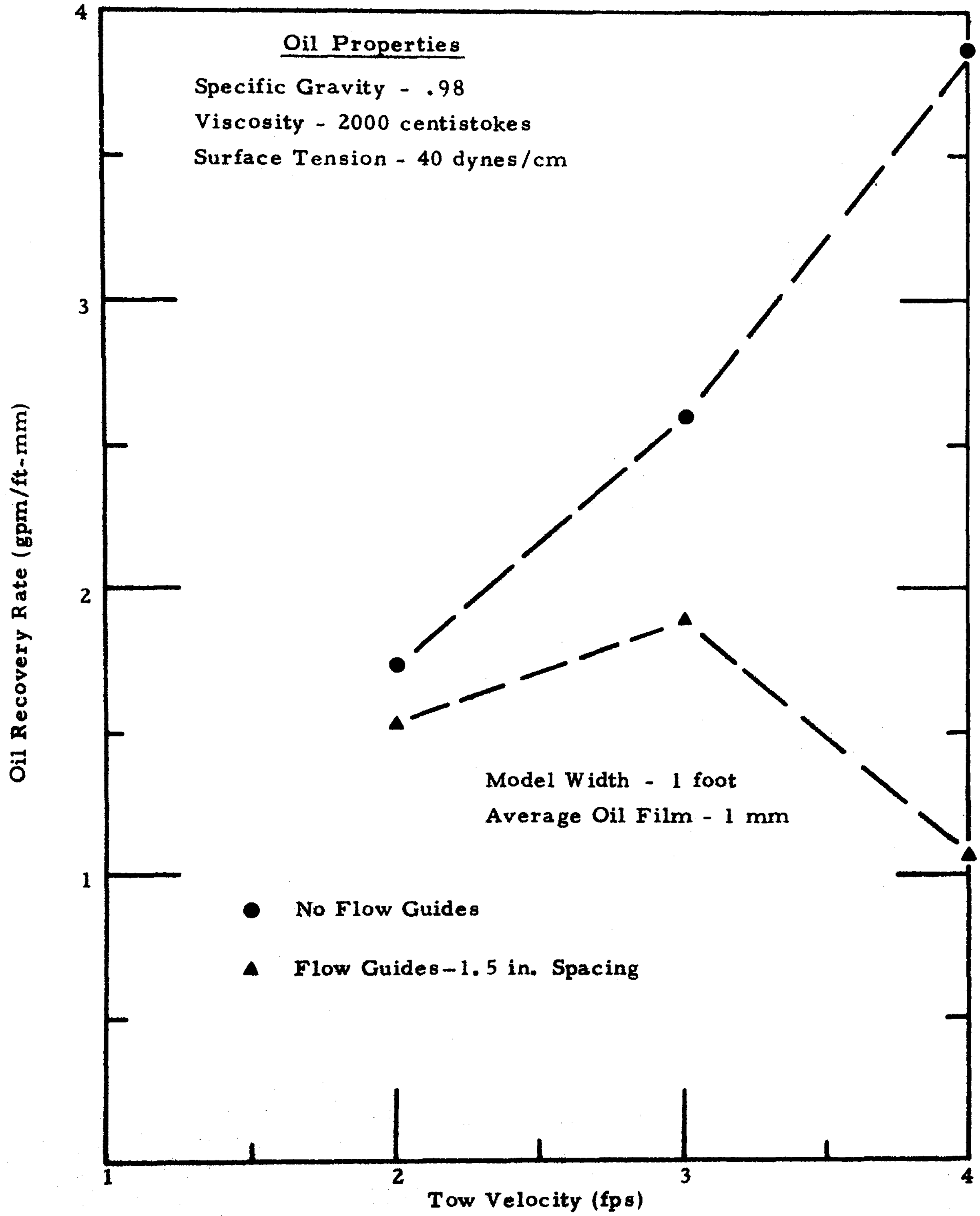


Figure 21. Tow Basin Data With and Without Flow Guides

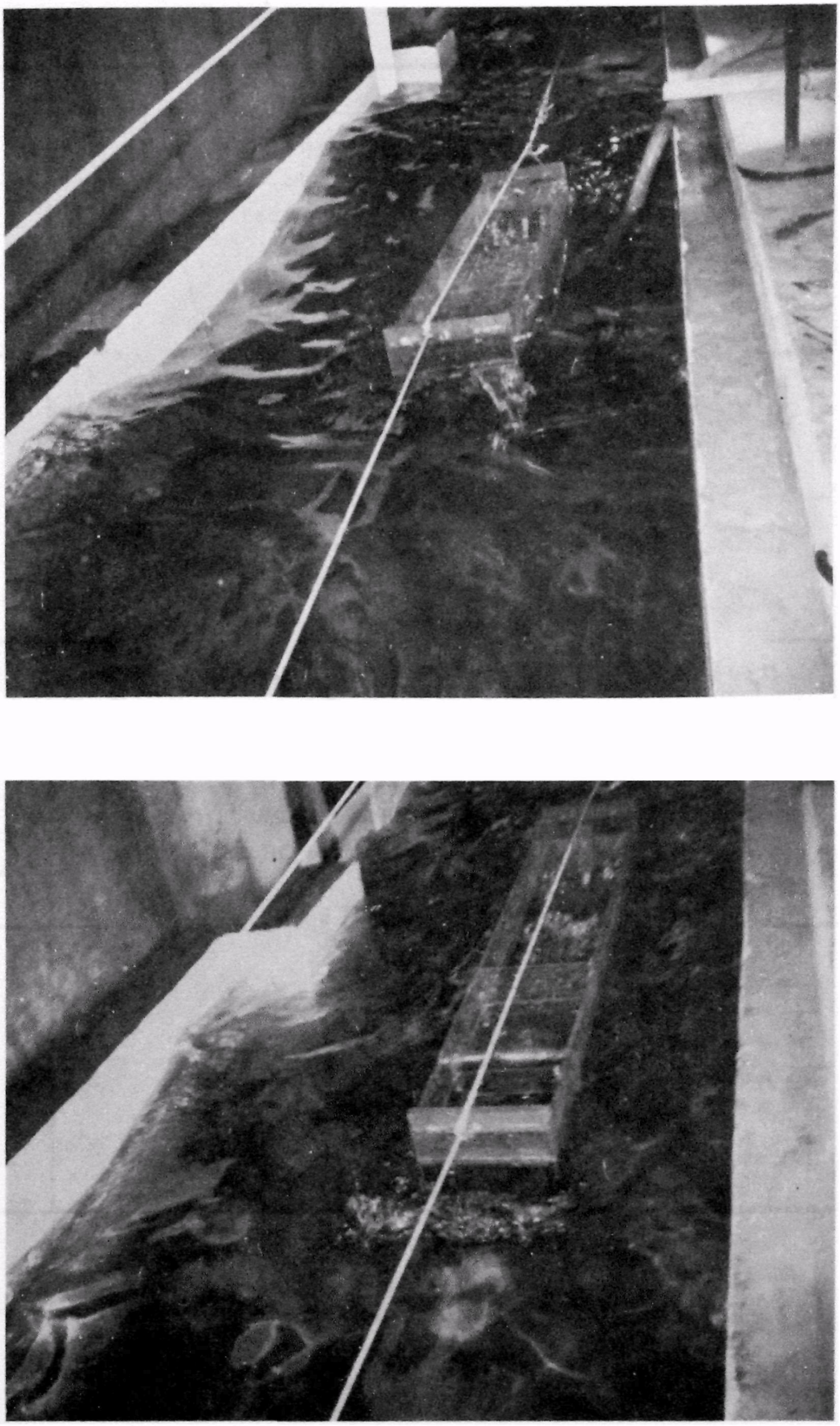


Figure 22. Tow Basin Model in Waves

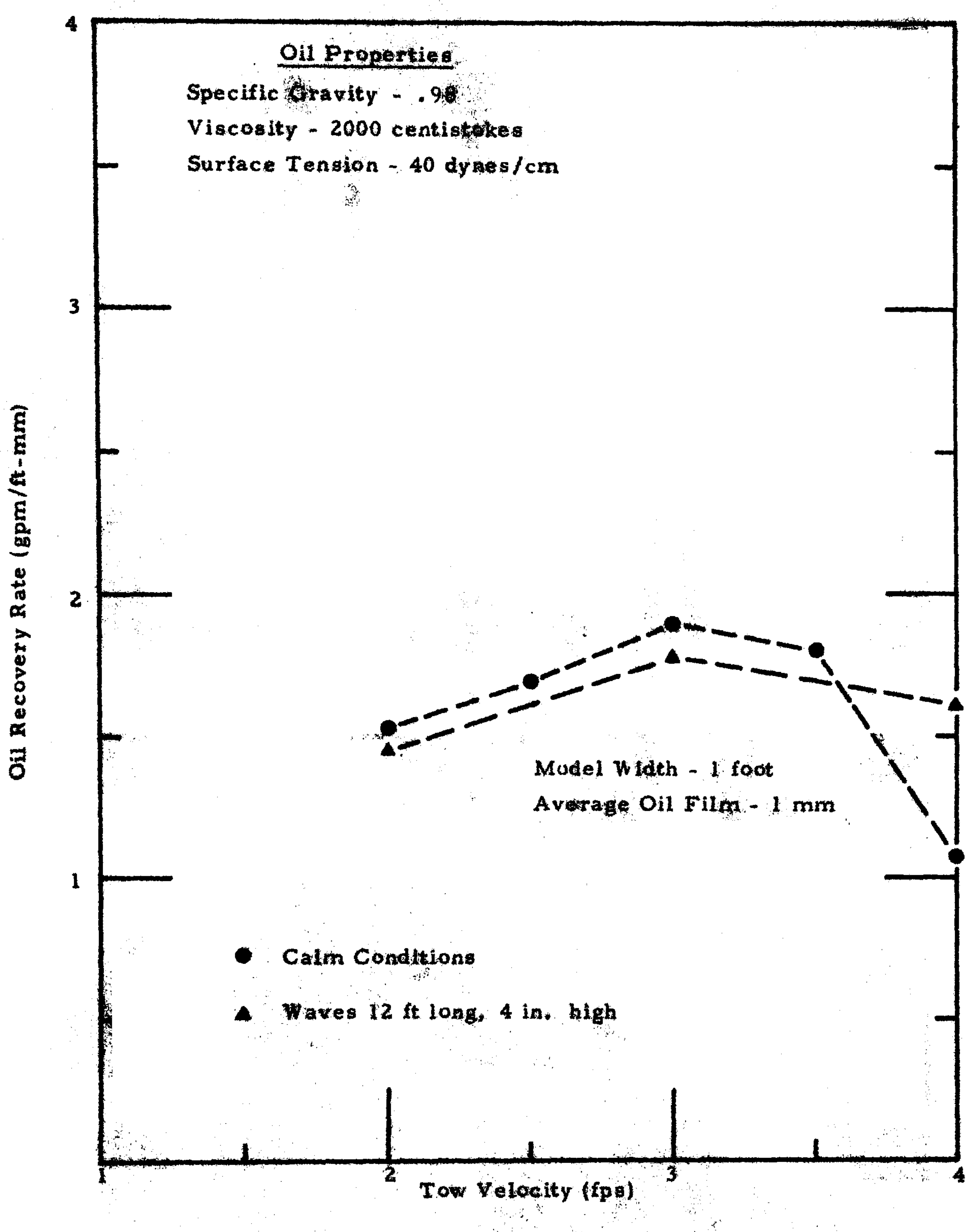


Figure 23. Tow Basin Data for Model in Waves

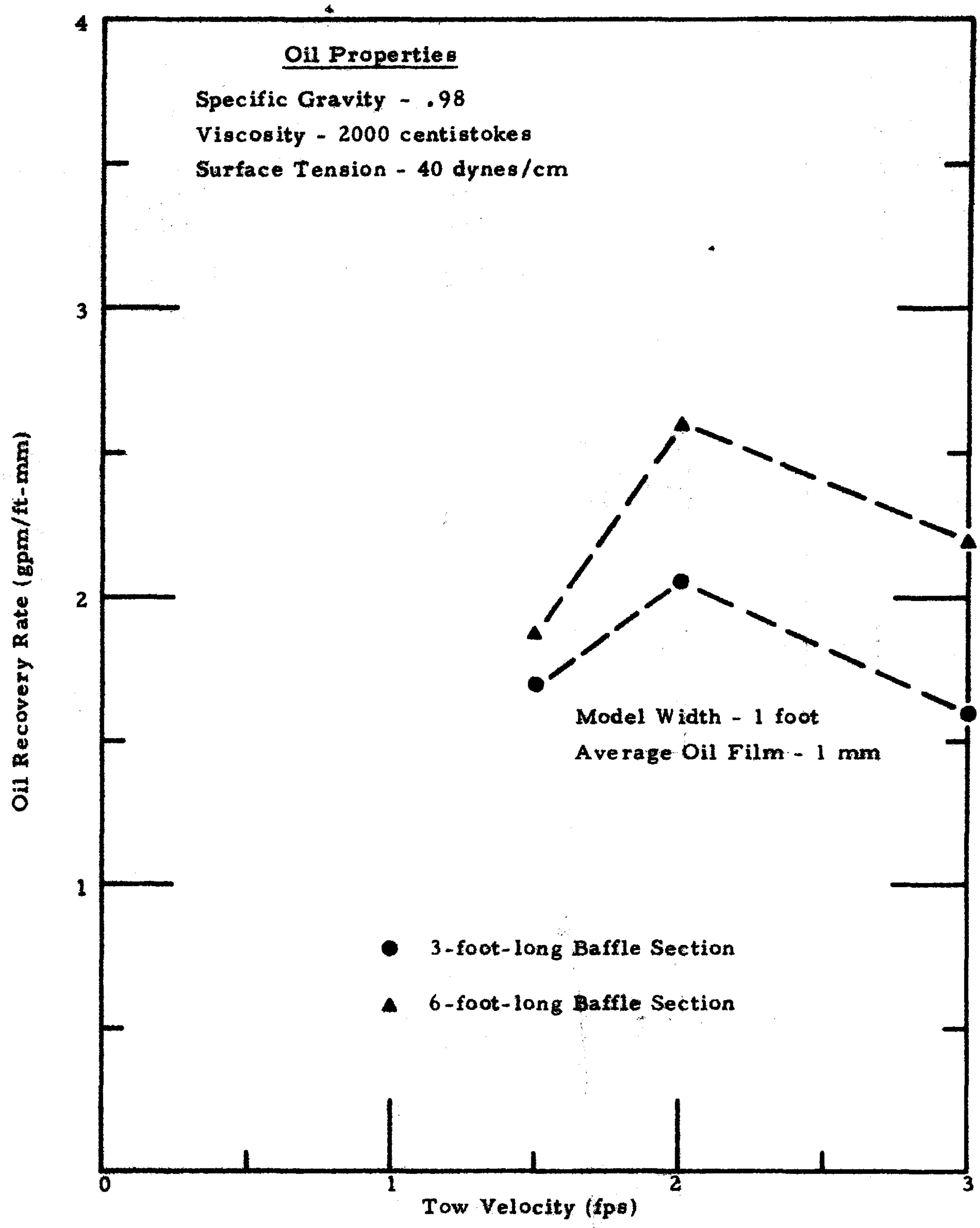


Figure 24. Tow Basin Data for Various Baffle Lengths

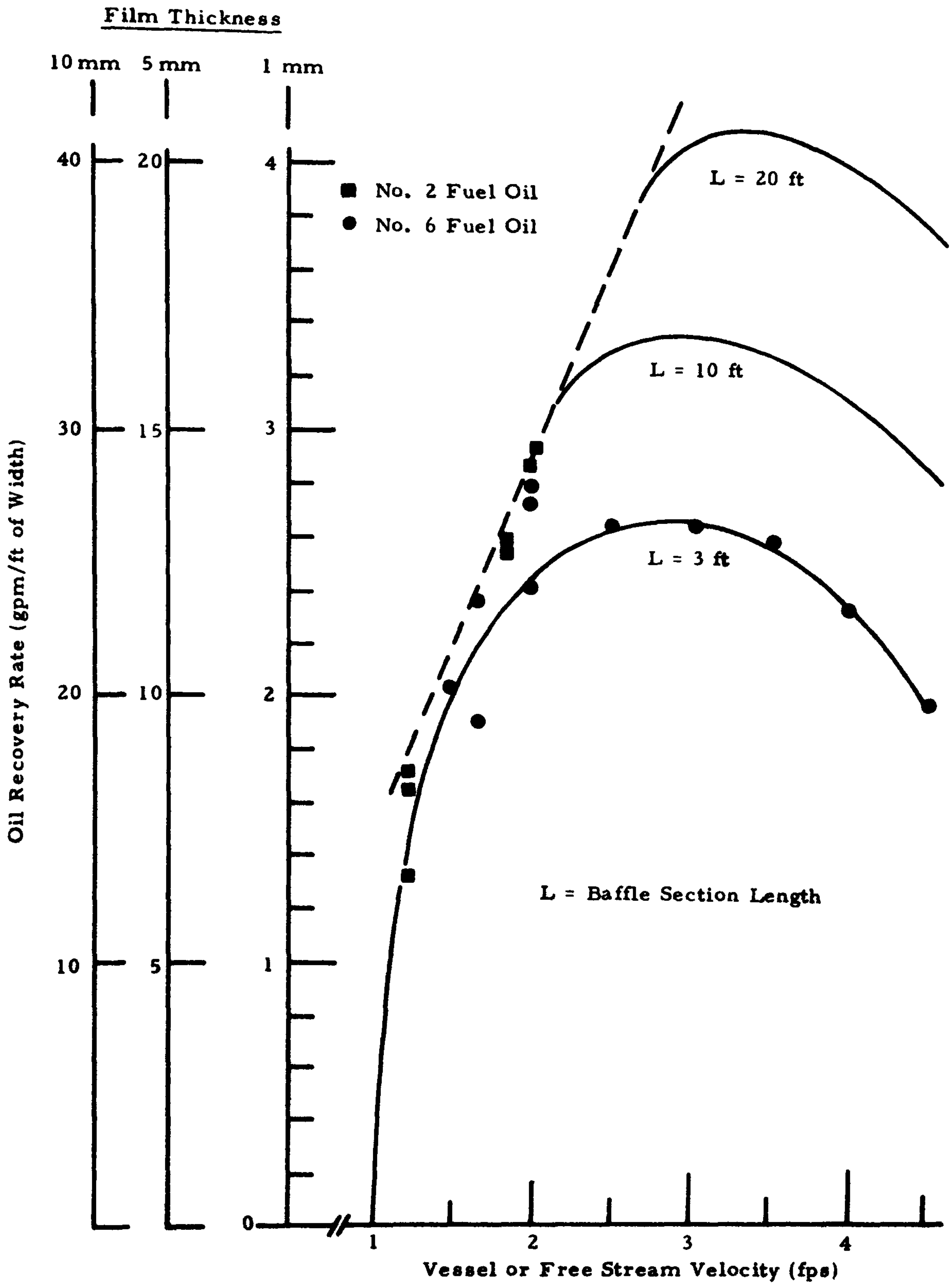


Figure 25. Design Curves for SHOC Oil Skimmer

The straight-line portion of the curve is based on the circulating tank tests with No. 2 oil. The data points shown were taken using No. 2 oil, No. 6 oil, and simulated No. 6 oil at oil film thicknesses between 0.5 mm and 8 mm. The projected parametric curves presented for the No. 6 oil were obtained from data available on submerged oil path trajectories. This information is presented in Appendix B.

The curves presented in Figure 25 show that a SHOC unit operates best at speeds between 1 and 4 feet per second. Below 1 foot per second oil will not go down the incline and above 4 feet per second the oil collection rate decreases rapidly. The larger the baffled section the more effective the collection. It should be recognized, however, that when <u>relative</u> velocities between the oil and water exceed 3 feet per second, the oil breaks up into fine particles and becomes entrained in the water column. However, at vessel velocities of 3 to 4 feet per second the actual relative velocity between the oil and water, since the oil is also moving, is much less than 3 feet per second. Assuming that a design will be operated near optimum speed, therefore, the oil recovery rate can be increased by (1) making the unit wider, (2) using a longer collection well, or (3) increasing the oil slick thickness in front of the device.

SECTION V

DESIGN, FABRICATION AND TEST

In order to best show the possible performance characteristics of a SHOC unit, it was felt that the demonstration unit should be as large as possible within our budget and time limitations. A unit on the order of twenty feet long and eight feet wide could easily be transported, could carry several people in the Boston Harbor environment without danger, and appeared to be within our budget. Within this dimensional framework it was decided to make the well 7.5 feet long and the incline angle 15°, with a well depth from the waterline of 21 inches. These basic dimensions were derived from the test data and the design curves to have a unit that would operate effectively between 1 and 2 knots vessel velocity.

Description

Figure 26 contains an outline drawing of the SHOC demonstration unit. The hull is partitioned into compartments, which are used for flotation and ballast. The flotation tanks were filled with sufficient foamed material to prevent the vessel from sinking in the event the tanks were ever ruptured. The ballast tanks were positioned so that the vessel could be trimmed in roll, pitch, and draft, using either solid ballast or sea water. A 275-gallon tank was also built into the hull to provide storage for the test oils.

The side view shows some of the details of the collection well. The baffles are 3 inches square by 9 inches high. These dimensions were selected from tests in the circulating tank, where a variety of geometries were examined. The well is truncated so that a deep pocket of oil concentrates at the top, where it is pumped to the storage tank.

The top view of the unit shows the oil handling system, which consists of a gasoline engine-driven screw pump that could operate at several speeds, pump a wide variety of oils, and handle 0.4 inch diameter particles. The system was capable of pumping oil from the collection well and transferring it to the storage tank or pumping oil from storage and deploying it in front of the vessel, as was done for demonstration purposes. The demonstration unit also has viewports for the purpose of observing the oil being collected in the well as the vessel moved through an oil slick.

Propulsion was provided by two 12.9 hp Crysler outboard gasoline engines with dual steering controls and individual throttle and shift controls, all located on a central console. Electricity was generated on board to power the running lights and charge the battery.

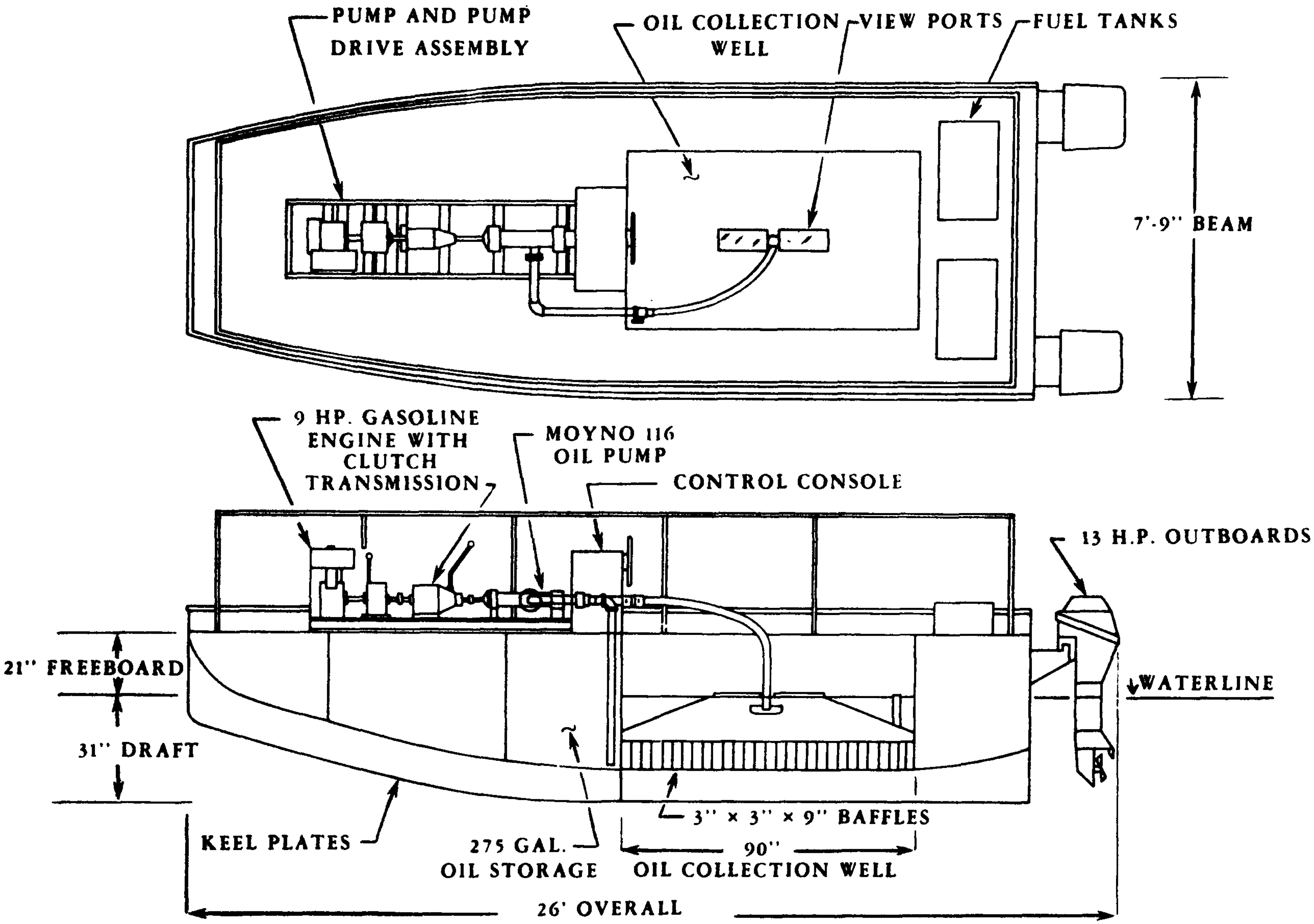


Figure 26. Outline Drawing of the SHOC Demonstration Unit

Fabrication

The demonstration unit was fabricated completely out of aluminum, and the dry weight of the hull and accessories was 5000 lbs. The unit fully ballasted and at its design draft and trim weighed 11,000 lbs. This weight represents a considerable amount of water ballast which could be used as oil storage capacity on an operational unit. Figures 27 and 28 are photographs of the hull, taken while it was being fabricated. Figure 29 is a photograph of the completed unit being launched at the Coast Guard Base, Boston Harbor. Figure 30 is a photograph of a scale model which shows the pump handling system and some deck details.

Stability and Wave Response

As described in previous sections, tests on plastic models have been conducted in the tow basin to determine the effects of waves on the oil collection rate. The results of these tests showed that there was little, if any, loss in recovery rate when the vessel heaves and pitches at single amplitudes equal to one-half the draft of the vessel.

In the design of the demonstration unit stability and wave response characteristics were calculated. A summary of these characteristics is given below.

Stability

Transverse Metacentric Height	3.75 ft
Longitudinal Metacentric Height	26.00 ft
Sinkage	855 lbs/in

Response	Period	Exciting Wave Length
Heave	2.1 sec.	22.3 ft.
Pitch	2.55 sec.	33.2 ft.
Roll	2.3 sec.	27.9 ft.

The values of metacentric heignts show that there is good stability in both the transverse and longitudinal direction. Two men and equipment would encounter only a few degrees of roll. The sinkage in pounds per inch of draft increase indicates that 5 men on board increased the draft by only 1 inch.

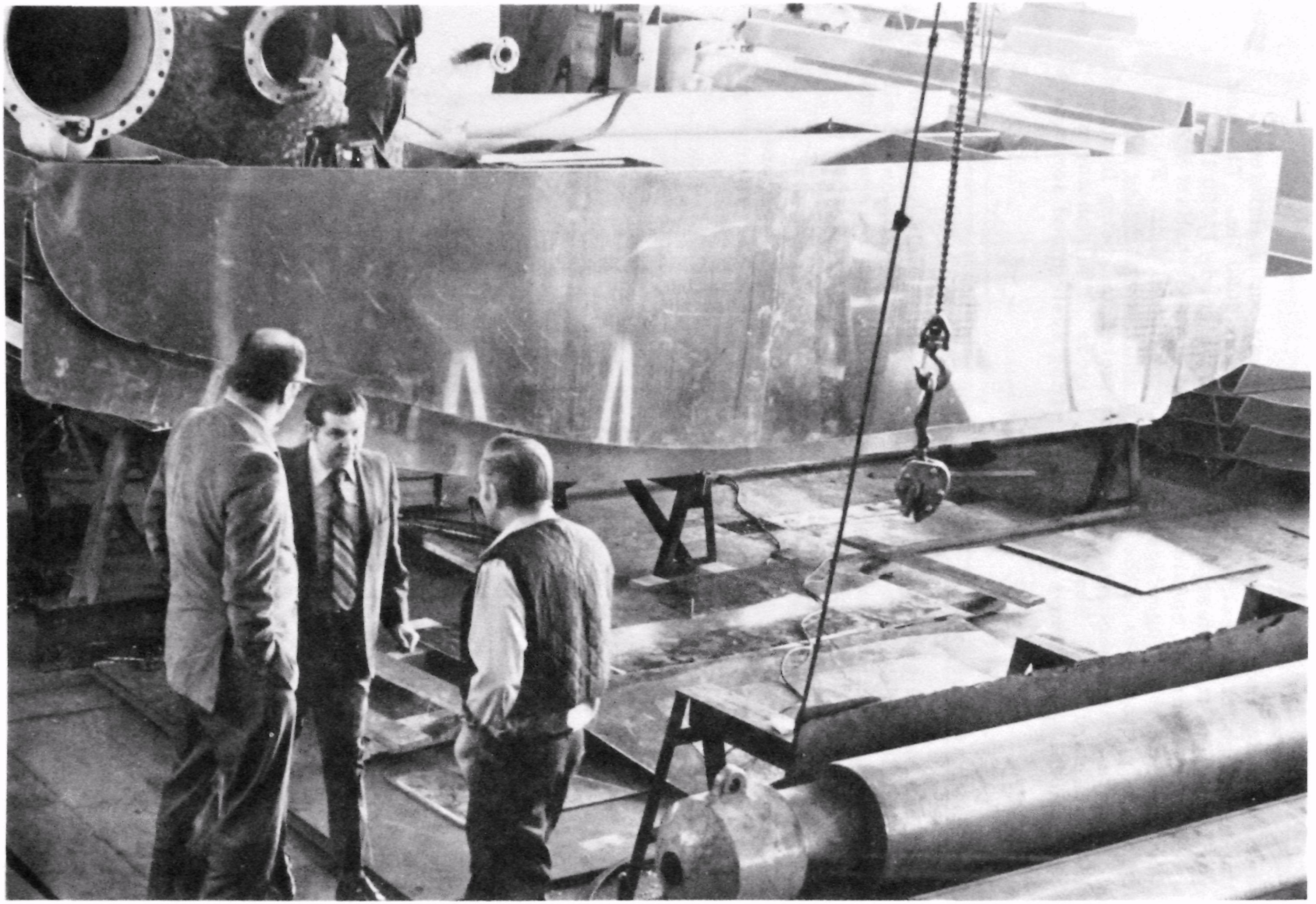


Figure 27. Side View of SHOC Hull Being Fabricated

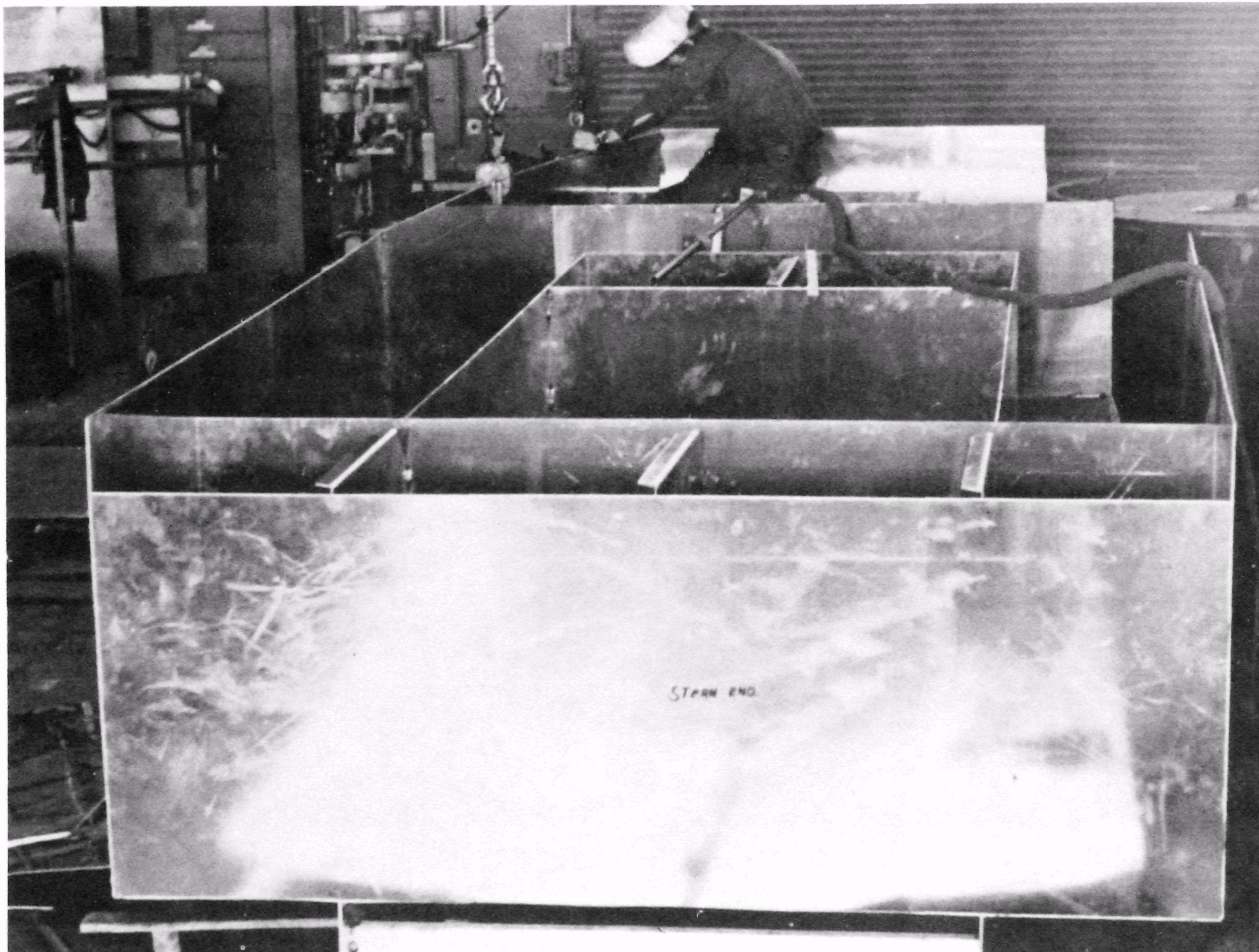


Figure 28. Stern View of SHOC Hull Being Fabricated

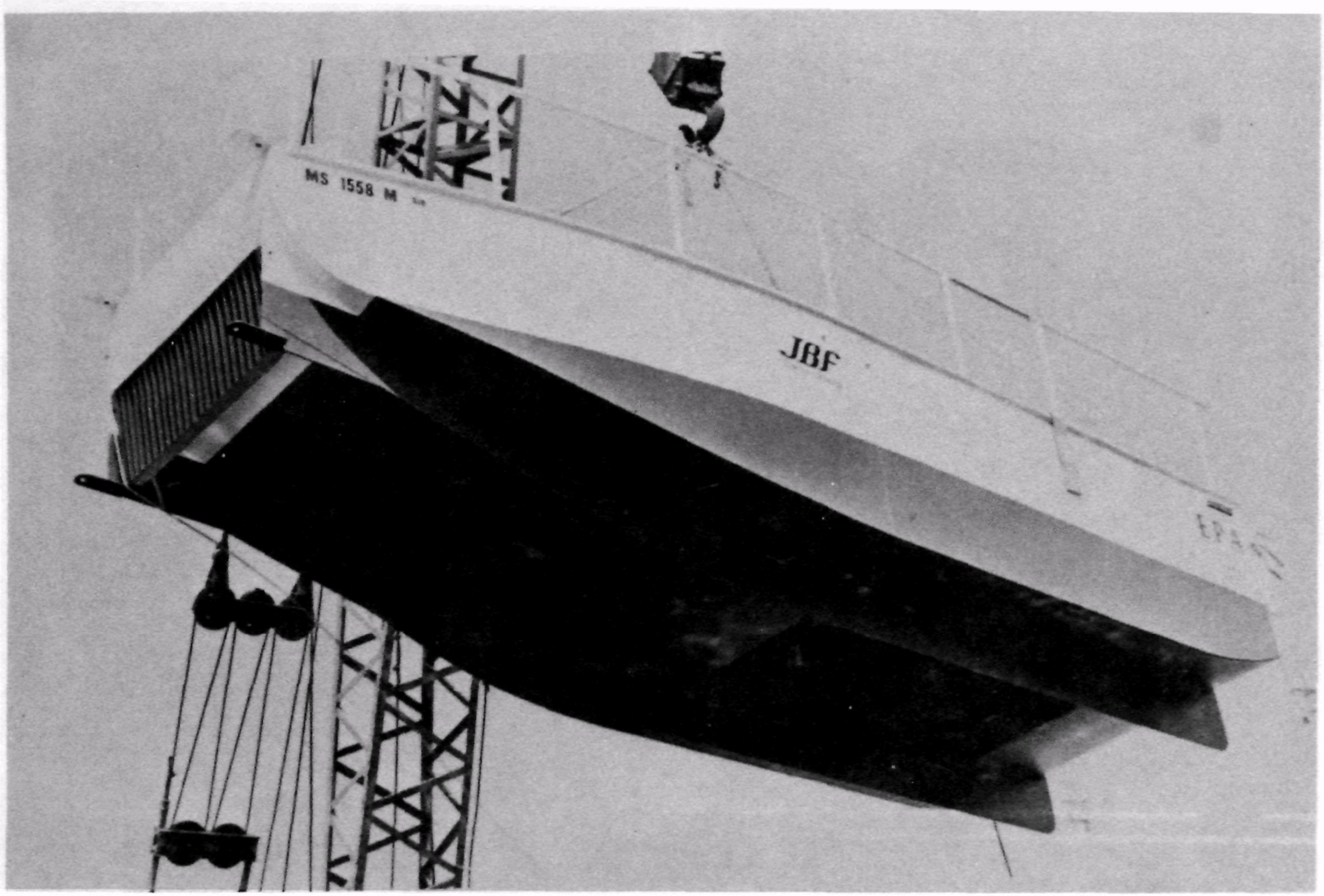


Figure 29. The SHOC Being Launched in Boston Harbor

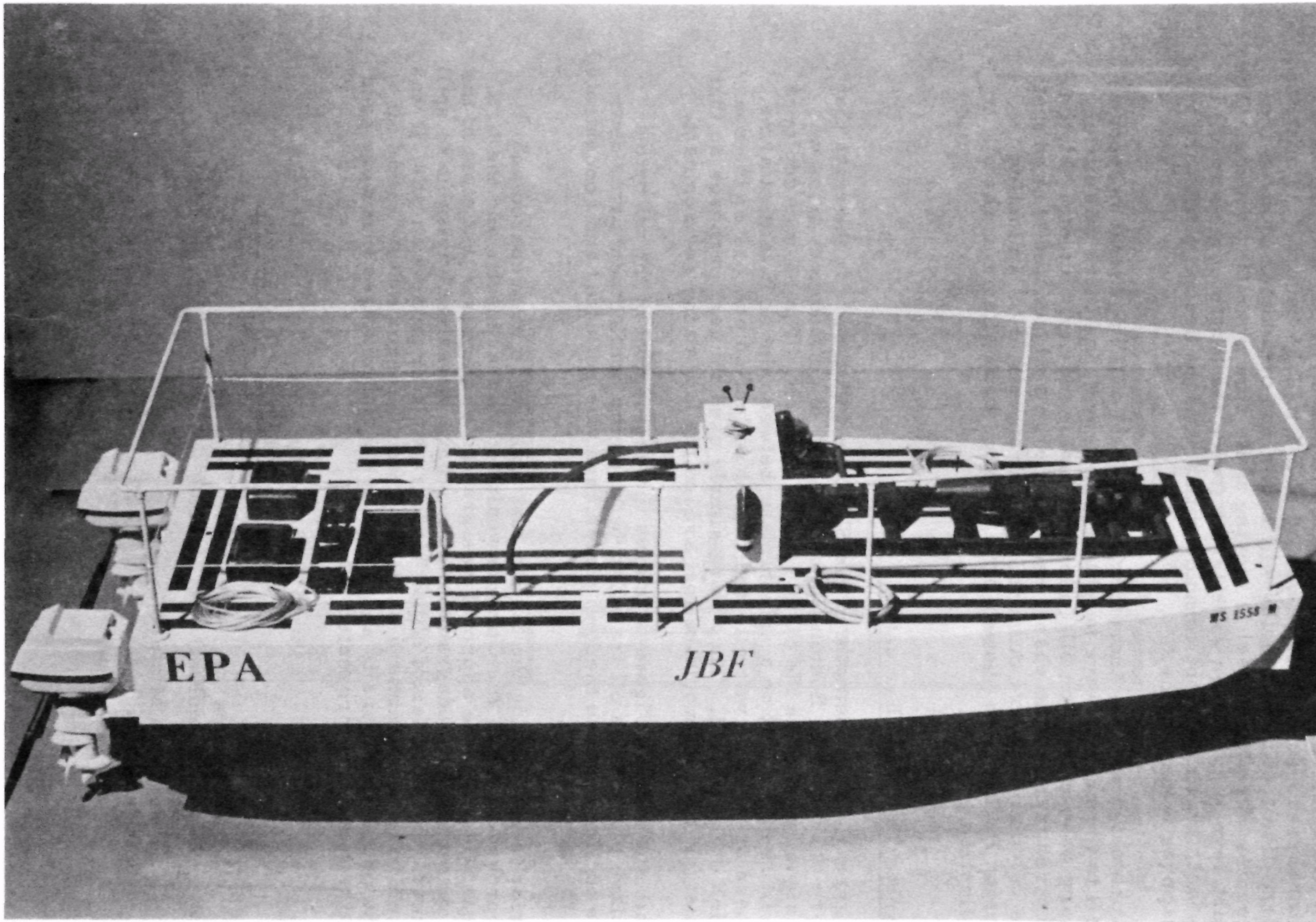


Figure 30. Scale Model of the 22-Foot SHOC Demonstration Unit

The response of the vessel to waves in heave, pitch, and roll have natural frequencies, with a period of 2.1 to 2.55 seconds. Twenty to thirty-five foot wave lengths will excite one or another of three frequencies when the vessel is moving at its slow operating speeds. The most severe excitation wave length (twice the length of the vessel) is 44 feet, which does not coincide with any of the heave, pitch, and roll response wave lengths.

In protected waters, therefore, the vessel will in general respond well to the normal wave heights encountered, and there was little, if any, wave effects on oil collection during the harbor tests. Motion pictures taken of the vessel response were analyzed and showed that the calculations were correct. Measurements of oil collection in Boston Harbor also showed little, if any, wave effects on the oil collection process.

Harbor Tests and Evaluation

Figure 31 is a schematic of the SHOC unit outfitted for the tests that were conducted in Boston Harbor. A set of confinement arms was designed to confine the oil in front of the unit. The oil was deployed in front of the unit on a splash plate between the confinement arms. These arms in no way affected the oil collection process or the operation of the vessel. They were simply used for test purposes so that no significant oil would be lost around the unit to the environment.

The side view in Figure 31 shows the deployment of the oil onto a splash plate. The oil travelled between the confinement arms down the incline between the keel plates, and was collected and concentrated in the baffled well.

Prior to performing the tests a test plan had to be prepared and approved by EPA, the Commonwealth of Massachusetts and the U.S. Coast Guard. The approval was granted on the basis that most of the tests employed biodegradable oils. Since it was not advisable to spill excessive quantities of either biodegradable or petroleum oils, it was decided to use a mixture of oils that would approximate a crude oil. The properties (density and viscosity) of the mixtures that were used in the tests, are presented below:

Oil	Viscosity (centistokes)	Specific Gravity
Bio Mixture (Crude simulant)	200	0.95
Petroleum Mixture (Crude simulant)	250	0.92

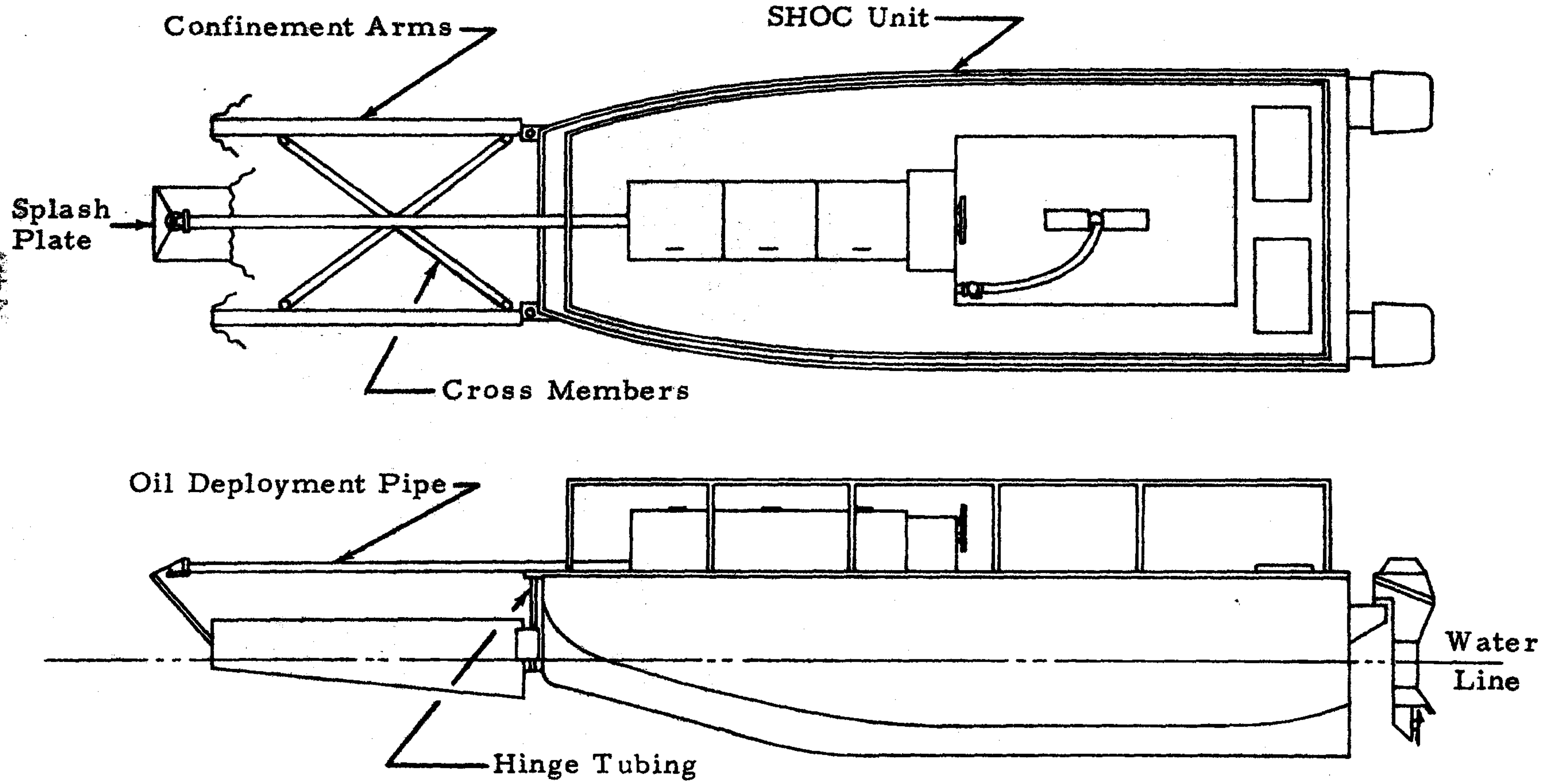


Figure 31. Schematic of the SHOC Harbor Test Arrangement

It was decided to re-use oil that was picked up for tests since it would provide for testing aged oil, and oil that might have been emulsified from the spilling and redeployment processes. There was no attempt, however, to control these variables.

The effectiveness or efficiency of the oil recovery process was determined by measuring the amount of oil deployed and comparing it with a measure of the volume of oil in the collection tank. The oil volume deployed was determined by measuring the difference in oil level in the storage tank before and after the test, with a steel tape. The determination of the oil volume collected was complicated by the irregular shape of the chamber and by the location of the oil-water interface. The oil volume collected, therefore, had to be determined by combining the oil-level measurement and the volume calibration for the collection chamber. The level of oil was obtained by measuring the immersion distance of a conductivity probe below the oil surface. The conductivity probe is in a continuity loop with an ohmmeter as is shown in Figure 32. The volume calibration for the collection chamber is shown in Figure 33 in terms of the immersion depth, h, and the exposed probe length, h'.

The procedure for measuring oil volume involved setting the end of the probe so that it just contacts the liquid surface. The exposed probe length, h's, was measured and the volume above the liquid surface was obtained from Figure 33.

After connecting the ohmmeter circuit as shown in Figure 32, the probe was removed slowly downward until its sharp point pierced the oil-water interface. This event was identified by the meter needle, which moves from an open circuit to a short condition. The exposed probe length was measured, and the volume above the oil-water interface was obtained from Figure 33.

The oil volume in the collection chamber was obtained by subtracting the volume obtained in the previous measurements. Samples of the oil were extracted from the well, placed in a plastic cylinder and allowed to stand for several hours. Some oil samples were placed in a centrifuge and subjected to a 1,200 g acceleration for 10 minutes to determine the water content.

The boat velocity was measured relative to the water, using the Signet Scientific Mark 9 Knotmeter, 0-12 knots full scale. The resolution of the instrument is better than .1 knots, and is linear below 1/2 knots as determined by velocity calibrations over a measured course.

The oil flow rate was measured with a 1-1/2 inch Hersey-Sparling meter, which was mounted in line with the Moyno oil pump. The meter was calibrated with a large graduate. This measurement was checked by noting the time of the run and the total volume deployed. Oil deployment rates were such that an average film thickness of between 0.5 mm and 1.5 mm was presented to the device.

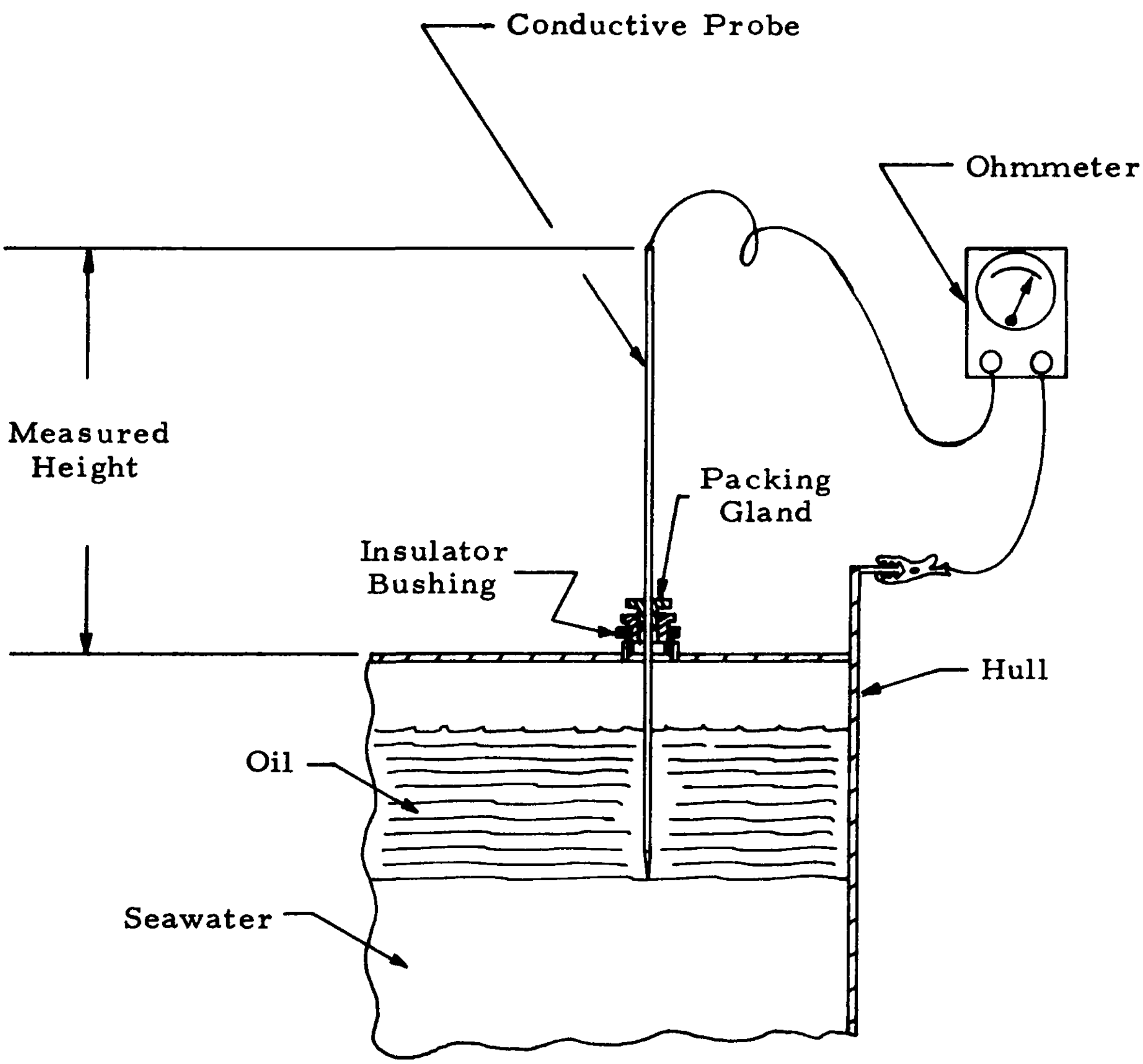


Figure 32. Schematic of Oil-Level Measurement Technique

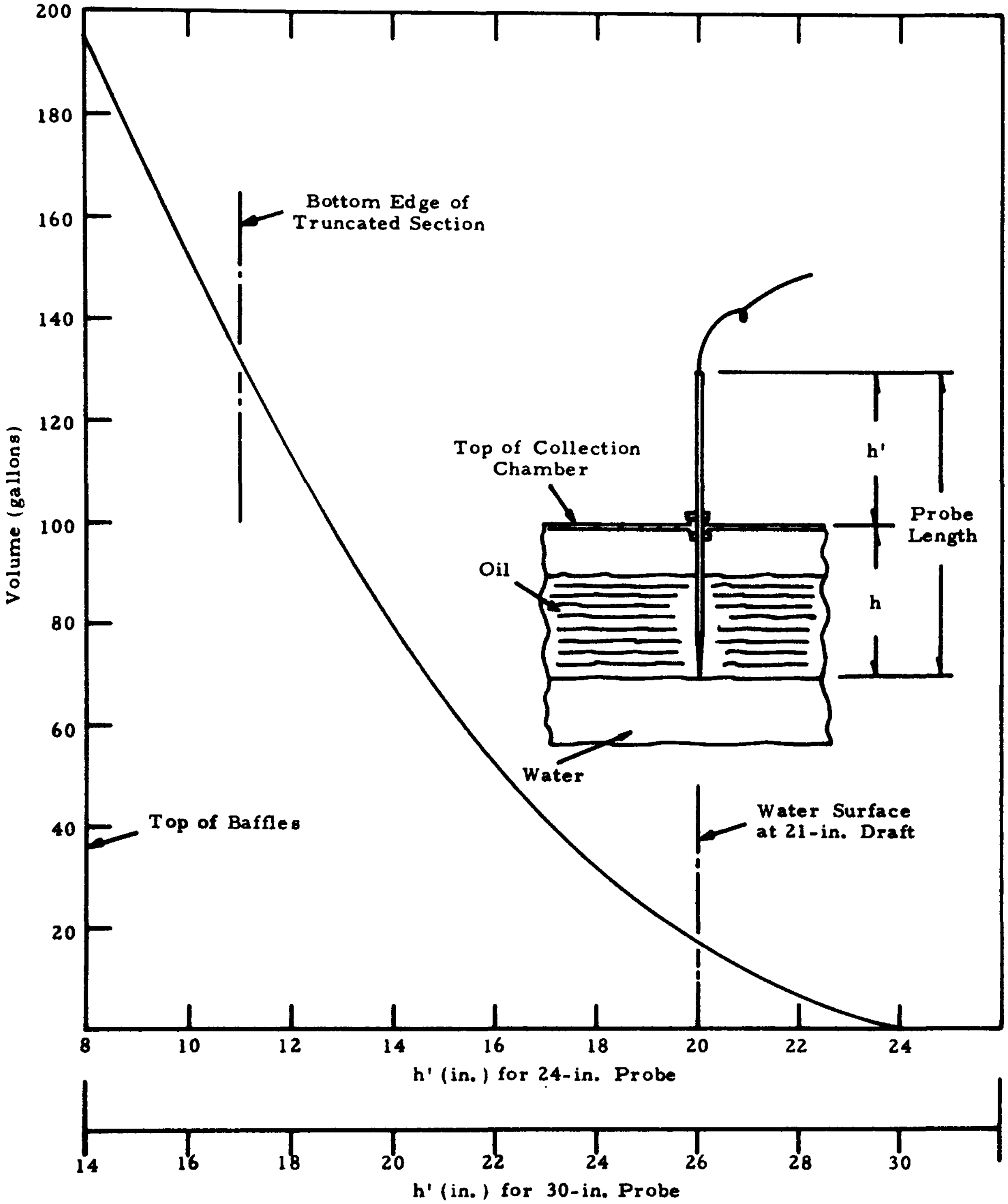


Figure 33. Collection Chamber Volume Calibration Chart

Because of the restrictions placed on the total amount of oil that could be spilled in any one test and the environmental damage associated with spilling oil, we did not carry out any more tests than were necessary to demonstrate the principle and to establish the design limits. A total of 14 tests were performed in Boston Harbor. The results of these tests are presented in Table 4.

It should be emphasized that the indicated efficiency number presented in the table is that associated with the oil recovered in one pass and that the oil collected contained no visible traces of water. From the centrifuge test it was determined that there was less than 1% water in the oil.

The first three runs shown on the table were performed in very calm water between two piers in an area approximately 1,000 feet long by 200 feet wide between Pier 6 and 7 of the South Boston Annex to the Boston Naval Shipyard. During these tests, a significant amount of oil leaked by the confinement arms to the side of the skimmer and was not presented to the inclined plane. This explains the relatively low indicated efficiencies. The reason for leakage was a poor seal where the confinement arms joined the front of the skimmer. Another reason for the relatively low readings of oil collection was that the propulsion was turned off before all the oil on the incline was allowed to travel to the collection well. These losses were eliminated in runs 4 through 14. The only other losses noted during the tests that caused errors were losses due to very rapid turns and maneuvers causing some of the oil that was deployed to be spilled to the side rather than in front of the vessel and some oil in the well to be drawn out of the bottom of the well.

Runs 4 through 14 were run in the main channel of Boston Harbor, where waves from 1 to approximately 3 feet high were encountered. Many days were windy, and a significant chop was present on the waves as well. In this typical open-water harbor environment the oil recovery effectiveness was not reduced.

Combining the results of Table 4 it can be shown that of the 958.3 gallons spilled, 691.5 gallons were recovered, resulting in an overall one-pass efficiency of 72.1%. If runs in which known experimental errors were eliminated (Runs 1, 2, 3, 5, and 12), then of the 600.9 gallons spilled, 467.5 gallons were recovered, resulting in an overall one-pass efficiency of 77.7%.

In addition to the specific controlled tests that were performed in Boston Harbor, there were a number of practical observations made during the tests. These are discussed below.

The confinement arms were originally designed as straight flat wooden plates, 2 feet high by 8 feet long, with a 4 inch by 4 inch longitudinal stiffening member. The arms created an excessive amount of drag

TABLE 4. Boston Harbor Tests of SHOC Oil Recovery Effectiveness

Reference Run No.	Vessel Velocity (knots)	Oil Mixture	Volume Spilled (gallons)	Volume Recovered (gallons)	Efficiency* (%)	Remarks
1	1.0	Bio Mixture	75.5	43.0	57	Oil lost during deployment
2	1.0	" "	64.7	35.5	55	Oil lost during deployment
3	1.0	" "	89.6	62.5	70	Oil lost during deployment
4	1.5	" "	74.4	62.5	84	No loss during deployment
5	1.5	" "	65.0	48.0	74	Turning loss
6	1.5	" "	60.5	46.0	76	No losses
7	1.5	" "	62.5	43.0	69	No losses
8	1.5	" "	54.0	40.0	74	No losses
9	1.5	" "	66.0	55.0	83	No losses
10	1.5	Petroleum Mix.	54.0	40.0	74	No losses
11	1.5	" "	65.0	56.0	86	No losses
12	2.0	Bio Mixture	62.6	35.0	56	Turning loss
13	2.0	" "	86.5	69.0	79	No losses
14	2.0	Petroleum Mix.	78.0	56.0	72	No losses
			958.3	691.5	72.1	
			600.9	467.5	77.7	

*Effeciency = ratio of the amount of oil collected in one pass to the amount of oil presented to the mouth of the demonstrator and turbulence on the back side. When they were angled outward approximately 30° to create a sweeping action, there was a considerable amount of additional turbulence created at the extremities. This turbulence resulted in an increased drag and what appeared to be a premature loss of oil under the sweep at all velocities. The forces were so high that at one point the 1-1/2 inch diameter stainless-steel hinge tubing, which held the confinement arms in front of the unit, and the joints of the cross members used to steady the arms in front of the unit failed.

These elements are indicated in Figure 31. The straight arms, which were 12 inches into the water, had to be redesigned so that they were tapered to the forward tip and with additional buoyancy so that their maximum draft did not exceed 6 inches. The sweeping mode was abandoned and the arms were returned to a 0° sweep angle and used strictly as confinement arms. The important observation made here is that considerable work needs to be done before effective broad-angle sweeps can be integrated with a skimmer.

Some other important observations were made while maneuvering the unit during the oil pickup tests. A sharp turn to change or reverse the direction of the unit caused a cross eddy in the collection well which resulted in some loss of oil from the well itself. Additional investigations of the well geometry and the geometry around the side plates (keels) can and should be made to minimize these losses. These maneuvers also created considerable turbulence between the confinement arms. This turbulence caused oil between the arms to become entwined in the water and to travel beneath the confinement arms to the side of the unit.

Although wave heights and wave lengths during the harbor tests were not precisely measured, there were a wide variety of conditions encountered. Several tests were run in chop and stiff winds, some were run with relatively closely spaced 2-foot waves, and others were run in long, high swells. The unit was directed at an angle to the wave patterns as well as normal to them. As was expected, the most severe oil collection conditions occurred when the vessel heaved and pitched due to its response to a given wave system. When this occurred, the flat plane would splash water and oil in front of the vessel. This splashing action did not affect the oil collection process. After the splash occurs, the vessel advances into the disturbed region and carries the oil down the plane to the well. Once the oil is beneath the water surface, the buoyant forces cause the oil to come in contact with the plane and slide down the well entrance, where it is collected. The oil deployed was immediately collected, and there was not any visible trace of water in the oil at the top of the well. Samples of this oil were allowed to stand overnight for these observations.

After 9 months of intermittent use in Boston Harbor, the demonstration unit was removed from the water for final disposition. It was noted that the baffles themselves were practically free of any fouling or clogging problem.* Figure 34 is a photograph showing the condition of the baffles when the unit was just removed from the harbor.

*All submerged portions of the vessel had been painted with marine anti-fouling paint.

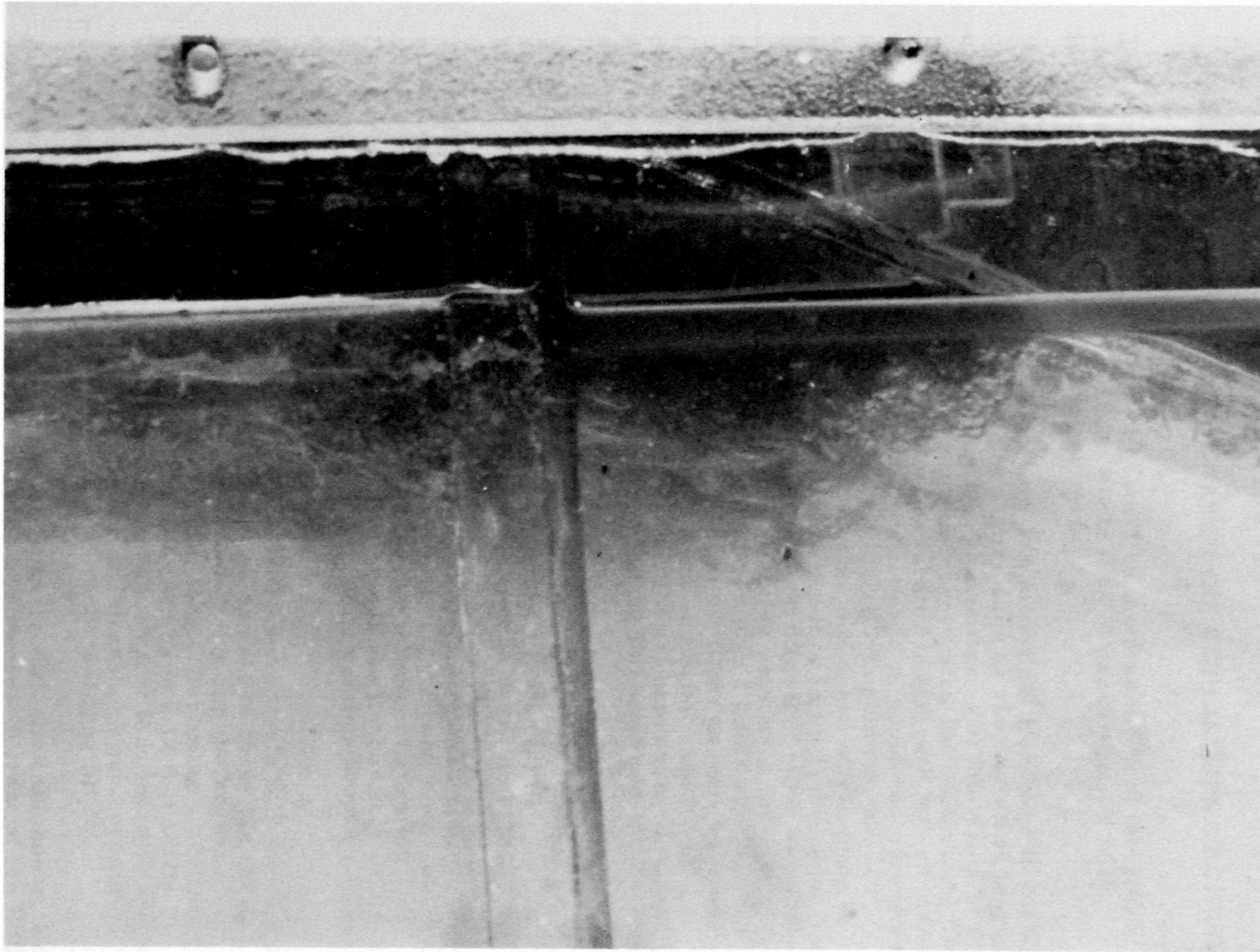


Figure 34. View of the SHOC Baffles After Nine Months in the Water

SECTION VI

ASSESSMENT OF THE UNDERWATER OIL COLLECTION TECHNIQUE

The goal of this program was to establish the feasibility of the SHOC concept or, more generally, the whole idea of harvesting oil with inclined planes beneath the water surface.

The specific goal of early laboratory and analytical work was to obtain data to make important design decisions, such as the angle and length of incline, the cross-section height of the baffles, and the length of the baffle sections, and to establish the recovery rates for various oil film thicknesses. Sufficient tests were performed to indicate that skimmers would remain effective in waves typically found in protected waters and that skimmers could be made of a large size. In general, all our analytical and experimental work indicated that there was nothing in the inclined plane underwater collection process to limit the upper size of a unit and thus, vessel size could be determined by other considerations. Our results showed that the operating velocities for effective oil collection were in the range from 3/4 knot to 2 knots and that this type of device will harvest thin (0.10 mm) oil films as well as thick (50 mm) oil layers. Waves typically found in harbor channels and protected waters did not adversely affect the oil harvesting process, and a properly designed vessel incorporating the principle should remain effective in 3 to 5 foot high waves.

When the SHOC is operated near the optimum speed, the oil recovery rate can be increased by (1) making the unit wider, (2) using a longer baffle, or (3) increasing the oil slick thickness in front of the device.

The unit width is primarily determined by its anticipated usage. For instance, it is difficult to transport by rail, air or road a unit wider than 12 feet unless this is done in a disassembled configuration. Similarly, it is difficult to maneuver a unit in the harbor if it is wider than say 20 feet. In open waters, a very wide configuration could be used.

Increasing the baffle length increases the recovery rate by providing a longer path over which the buoyant forces can act to bring the oil up into the well. A SHOC with a draft of 2 to 3 feet for the angles of interest would contain an incline ten feet long. Assuming a 10 foot plane length; a 25 foot long SHOC could then have a 12 foot baffle section. A 35 foot long SHOC would have a 15 foot long incline, and a 20 foot baffle section. For the harbor and nearshore environment it is not unrealistic to consider using a 25 to 35 foot long SHOC.

Since the SHOC recovery rate varies linearly with slick thickness, one way to increase the recovery rate is to use sweeps in front of the SHOC to increase the effective width of the unit. Sweep technology is not very advanced at the present time. The sweeps have to be towed at a speed such that the oil velocity component normal to the sweeps does not cause the oil to go under them. A number of sweep studies have been conducted but these have not resulted in a viable solution to the problem.

Prior to the start of the program to evaluate the SHOC concept, a new oil-harvesting concept was developed by JBF Corporation. This new concept involved the use of a moving inclined plane. As in the SHOC concept, oil is collected beneath the surface of the water, however, in the new concept an endless belt travels over the inclined plane and carries any floating material downward into the water and up into the collection well. The floatables (usually oil or sorbents, but it could be any material) are held against the plane by a combination of hydrodynamic, buoyant, and cohesive forces. The oil and sorbents are collected in the well, and any residual material is scraped off the belt as it passes through the well volume. The principle allows collection while there is no current or vessel movement, and it carries sorbent materials to the well as effectively as it carries oil alone. A more detailed description of this concept, which is called the DIP (Dynamic Inclined Plane), is presented in Appendix C.

Laboratory tests indicate that the DIP may work more effectively than the SHOC at higher velocities because the motion of the plane does not require that the oil slide in shear on the incline, which could result in less oil breakup.

The DIP concept was presented to EPA, and as a result, the SHOC contract was extended to include the design of an operational harbor unit incorporating a moving plain. The unit will be self-propelled, 30-35 feet long, and will have on-board storage sufficient to handle practically all harbor spills. The results to date indicate that the use of a moving plane results in a significant improvement in the underwater oil collection process.

In summarizing, it can be said that the methods of collecting oil beneath the surface of the water have the advantages that the process concentrates the oil and separates it from the water as it harvests, and there is a minimal effect due to waves and chop. Additional investigations should be made to fully develop the dynamic inclined plane (DIP) concept, to develop an effective set of sweeps, and to improve the collection effectiveness during maneuvers and turns.

SECTION VII

ACKNOWLEDGEMENTS

The support and assistance of the Project Officer, Mr. Thomas Devine of the Environmental Protection Agency, are acknowledged with sincere thanks. In addition, the suggestions of Mr. R. T. Dewling and the assistance of Mr. S. Dorrier of EPA, Edison, have been appreciated.

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The cooperation and assistance of the U.S. Coast Guard has been gratefully acknowledged through Cdr. J. Fournier, Lt. H. Schmecht, and several crews of the First Coast Guard District, Boston, for their important contribution to the harbor test program.

SECTION VIII

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APPENDIX A

LITERATURE SEARCH

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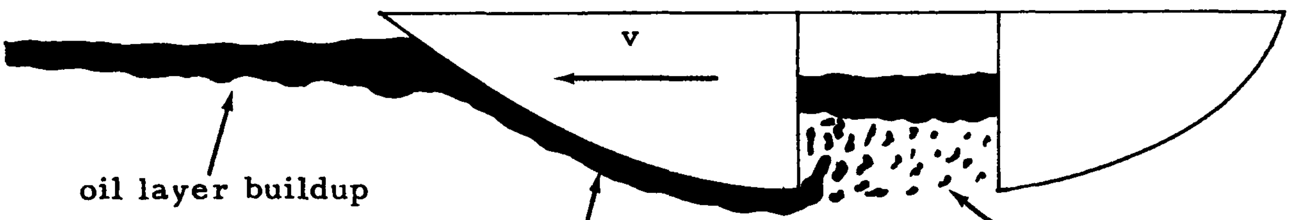
APPENDIX B

THEORETICAL BASIS FOR EXPERIMENTAL DESIGN OF THE SHOC CONCEPT

The basic principle which is responsible for the operation of the SHOC Concept is that material which is less dense than water will, if submerged, rise to the water surface and float. Thus, oils having specific gravities less than one are capable of being collected. A schematic drawing of a vessel with an inclined plane illustrating the principle of operation is shown below. The forward velocity v, of the vessel causes



Schematic Illustration of the Fixed Plane Concept

the oil to be driven down the underside of the unit. The positive buoyant forces cause the oil to eventually rise in the well. The nature of the oil-layer buildup in front of the plane, the flow of oil down the incline and subsequent collection in the well depends directly on the geometry and velocity of the vessel as well as on the physical properties of the oil. These three flow regimes are not independent of each other and from a hydrodynamic viewpoint manifest themselves in a complex method of oil collection.

Recognizing the complexity of the collection mechanism and the need for a thorough understanding of it so as to permit rational scaling to large prototypes, a comprehensive literature search was conducted. The results of the survey and a discussion of the analyses describing the collection are presented in the following sections.

By the nature of its operation the SHOC concept requires that oil on the water surface move relative to the vessel so as to flow down the incline to the draft of the unit. The conditions for successfully collecting oil are:

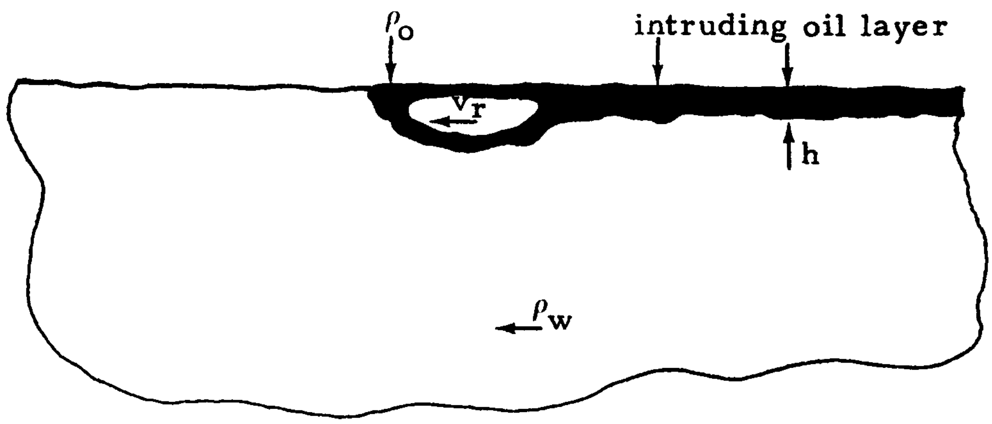
(a) When the oil-layer buildup extends sufficiently far in front of the plane to cause the depth of oil layer to exceed the draft of the vessel;

(b) If operating conditions are such that the oil buildup in front of the plane shears off in globules that become transported by the water and flow down the inclined surface;

(c) When sufficient shear stresses are developed between the water and oil layer adjacent to the incline, causing the oil to travel in sheets with a wavelike action.

These conditions are shown schematically in Section IV (Figure 2). Condition (a) would occur at very low operating velocities. It is not an effective mode of operation for a fixed plane and is, therefore, not considered here.

As the vessel moves through the water the oil slick will progressively thicken. The hydrodynamics of the buildup and subsequent behavior of the oil is typical of two fluids intruding on one another, e.g., a cold front entering into warm air or salt water into fresh water. Thus, the mode of operation associated with the breakup of the oil layer (condition (b)) can best be understood by considering the unstable behavior of a layer of fluid intruding with velocity v_r on a more dense fluid (e.g., oil on water), as shown below.



For such a system a head wave develops and thickens to a little over twice the mean height of the oil layer. There is a turbulent zone on its leaward side after which the interface becomes somewhat horizontal. [2] An approximate relation between the mean height $\underline{h}$ and the velocity v_r can be obtained from Bernoulli's equation resulting in [3]

$$v_r = \sqrt{2gh\left(\frac{\rho_w}{\rho_o} - 1\right)} \tag{1}$$

where g = local gravity constant

ρ_w = mass density of water

ρ_o = mass density of oil

The stability of the layer behind the head wave has been investigated by Benjamin by considering the effects of a perturbation at the interface [4] .

$$kh \coth kh > \frac{1}{2}\left(1 + \frac{\rho_o}{\rho_w}\right)$$

where $k = \frac{2\pi}{\lambda}$ (2)

λ = wavelength

which is satisfied for all real values of $\underline{k}$, meaning that the flow is unstable to all small disturbances. Such an instability is manifested physically either as a spatially periodic disturbance that grows exponentially with time or where a disturbance grows with distance downstream. At relatively small velocities the amplitude of the interfacial waves is small because of the damping effects. However, as the relative velocity of the two layers is increased, the amplitude increases because of greater energy being transmitted to the oil layer. As the amplitude progressively increases, globules and eventually droplets of oil will be torn off the interface and become entrained in the water. The velocity at which oil is torn off the wave face can be estimated using the equation developed by Hinze for breakup and formation of globules of a dispersed phase. [5]

This relationship is based on the critical Weber Number, W_c.

$$W_c \approx 22 = \frac{\rho_o d v_c^2}{\sigma} \tag{3}$$

v_c = critical relative velocity between the oil and water

d = diameter of oil droplets

σ = interfacial tension between the two liquids

Weber's number, W_c, is approximately equal to 22 and has been found to give good predictions for oil-water systems [6]. The equation relates, for a given fluid (fixing ρ_o and σ), the diameter of droplets formed at various velocities. Now the maximum diameter of a stable droplet can be estimated using the results of Christianson and Hixson obtained for breakup of liquid jets in denser liquids, viz., [7]

$$d_{max} = \pi \sqrt{\frac{\sigma}{g(\rho_w - \rho_o)}} \tag{4}$$

Now combining Equations (3) and (4) one then obtains critical relative velocity below which no droplets are formed

$$v_c = 6.27 = \left(\frac{\sigma}{\rho_o}\left(\frac{1}{\lambda_o} - 1\right)\right)^{1/4} \tag{5}$$

where λ_o = Specific Gravity of oil

Typical values of σ are .0016 lbs/ft to .0024 lbs/ft for oil and the range of λ_o which is of interest is .85 to .97. The results obtained from Equation (5) using the above cited ranges of oil properties are given in Table B-1.

The results contained in the table indicate lower bounds of the velocity for droplet formation, i.e., no droplet will form below .45 ft/sec regardless of the type of oil. It should be noted the specific gravities in the order of .85 are indicative of #2 fuel oil and specific gravities of .97 are indicative of the residue oil such as #6. Furthermore, it should be realized that the velocity values given in the table do not mean that oil droplets will form at those velocities but are values below

Table B-1. Critical Velocities for Various Oil Properties Below Which No Oil Droplets are Formed

σ	λ_o	v_c
lbs/ft		ft/sec
.0016	.85	.72
.0024	.85	.79
.0016	.97	.45
.0024	.97	.50

which no droplets are expected to form. In order for the droplets to form, sufficient undulation of the oil-water interface will be necessary which may well require significantly higher relative velocities to overcome damping in the oil buildup system. Velocities may be 50 to 100 per cent above those given in the table, viz, in the order of 1 to 1.5 ft/sec. Also indicated by the results in Table B-1 is that the more dense oils will tend to break up more easily.

It is worth noting that it may be desirable to intentionally induce damping by the addition of surfaces in the vicinity of the incline. This would tend to raise the velocity for a given size oil particle to occur.

Having obtained estimated minimum operating speeds for oil globule formation, resulting in oil becoming entrained in the water stream, it is now necessary to examine the trajectories of such formations in order to estimate the length of the collection well. Since the oil globule paths are directly governed by the forces acting on them, and since a significant force, viz, the drag force, is a function of the size of the globule, Equation (3) must be used to obtain a value of a mean globule diameter. The globule size is a function of velocity for typical values of oil density and surface tension. Figure B-1 contains a plot of mean oil globule diameter as a function of operating speed, v_r, for typical limiting values of surface tensions and specific gravities. It is interesting to note that a limiting value of the relative velocity will be in the order of 3 to 4 ft/sec, since above this velocity range the particles sizes are in the order of .025 inches which will cause problems in extracting them from the water. It should be recognized that oil flowing on the plane has a velocity so that the actual operating velocity of the vessel or the water velocity can be higher than 4 fps.

Droplet Motion

Let it be assumed, for calculation purposes, that droplets form sufficiently close to the inclined surface such that the downward velocity imparted to the droplet is given by:

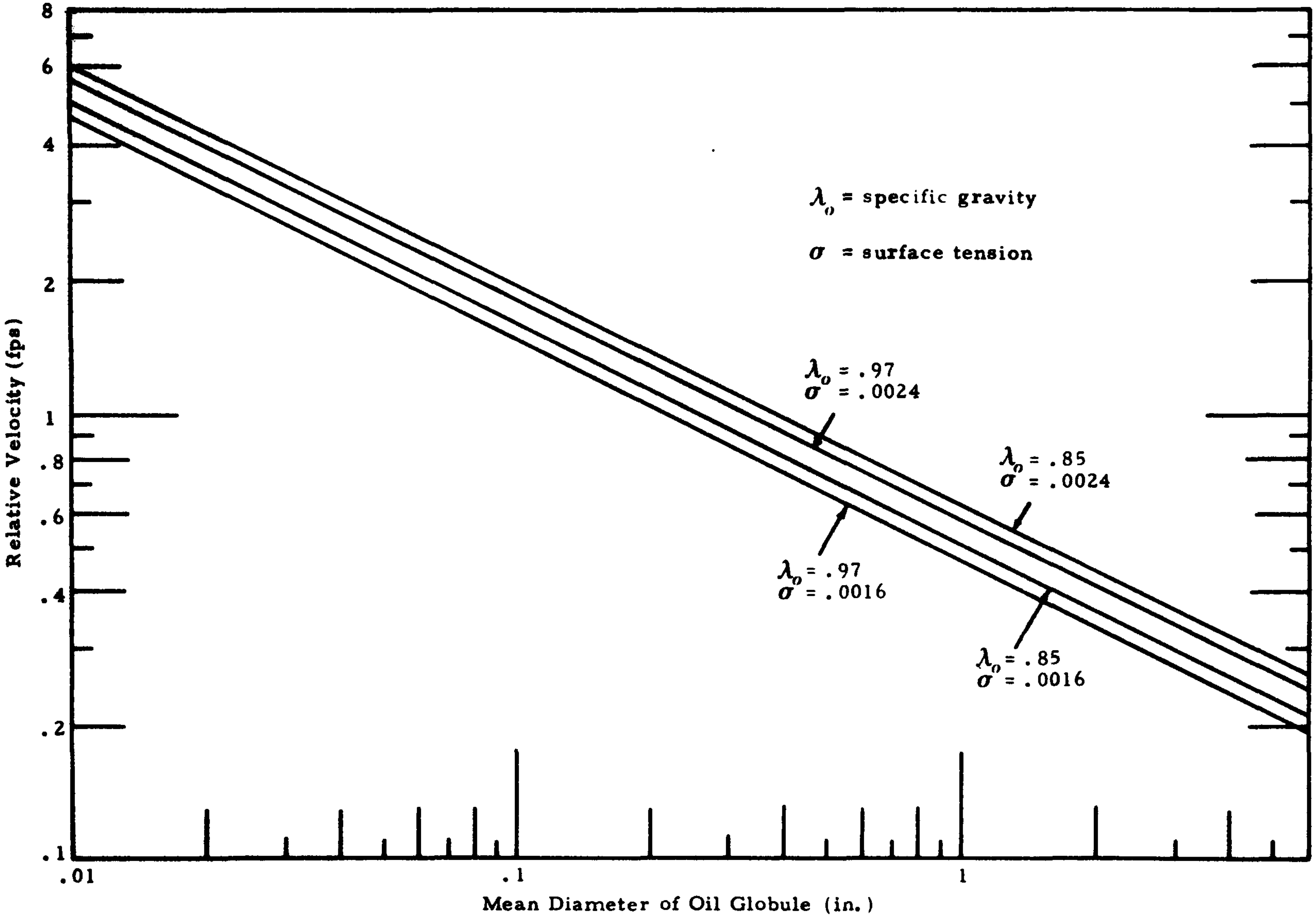


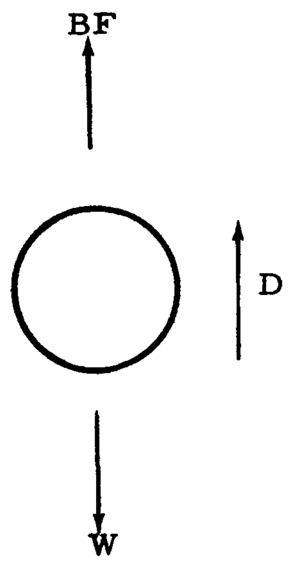
Figure B-1. Oil Globule Size vs Oil-Water Relative Velocity

$$v_{py} \approx v \sin \theta$$

where v_{py} = imparted downward velocity

θ = incline angle of the plane

Such an assumption results in an upper bound on the magnitude of imparted downward velocity since many particles will form at some distance from the inclined surface and consequently have a lower value of downward velocity. Furthermore, it is reasonable to assume that the flow of water can be described by potential flow theory. Once the droplets become entrained in the water their motion will be governed by the various forces acting on them. The significant vertical forces acting on a droplet are shown below.



BF = buoyant force

W = weight

D = drag force

An additional sidewise force exists because of velocity gradients but such a force is small compared to the others shown and consequently will not be included [1] . The implicit assumption of uncoupling the vertical and horizontal motion will also be used which is justified in Stokes' region.

The buoyant and weight forces are:

$$BF = \frac{\pi d^3}{6} g \rho_w \tag{6}$$

$$W = \frac{\pi d^3}{6} g \rho_o \tag{7}$$

where $\underline{d}$ is the diameter of the oil droplet

The drag force on a liquid particle can be determined from the work of Hu and Kintner [6]. They investigated various immiscible liquid systems and found that the motion of liquid drops differs from that of rigid spheres because of deformation and oscillation of the drops as well as flow on the drop surface and internal circulation. Their investigation resulted in the following relationship between the drag coefficient, densities,

$$C_D = \frac{4/3\,[Re/P^{.15} + .75]^{1.275}}{We\,P^{.15}} \qquad (8)$$

where $Re = \dfrac{d v_y \rho_w}{\mu}$ Reynolds' Number

$We = \dfrac{v_y^2 d \rho_w}{\sigma}$ Weber's Number

$P = \dfrac{\rho_w (\sigma)^3}{g \mu_w^4} \; \dfrac{\rho_w}{\rho_o - \rho_w}$

C_D = drag coefficient

The drag force is

$$D = \frac{1}{2} \rho_w C_v v^2 \frac{\pi d^2}{4} \qquad (9)$$

C_D being given by Equation (8)

The sum of all the forces in the vertical direction must be equal to the rate of change of momentum of the particle plus the effect of virtual mass. Hence, combining all the forces, one obtains

$$BF - W + D = (m + m_v) \frac{dv_y}{dt} \qquad (10)$$

where m_v = virtual mass of droplet

v_y = vertical velocity

by substitution

$$\frac{\rho_w}{\rho_o} + \frac{3 C_D \rho_w v_y^2}{4 g d \rho_o} - 1 = \frac{1}{g}\left(1 + \frac{\rho_w}{2\rho_o}\right) \frac{dv_y}{dt} \tag{11}$$

Equation (11) is a first order non-linear differential equation which when solved, gives the vertical velocity as a function of time which can be related to a horizontal position through

$$v_y \cdot (t) = v_y \left(\frac{x}{v}\right)$$

x = horizontal distance

t = time

the velocity profile can then be integrated to give vertical position as a function horizontal position. Following such a procedure with appropriate initial conditions, particle trajectories can be obtained. Such an approach was used by Wicks [1] considering droplets to have an initial downward velocity v_{py} of which $\frac{v}{z}$ which would correspond to an incline angle of 30°. His results were surprising in that it was shown that no significant error exists if it is assumed that the droplets have no initial downward velocity and achieve terminal speeds instantaneously. Thus, the right side of Equation (11) can be set equal to zero resulting in

$$\frac{\rho_w}{\rho_o} + \frac{3 C_D \rho_w v_{yt}^2}{4 g d \rho_o} - 1 = 0 \tag{12}$$

where $v_y t$ is the terminal vertical velocity

Using the value of C_D given by Equation (8) one obtains a cubic equation on v_{yt}, viz.

$$(v_{yt})^3 + C_1 v_{yt} + C_2 = 0 \qquad (13)$$

$$\text{where } C_1 = 858 \left(\frac{p^{.15} \mu_w}{\rho_w d} \right)^2 .$$

$$C^2 = -9.34 \left[\frac{p^{.30} gd \left(1 - \frac{\rho_o}{\rho_w}\right) \mu_w}{\sigma} \right] \left[\frac{7_p^{.15} \mu_w}{\rho_w d} \right]^2$$

Equation (13) has been solved in Wicks [1] , and the results are presented in Table B-2 for various values of oil densities, interfacial tensions, and particle diameters. The results from Table B-2 can

Table B-2. Terminal Velocities of Various-Size Droplets for Oils of Different Specific Gravities and Interfacial Tensions

	Interfacial tension = .0014 lbs/ft		Interfacial tension = .0027 lbs/ft	
	Sp.Gr. = .85	Sp. Gr. = .97	Sp.Gr. = .85	Sp. Gr. = .97
Drop dia. Inches	Term. Vel. ft/sec	Term. Vel. ft/sec	Term. Vel. ft/sec	Term. Vel. ft/sec
.002	.0054	.0017	.0051	.0016
.004	.0109	.0035	.0101	.0033
.010	.0272	.0088	.0254	.0082
.020	.0544	.0176	.0508	.0165
.040	.1087	.0353	.1015	.0329
.100	.2578	.0878	.2471	.0821
.200	.3719	.1668	.3962	.1601
.400	-----	.2394	.4329	.2554

be used with critical droplet size from Figure B-2 to determine required collection well lengths. For example, oil droplets of a No. 6 oil (Sp. Gr. 97) at a relative velocity of 2 ft/sec have a terminal rise velocity of about .061. Thus if such particles were in front of and 1 inch below the level of the collection well, the required well length L, would then be

$$L = 1 \text{ in} \frac{\frac{1 \text{ ft}}{12 \text{ in}}}{.061 \text{ ft/sec}} \times 2 \text{ ft/sec} = 2.8 \text{ ft}$$

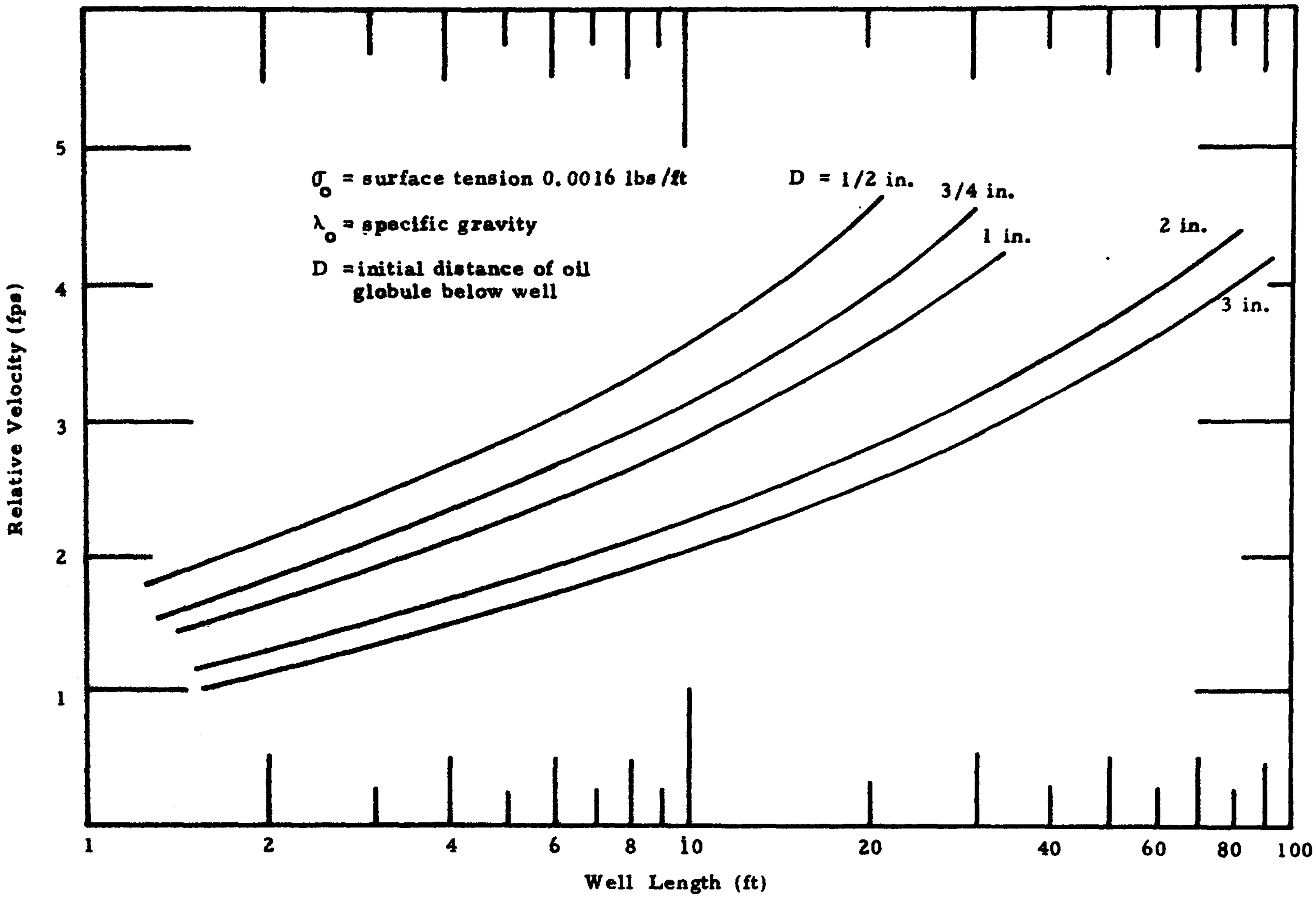


Figure B-2. Well Length vs Oil-Water Relative Velocity

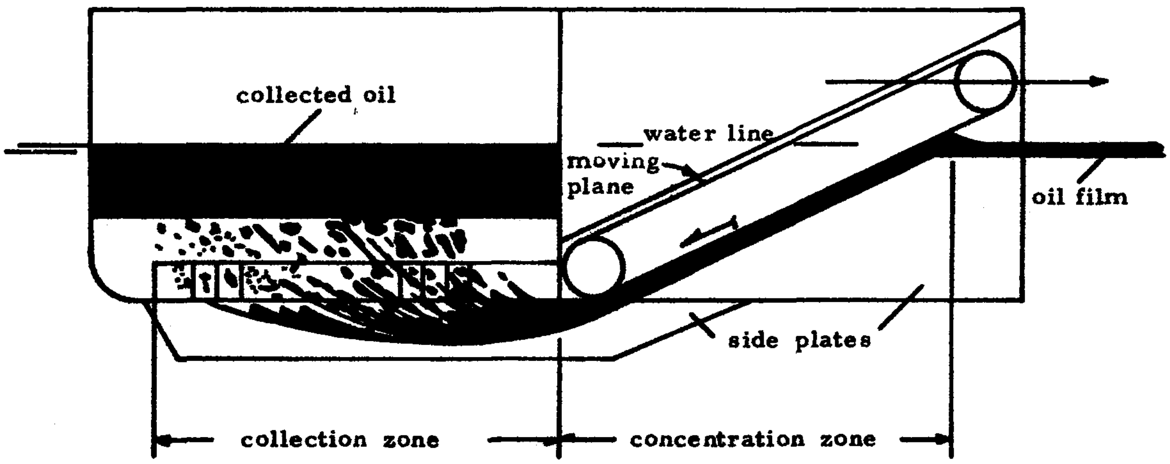
Because of the difference in Sp. Gr. of the No. 2 and No. 6 oils, the well lengths must be governed by the behavior of the No. 6 oil. Figure B-2 contains a plot of required well length versus relative velocity for oil droplets having a Sp. Gr. of .97 σ = .0016 lbs/ft and which are various distances below the bottom of the well.

It should be kept in mind that these collection-well lengths are based on the assumption that the oil layer breakup and oil droplets become entrained in the flow. There is, however, condition (c) where the relative velocity between the oil layer and water is such that a sheet like flow is obtained on the incline. Such a condition occurs at shallow incline angles, with dense oils since the contribution of the buoyant forces to resistance of flow down the incline is small.

APPENDIX C

THE JBF DIP CONCEPT

The principle of operation of the JBF DIP* (Dynamic Inclined Plane) oil harvesting device is best described by reference to the figure below.



An inclined plane is located beneath the surface of the water, and there are vertical plates on either side of the plane so that the water and oil are confined between the plates. As the device moves through the oil, the oil cannot move to the sides because it is confined by the side plates, and thus it is concentrated at the intersection of the inclined plane and the oil/water surface. The oil is then forced on the incline and carried beneath the water, either by the forward movement of the device (or the flow of water) or by the downward movement of the plane itself. This movement of the plane is accomplished by operating an endless belt over the rollers, as is schematically shown above. Oil is held against the plane by a combination of hydrodynamic, buoyant, and cohesive forces. The oil is collected in the well, and any residual oil is scraped off the belt as it passes through the well volume. Buoyant forces cause

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*JBF Scientific Corporation has patents pending on this device.

the oil to surface in the well, forcing water out the bottom. As the oil collects it is pumped off to storage tanks. Separation occurs automatically, and virtually no water is collected.

Since the oil is beneath the water surface, waves and rough water have a minimal effect on oil collection.

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10 *Author(s)*

Bianchi, Ralph A.
Henry, George

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22 *Citation*

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*Water Pollution Control, Oil; Pollution Abatement

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*Mechanical Clean Up, Oil Spills; *Oil Recovery Systems, JBF Scientific Corporation

27 *Abstract*

Analytical studies and harbor tests were conducted to determine the feasibility of harvesting oil beneath the surface of the water with the use of inclined planes.

The analytical and laboratory investigations provided basic information to design and build units and showed that this kind of device could harvest both light and heavy oils between 3/4 knot and 2 knots. Information was obtained regarding the geometry of the device. Tests showed that oil could be collected in waves without seriously affecting efficiency.

A 22-foot-long unit was designed, built, and demonstrated in Boston Harbor. The results showed that the fixed-plane concept is highly effective in areas where the vessel can travel through the slick. Recovered oil is virtually water free and the unit recovered between 70% and 85% of the oil presented to it.

The fixed inclined plane (SHOC) demonstrator unit works between 3/4 knot and 2 knots. To extend the velocity range down to zero knots and over 2 knots, it is recommended that a moving inclined plane be used. It is also recommended that a set of effective sweeps be investigated and developed.

Abstractor	Institution
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