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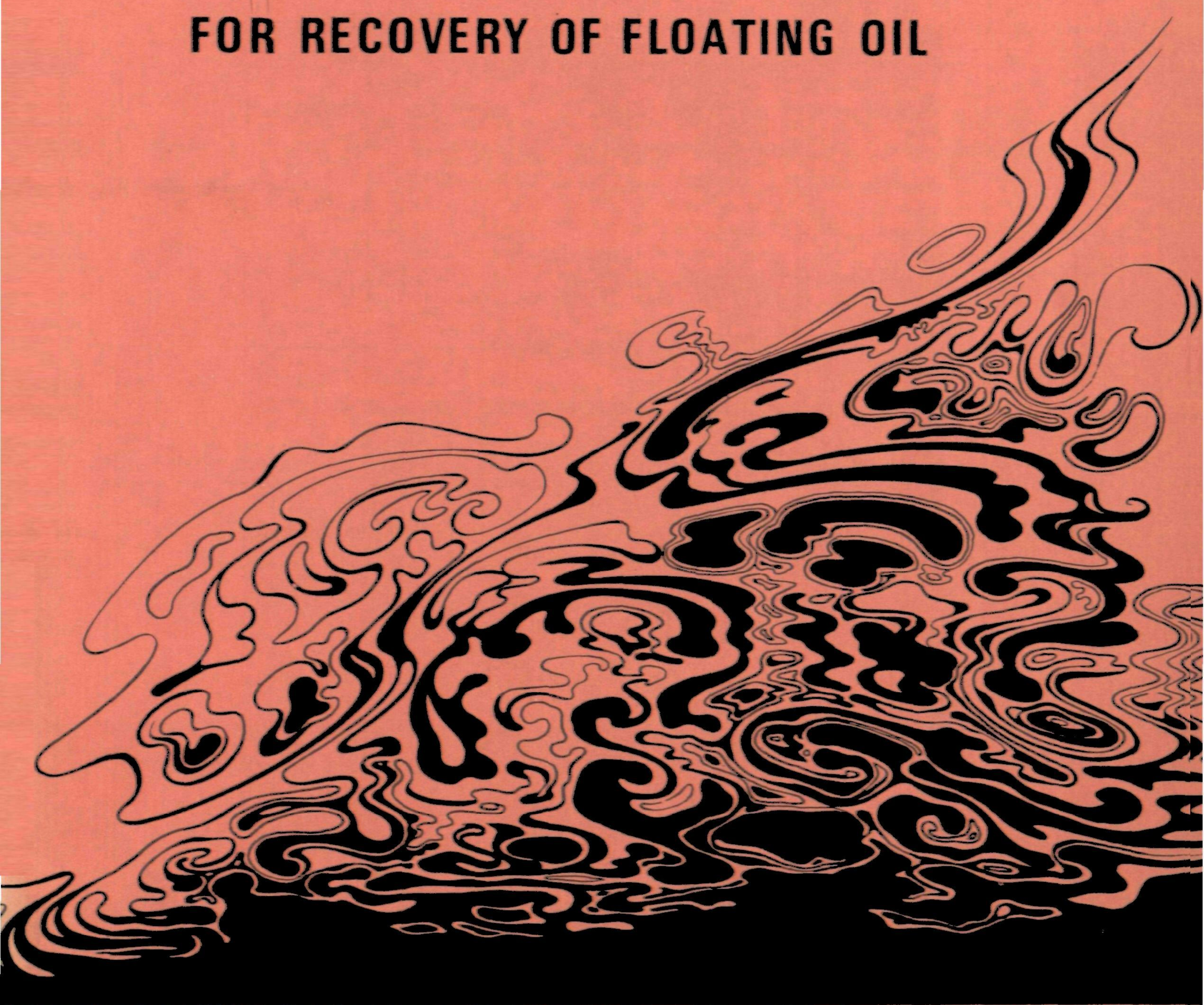
CONCEPT DEVELOPMENT OF A HYDRAULIC SKIMMER SYSTEM FOR RECOVERY OF FLOATING OIL



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CONCEPT DEVELOPMENT OF A HYDRAULIC SKIMMER SYSTEM FOR RECOVERY OF FLOATING OIL

by

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for the

ENVIRONMENTAL PROTECTION AGENCY
WATER QUALITY OFFICE

Project # 15080FWP 04/71
Contract # 14-12-884

April 1971

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ABSTRACT

Efforts are being directed to develop effective countermeasures against floating oil slicks. Mechanical recovery methods, which do not cause additional environmental insult, are most attractive. Such a concept, a hydraulic skimmer, was investigated.

Floating headers, providing a linear water spray pattern on the water surface, are attached to an open sea workboat. Sea water is pumped through spray nozzles mounted on the headers to move an oil slick toward the boat. Side mounted chambers are positioned to collect the concentrated floating oil. Recovered fluid is pumped to an onboard separation system from which the oil is transferred to floating tanks or barges and the water is recycled to the spray system.

Experimental work was directed toward component development and evaluation of a large system model in a simulated environment. A 35 foot support vessel, a 40 foot spray header, and a 9 foot collection chamber provided the 23 1/2 foot model sweep width. Speeds of advance to five knots, random waves to 30 inches significant height and three oil types were used in evaluating this system. Other equipment such as an ultrasonic oil thickness gauge, process pumps and tankage were also used.

Model experiment results showed, for light oils, 80 to 100 percent effectiveness and oil recovery rates of 6600 to 8700 gph. Results with Bunker fuel were not as good, being on the order of 1300 to 1800 gph and 12 to 30 percent effective in recovering oil from the water surface. However, program time constraints did not permit experimental verification of modifications expected to increase performance on heavy oils.

Further development of the concept, including additional model testing with heavy oils plus open sea evaluation of a prototype system was recommended.

This report was submitted in fulfillment of Contract No. 14-12-884 between the Federal Water Quality Administration and Battelle-Northwest, a division of Battelle Memorial Institute.

KEY WORDS: Concept, equipment development, oil skimmer, open sea, evaluation, oily water, separation techniques, technical feasibility, efficiencies, hydraulic studies, hydrodynamics, jets, mathematical studies, testing, water pollution treatment.

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SECTION I

CONCLUSIONS

1. The hydraulic skimmer system concept is a feasible approach to the mechanical removal of floating oil from the open sea water surface. The test program has proven the concept to have sound technical and practical bases. Advancement of the concept to a full scale operating oil pollution abatement tool has a high probability of success. A modular system involving linear floating spray headers, floating chambers to concentrate and collect the oil, plus deck mounted equipment--pumps, tanks, winches, etc.--is conceived to be easily and quickly transported to an oil spill cleanup deployment site and then fitted to an existing workboat, barge or tug.

2. System performance appears to be superior to known methods of oil slick recovery in open sea environments. Conclusions are based on experimental results from a half system model approximately 40 percent of full scale (23 1/2 foot sweep width) operating on several types of oil slicks on fresh water.

   (a) Model performance varied with speed of advance with all types of oil used in the experimental program. The following values represent maximum performance achieved: 2.0 knots--97 percent effectiveness and 6800 gph recovery rate; 3.0 knots--55 percent effectiveness and 8700 gph recovery rate, and; 4.0 knots--24 percent effectiveness and 3000 gph recovery rate.

   (b) Model performance was affected by the characteristics of the oil being recovered. Performance on light oils ranged to 80 percent effectiveness and 6800 gph recovery rate for diesel fuel (No. 2 fuel oil) and 100 percent and 8700 gph for crude oil (40-42° API).

   Operation was less efficient for heavy oil recovery--30 percent effectiveness and 1870 gph recovery rate for Bunker fuel (No. 5 fuel oil). Additional evaluation with heavy oils and with system and component modifications would be expected to show significant performance improvement. Time constraints precluded such efforts.

   (c) No model system performance degradation was detected with operation in waves up to 30 inches significant wave height (short "chop" partially suppressed). The ability of system components to follow wave action indicated that longer and higher waves would cause no detrimental effect.

3. An empirical factor involving system variables (spray flow rate, spray pressure and speed of advance) and oil characteristics (oil thickness and oil type--No. 2 fuel, No. 5 fuel, 40-42° API (crude) became evident in data reduction. This factor--flow times the square root of pressure divided by the product of oil thickness and

and square of the rate of system advance--correlated with effectiveness and oil recovery rate for the oil types used. Extrapolation indicated system requirements for various levels of performance for oil thicknesses for 1 to 3 mm. For No. 5 fuel, the extrapolation was necessary over a range in system variables not evaluated by model test, i.e., for an effectiveness greater than 30 percent.

4. Measurement of system effectiveness for oil slick recovery techniques is difficult especially in the presence of wind and waves. Continuous measurement of oil thickness was mandatory for such performance evaluations and was used in this model test effort. The ultrasonic method employed, although not optimized in this program, represents a feasible method for instantaneous measurement of oil layers down to 0.025 mm (.001 inch) thickness.

5. Recovered materials (oil, water and emulsion) are of adequate quality to eliminate the need for sophisticated treatment equipment, such as centrifuges, in the onboard process flow system. No. 2 and crude oil recovered contained from 11 to 46 percent free water by volume. The oil-water mixture remaining when allowed to separate, contained 3 to 70 percent water, 8 to 94 percent stable emulsion, and 3 to 25 percent free oil. No. 5 fuel oil (Bunker fuel) formed no emulsion with water, although it did contain 8 to 43 percent air by volume. An initial coalescence, in order to remove the free water, plus pumping direct to tankage for eventual landside processing and disposal is concluded to be an effective means of handling recovered oil.

6. Behavior of the model system under dynamic conditions presented no direct difficulties. Tests at speeds of advance to seven knots without waves and to nearly three knots with waves produced no instabilities or detrimental effects on performance of the system. Evaluation of the high speed mode (boom angled to 10° of the vessel centerline) at up to 3.75 knots proved not to be structurally detrimental to the system. The effects of high intensity winds were not evaluated by actual test. However, their effect cannot be of the order of magnitude of the water currents and waves sustained during testing on the low profile linear floating spray boom and the low draft collection chamber. Maneuverability analyses of a prototype oil recovery system mounted on a support vessel show that low speed turns should be approached with caution. The liklihood of overrunning one of the side mounted boom assemblies can be decreased by operation of the spray system.

SECTION II

RECOMMENDATIONS

1. It is strongly recommended that the concept be carried to the next step of development--prototype design and development. The following specific activities are recommended:

   (a) Secure additional system requirement design data to ascertain system performance improvements expected with minor system changes and with heavy oils. Perform additional model testing.

   (b) Develop a feedback device for automatic control of the suction head level, with respect to the oil-water surface, within the collection chamber. Model testing is recommended.

   (c) Review vessel characteristics--length, deck space and dimensions, horsepower rating, bulwark height above the deck and overall freeboard--as bases for the design of components which must be compatible with workboats, barges and tugs available in major West Coast, Gulf Coast or East Coast ports as possible support vessels. A vessel inventory is recommended.

   (d) Design a full scale system such that it can be palletized and air transported and then easily fit to existing available vessels.

2. Advance the concept to a state of readiness for future oil pollution incidents by performing the following recommended activities:

   (a) Fabricate all required components of a total system prototype for use in open sea test evaluation and for eventual use on offshore spills.

   (b) Plan and perform open sea tests to confirm the prototype system performance, operability and seaworthiness.

   (c) After minor system modifications, anticipated as a result of open sea testing, plan and perform a demonstration for all interested parties--federal representatives, oil company industry conservation coordinators and major port authority representatives. The presentation should include first-hand observation of the system in operation, plus a plan of action necessary for further use of the system in actual spill incidents. The plan should be designed by the coordinated efforts of government and industry.

   (d) Prepare a complete set of installation, maintenance and operating procedures of such simplicity and completeness that competence to operate the system is possible within a very few hours by relatively inexperienced personnel.

3. Further develop the oil slick measurement device which was used in this program. Potential applications include industrial process control, enforcement of regulations regarding floating pollutants, monitoring of oil spill cleanup progress, as well as evaluation of oil spill abatement equipment.

SECTION III

INTRODUCTION AND SUMMARY

The Federal Water Pollution Control Administration desires to develop new and efficient devices and techniques for removing spilled oil from the water surface in both protected and unprotected waters. This study was directed toward the development and evaluation of a concept for the recovery of oil from unprotected waters as defined in Request for Proposal (RFP) No. WA 70-23, "Recovery of Floating Oil".

CONCEPT DESCRIPTION

The concept evaluated was based on the employment of generally available vessels (workboats, barges or tugboats) of a class compatible with open sea waters and capable of sustaining the speeds and environmental conditions to be encountered in oil recovery in such unprotected areas.

The concept features a general "Vee-shape" arrangement formed by linear spray headers on each side of a support vessel. The concentrating effect of the advancing "Vee" is obtained by water spray which induces surface currents toward a collection point on each side of the vessel.

The so called "spray boom" is an array of spray nozzles providing a continuous spray impingement pattern on the water surface. When the nozzles are arranged in a linear pattern and the spray is directed generally perpendicular to the direction of travel, sweeping of floating oil toward a collection point is affected. A continuous floating manifold provides pressurized water to the nozzles. The conceptual boom is a low profile floating assembly with relatively short flat members pivoted at each connection. Attachment is to the support vessel by mechanical pivot and flexible hose connections; the spray boom orientation is maintained by cable rigging to the bow. A possible prototype arrangement derived from this concept for three classes of offshore support vessel is shown on Figure 1.

The "collection chamber" forms another major component of the concept system. It consists of a deep, narrow and long hull shape with an entry for floating oil at the side near the rear of the chamber. The spray system is required to direct the oil into this side entry. Vertical baffles and an open bottom, plus the use of internal spray nozzles provides for moving oil from the side entry location to the front stagnation area. A floating suction head provides for recovery of the thickened oil. A collection chamber is attached to the vessel at each side, toward the rear of the vessel.

Finally, the concept must provide equipment which processes the material recovered from each collection chamber into a high quality oil for storage and subsequent disposal. The oil recovery process employs oil recovery pumping units, oily water separation units and tankage filling units. The process flow chart in Figure 2 indicates the interrelationship of these units. One particular characteristic is that all water from the separation unit may be recycled through the spray boom and ahead of the skimmer. This approach makes it possible to reprocess any oil which may be lost in the water discharge of the separator.

Oily water pumped from the oil-water separator may be dumped to waste (land fill or incineration) or processed for bunkering or refining. The use of landside polishing process units may be required. Space and weight limitations on board typical support vessels will likely preclude carrying such final process equipment.

Storage and transporting of recovered oil to a landside base is assumed to be by moderately sized pillow tanks.

EVALUATION PROGRAM DESCRIPTION

Major concept components, the spray boom and the collection chamber were developed separately by experimental model work. All components and support facilities were then fabricated for evaluation of the total system.

Development of the spray boom entailed analysis, experimental component design, and evaluation. Analysis revealed the basic mechanisms involved in the induced motion of oil slicks by water spray. System parameters were determined from basic assumptions and were used as initial design criteria.

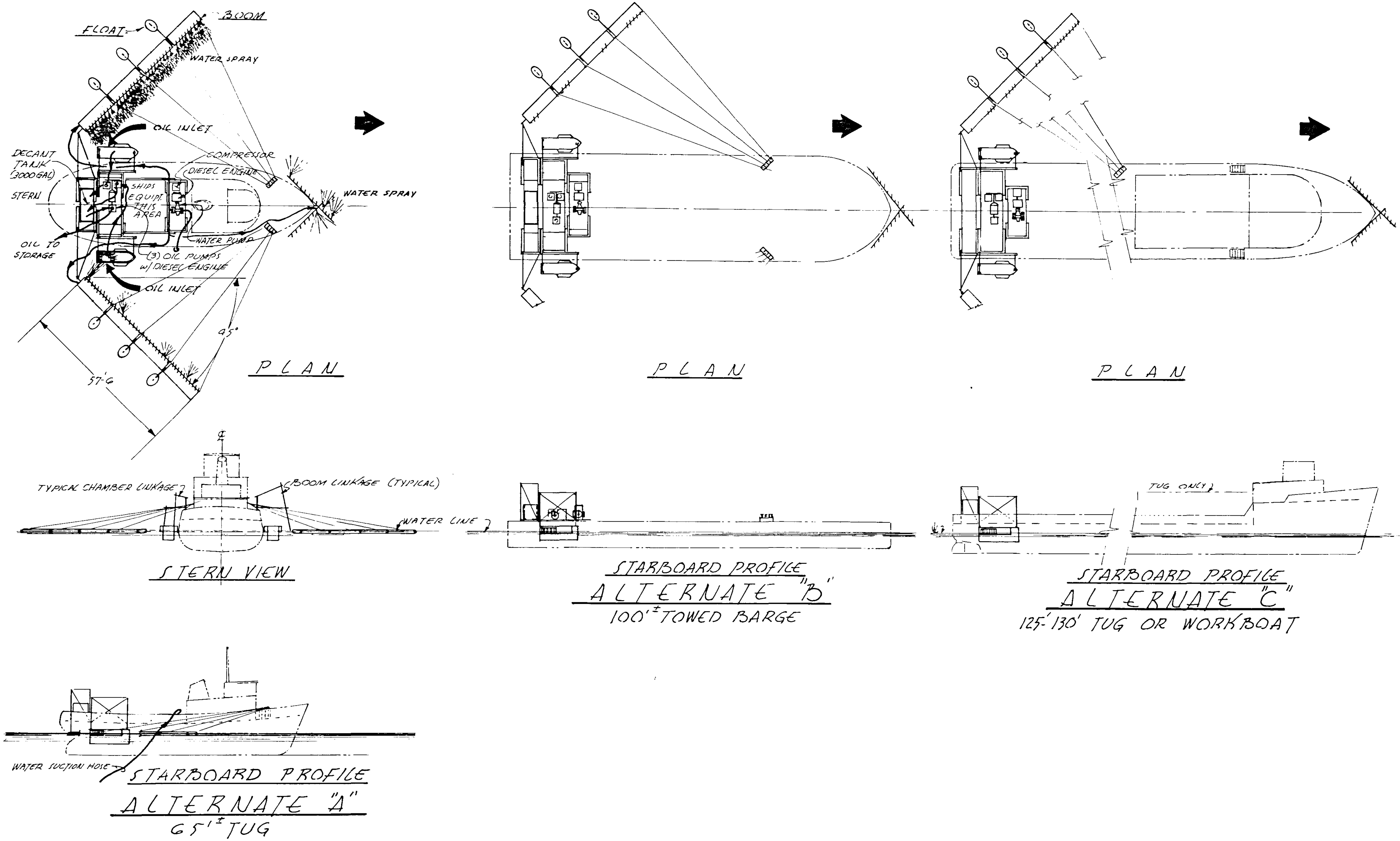
A simulated spray boom, consisting of a mobile spray nozzle manifold supplied with high pressure water, was cantilevered over the side of a large water basin. It was used in determining nozzle characteristics which most efficiently provide oil slick movement. This simulator, mounted on a truck which could be driven parallel to the basin wall, also provided reliable information on the most promising spray flows, pressures, nozzle heights, and orientations. Additional information was drawn from observation of a similar device undergoing open sea evaluation at Santa Barbara. This device, as part of the American Petroleum Institute-Federal Water Quality Administration supported Project Sea Dragon employed a spray boom. It was supported above the water surface by discretely spaced catamaran hull floats.[1,2,3]

The final design was accomplished and the 40 foot spray boom was fabricated as shown in Figure 3 which follows:

Development of the collection chamber was an iterative procedure involving small models testing and analysis of the mechanisms involved. Major deficiencies were overcome and a concept evaluation model was designed by scale-up of the models tested. Figure 3 shows the final design used to fabricate the nine foot long chamber.

Figure 1

Oil Recovery Concept



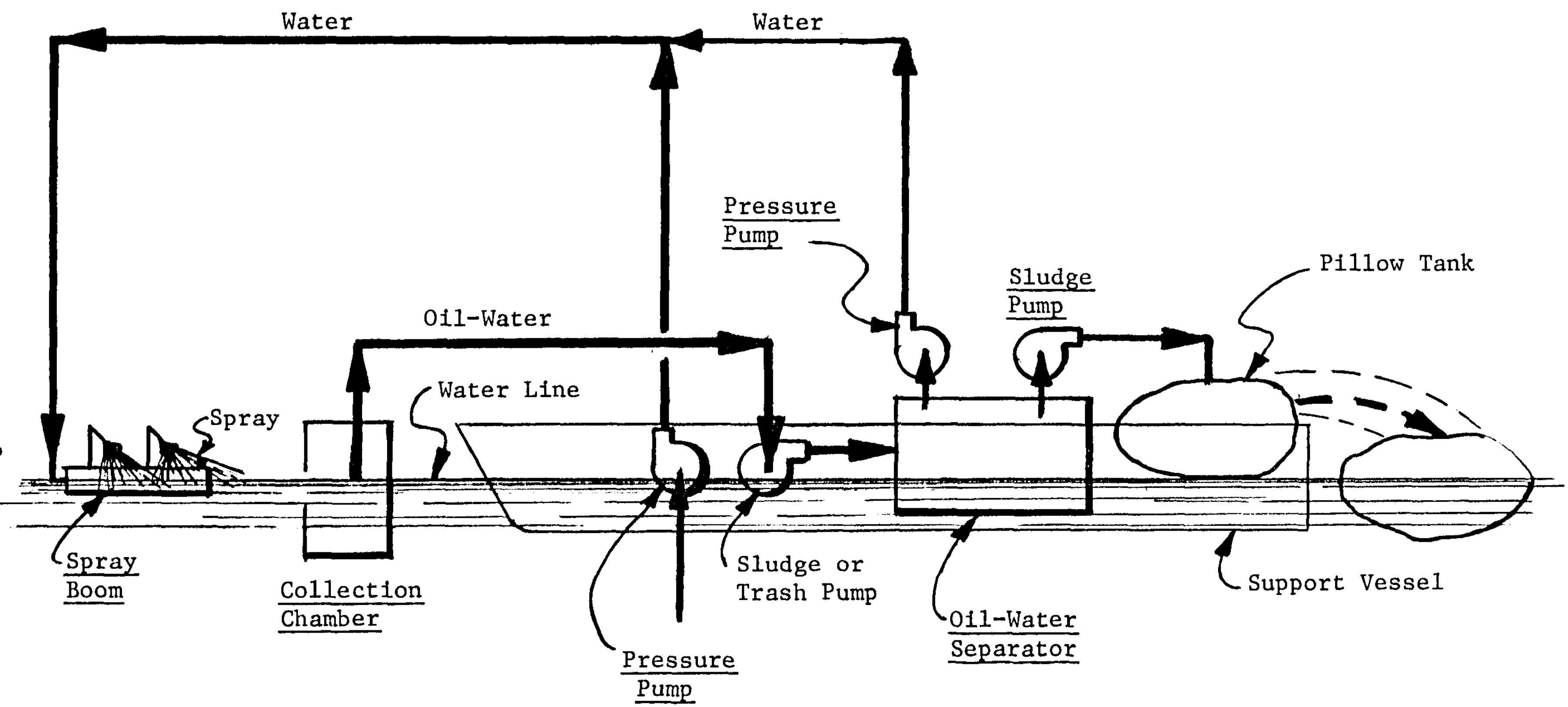
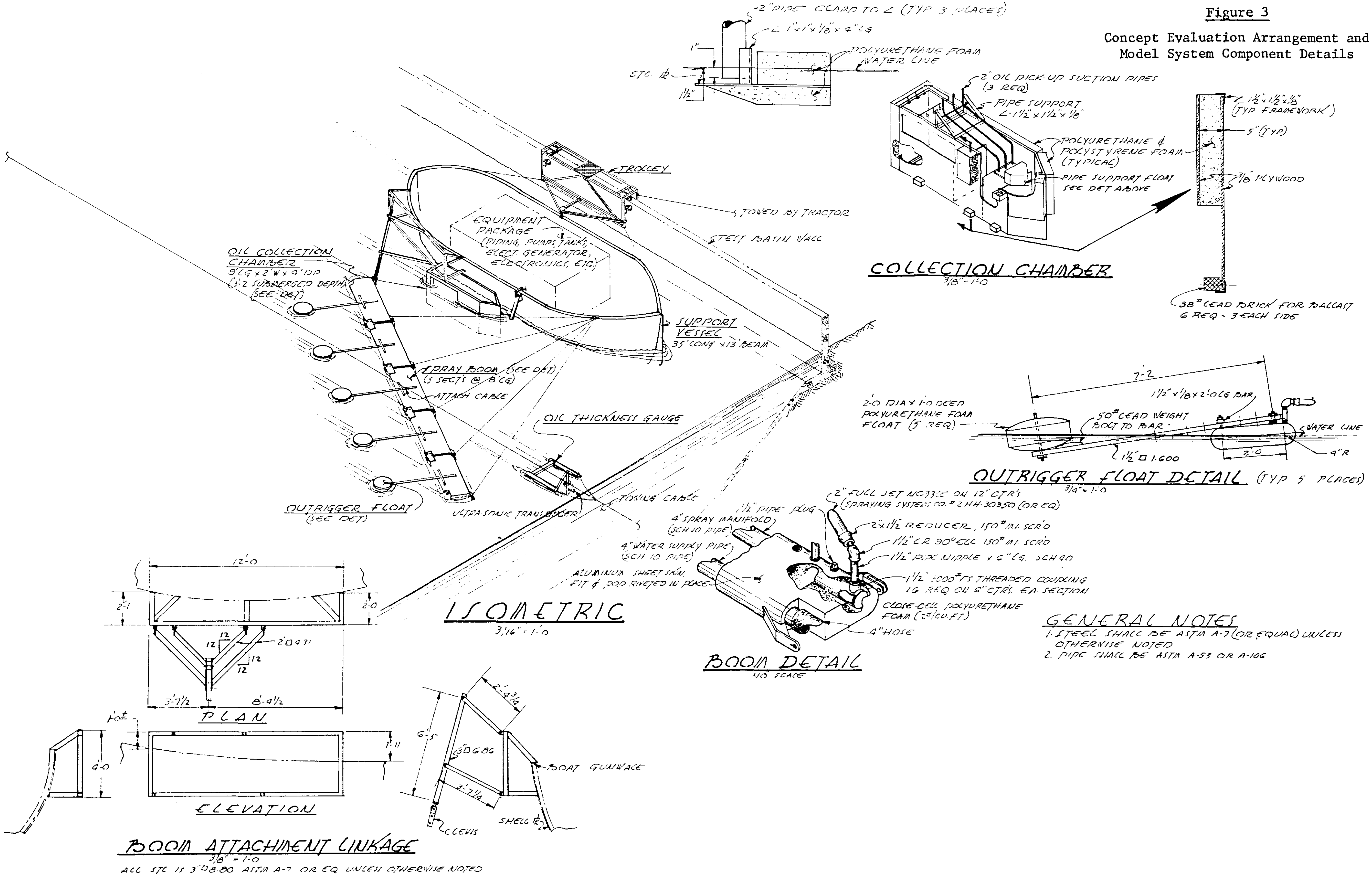


Figure 2

Process Flow Chart

Figure 3

Concept Evaluation Arrangement and Model System Component Details



The support vessel, spray pressure pumps, process pumps, tankage, towing arrangements and interfaces were also designed for use in the evaluation testing phase as shown on Figure 3.

CONCEPT EVALUATION

Concept evaluation was performed in a large water test basin 209 x 432 x 16 1/2 feet deep. A flap-type wave generator capable of producing random three foot choppy wave patterns on the entire surface was used. Support equipment included: electric power supplies, towing harnesses, booms for restriction of oil spreading and devices to measure waves, currents and oil slick thickness.

Initial experiments were performed to identify minor modifications required for operability. Speeds of advance up to seven knots were achieved on calm waters and speeds to approximately five knots in waves to 36 inches significant wave height--average height of the one-third highest waves, crest to trough.

Subsequent skimming evaluation experiments showed system effectiveness--oil recovered versus oil encountered--to be up to 100 percent for crude oil and diesel fuel at speeds of advance in the 2.5 to 3.5 knot range. Recovery of Bunker fuel was less effective with a maximum of only 30 percent. Oil recovery rates for the 23 1/2 foot sweep width of the model system were 7000 to 8000 gph for light oils and 1000 to 1500 gph for Bunker fuel. Improved skimming performance on heavy fuels is likely based on spray boom performance analysis. At the low temperatures during the heavy oil tests, 32 to 45°F, the high viscosity Bunker fuel tended to be in the form of a cohesive mass which sluggishly rolled beneath the water surface when being moved by the spray system. Its high density also caused it to be more readily submerged by impingement of the water spray. The sluggish motion combined with the minimal buoyancy of the heavy oil contributed to this poor performance. It is probable that empirical adjustment of parameters (speed of advance, water pressure, water flow) would significantly improve performance. Also, locating the spray nozzles at or near the water surface so that the maximum horizontal spray force can be transmitted to the slick would improve performance. However, time limitations prevented experimental verification. It was concluded that there is no inherent reason to prevent the efficiency of heavy oil recovery from approaching that demonstrated for light oils.

The oil-to-water ratios in recovered materials varied considerably. Some high oil-to-water ratios were obtained, however. This suggests that adjustment of the system parameters and operation on a continuous basis will result in good recovered oil quality. Formation of emulsions did take place, but only on the light oil products. Proper design of pumping systems and continuous, once through, recovery does not appear to present problems of a significant magnitude, at least for those oils used in this development project.

SECTION IV

SPRAY BOOM DEVELOPMENT

Development activities entailed an initial analysis, followed by model evaluation. A large scale device was then designed for overall concept demonstration.

SPRAY BOOM ANALYSIS

In the concept under investigation, the floating spray boom has two functions. First, it produces a water spray impingement on the water surface. Second, it is the buoyant support of a spray header. The first function produces the effect of moving an oil slick in a controlled direction and rate; the latter is an assembly arranged in a configuration to support the header and to produce this effect. The two functions are separately treated as; (a) spray effectiveness and, (b) boom stability and integrity.

SPRAY EFFECTIVENESS

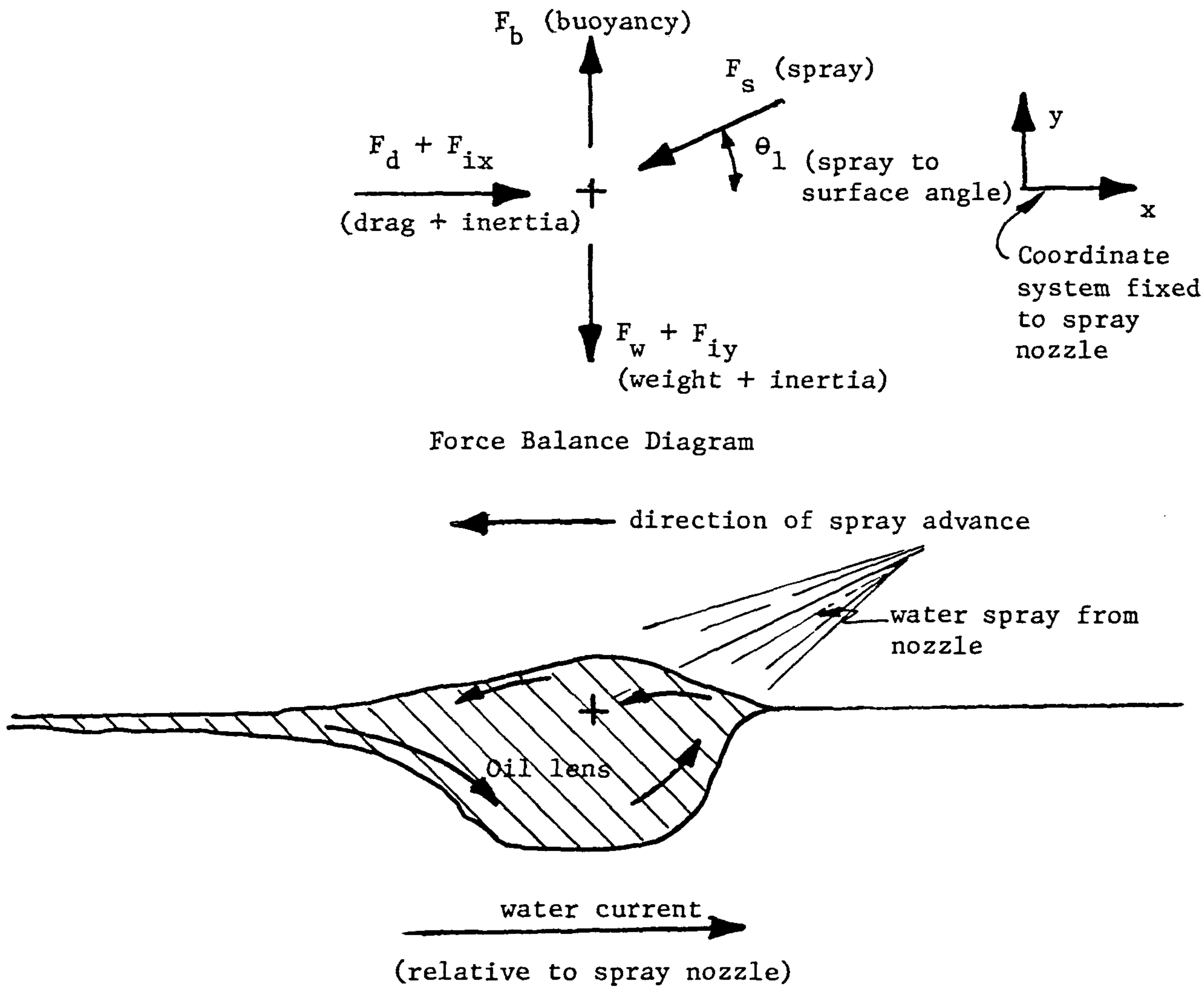
The movement of surface oil slicks has been characterized for many wind and current situations and for several spreading regimes from instantaneous spillages.[4,5,6] However, these empirical formulations are not easily adapted to describe induced movement of oil slicks by high pressure water sprays.

Consider an oil slick retained from following the underlying current by the use of high pressure spray. The spray reaction force arrests the surface flow of oil and thus contains the oil slick. This is essentially the mechanism which produces the effect of oil skimming--a spray manifold is angled into the direction of travel thus imparting a side motion to the surface in such a way that oil travels down the boom length and into a collection device.

The oil slick is assumed to be a flat plate slipping across the underlying water column. The underlying current may be equated to advancing the water spray at a rate equal to the hypothetical current. An effective mass equal to the mass of oil is assumed. Vertical movements of oil relative to the adjacent water would be effected by viscosity (drag). However for this analysis such an effect is considered as second order and is neglected.

Figure 4 illustrates the water spray skimming mechanism.

The force balance which causes the skimming effects can be obtained by considering that, in the horizontal direction, the drag force on a stationary oil lens due to an underlying water current (or advancement of the spray) plus a force which resists the acceleration of an effective mass of material must be balanced by a horizontal component of the spray reaction force. This is also expressed by equation (1), following. In the vertical direction, as a first approximation, assume



<u>Figure 4</u>

Illustration and Force Balance Diagram of the Spray Induced Skimming Mechanism that the vertical component of the spray reaction force must be balanced by the relative oil buoyancy in water and by a vertical acceleration of the effective mass of material. This statement is expressed as equation (2).

$$F_d + F_{ix} = F_s \mathrm{Cos}(\theta_1) \quad (1)$$

$$F_b - F_w - F_{iy} = F_s \mathrm{Sin}(\theta_1) \quad (2)$$

where,

F_d = drag force between oil and water considering the slick to be a rigid flat plate moving across the water surface.

$= C_f \text{ Area } D_w(V_{ow}^2)/2$

F_{ix} = Force to accelerate an effective mass in the horizontal direction

$= D_o T \text{ Area } \alpha_x/g$

F_s = Water spray reaction force generated through the concept spray boom

$= D_w Q_w (2gH_w)^{0.5}/g$

F_b = Buoyancy due to water displaced by the oil slick

$= \begin{cases} D_o T \text{ Area, with no spray} \\ D_w T \text{ Area, when oil is submerged} \end{cases}$

F_w = Weight of oil slick

$= D_o T \text{ Area}$

F_{iy} = Force to accelerate an effective mass in vertical direction

$= D_o T(\text{Area})\alpha_y/g$

θ_1 = Angle of water spray impingement on the water surface

C_f = Drag coefficient

Area = Spray impingement area per foot of boom length

T = Oil slick thickness

V_{ow} = Relative oil to water velocity

Q_w = Spray flow rate per foot of boom length

H_w = Spray pressure at the nozzles

g = Acceleration of gravity

D_w = Density of water

D_o = Density of oil

α_x = Acceleration of oil in horizontal direction

α_y = Acceleration of oil in vertical direction

The solution to force balance equation (1), the summation of forces in the horizontal direction (x-direction) will imply the water spray flows required to horizontally move an oil slick. Inserting the force relations into equation (1) and algebraically manipulating the result produces the following relationship:

$$\alpha_x = \left[D_w/(D_oT)\right]\left[(Q_w(2gH_w)^{0.5}\ \mathrm{Cos}(\theta_1)/\mathrm{Area}) - C_fV_{ow}^2/2\right] \tag{3}$$

Also now, assume that in order to retain the oil ahead of the spray boom, the average acceleration α_x Avg. must be such that the relative oil to water velocity is reduced to zero by the time it traverses the first half of the spray impingement area. Average acceleration over a given distance equals the relative velocity change squared divided by twice the distance, or α_x(Avg.) = $V_{ow}^2/2x$. In this case, x would be half the spray impingement length or L. With this assumption and after rearranging, note the following equation.

$$Q_wH_w^{0.5} = \left[\frac{\mathrm{Area}\ V_{ow}^2}{(2g)^{0.5}\mathrm{Cos}(\theta_1)}\right]\left[\frac{D_oT}{D_wL} + \frac{C_f}{2}\right] \tag{4}$$

Equation (4) identifies the important variables and to what extent they affect performance as follows:

- Increases in drag coefficient, possibly caused by eddy formation at the oil/water interface produces an added flow and pressure requirement. Poor nozzle types could have this effect.

- Increases in oil slick thickness requires that a greater mass be accelerated to retain the oil lens, thus increased flow and pressure.

- Decreases in the effective spray impingement length (a function of the spray pattern and height above the water surface) requires greater acceleration of the oil as the spray advances.

- Increases in the relative oil-to-water velocity, V_{ow}, have important effects on the spray flow and pressure requirements. High rates of advance are required to obtain a high oil recovery rate. A trade off here is necessary--minimum speed for adequate recovery rates, maximum speed for good performance with a given spray flow and pressure.

- Changes in spray angle (θ_1) near zero degrees for this application have practically no effect on spray requirements.

- The relative oil density (D_o/D_w) varies over a range of about 20 percent--suggesting that oil type has minimal effect on spray flow and pressure requirements.

- Required hydraulic force for effective oil slick movement is proportional to the spray flow rate and to the square root of spray pressure. Therefore, arrangements which operate at low pressure and high flow will require the least pumping power for a given level of performance.

The previous analysis may be expanded to the case of a spray boom angled from the direction of the current (or spray advance) by an angle (θ_2) and with spray nozzles angled from this boom by (θ_3). Figure 5 illustrates this side-skimming configuration.

The vector summation of the velocities shown in Figure 5 results in the following:

$$\vec{V}_{ov} = \vec{V}_{ow} + \vec{V}_{wv} \tag{5}$$

where,

$\vec{V}_{ov}$ = oil current vector

$\vec{V}_{wv}$ = water current vector

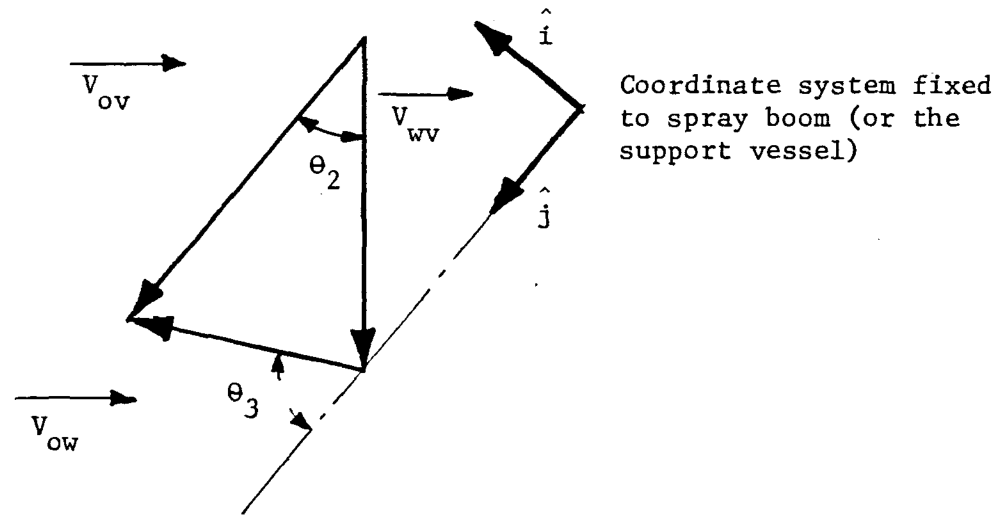
$\vec{V}_{ow}$ = relative oil to water current vector (same direction as the spray forces)

The critical value of $\vec{V}_{ov}$ is that velocity which results in a vector of oil current in essentially the direction of the spray boom, or θ_2 relative to the vessel. This is the situation depicted by the velocity vector diagram of Figure 5. If the water current (speed of advance) were increased and the spray force were reduced, the oil current vector would have a reduced angle, resulting in oil escapement along the length of the boom. Conversely, the reverse situation would result in moving the oil well ahead of the spray, thus wasting pumping power.

Equation (5) when broken into scaler equations and when the critical value of $\vec{V}_{ov}$ is assumed, results in the following equation:

$$V_{ow} = V_{wv} \, \mathrm{Sin}(\theta_2)/\mathrm{Sin}(\theta_3) \tag{6}$$

This expresses the relationship between the vessel speed (V_{wv}), the oil to water relative velocity (V_{ow}) and the spray boom configuration (θ_2, θ_3). From equation (6) it can be determined that to be the most effective, the spray nozzles should be perpendicular to the boom ($\theta_3 = 90°$). This case enables the greatest value of vessel speed for a given spray flow and pressure and level of effectiveness as in equation (7).



Vector Velocity Diagram

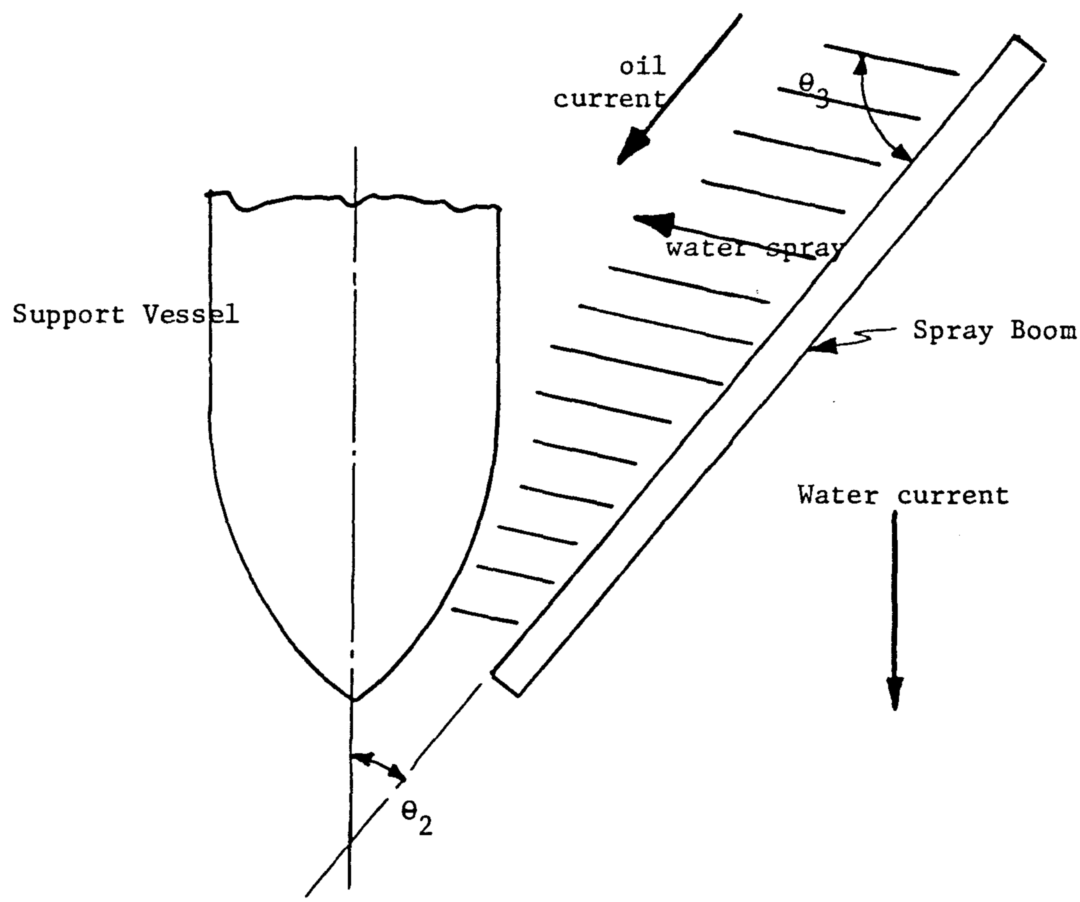


Figure 5

Illustration and Vector Velocity Diagram of the Side-Skimming Arrangement

$$V_{ow} = V_{wv} \operatorname{Sin}(\theta_2) \tag{7}$$

By substituting equation (7) into equation (4), derived for the simplified case of a current perpendicular to a spray boom, a relationship useful to the side-skimming technique is obtained:

$$Q_w H_w^{0.5} = \left[\frac{\text{Area } V_{wv}^{2} \operatorname{Sin}(\theta_2)^{2}}{(2g)^{0.5} \operatorname{Cos}(\theta_1)}\right]\left[\frac{D_o T}{D_w L} + \frac{C_f}{2}\right] \tag{8}$$

Implications derived from equation (8) are:

- Reduced angles of boom to vessel require lower spray pressure and flow.

- Reduced vessel speeds significantly reduces required spray pressure and flow.

The effect of angling the skimming mechanism deserves additional attention. Equation (7) is graphically expressed in Figure 6 to show the effect of this variable on the vessel speed for given oil to water relative velocities. (Also implied by a given oil to water relative velocity, is a given spray flow and pressure requirement--see equation (4)).

The sweep width is also directly related to the boom to vessel angle for a given boom length. This would control the system capacity, all other things being equal.

A simple derivation reveals the relationship of sweep width to system variables as shown in equation (9).

$$W = \frac{Q}{V_{wv} T} \tag{9}$$

where:

W = sweep width

Q = oil recovery rate

V_{wv} = vessel to water velocity

T = oil thickness

This equation is shown graphically in Figure 7, using the design goals of 50,000 gph oil recovery rate at an oil thickness of 1.5 mm and less.

Decreasing the spray boom angulation (θ_2), to achieve improved skimming performance is constrained by the sweep widths required to achieve the recovery rate goal and by the maximum boom lengths which are practical for available support vessels. These vessels can be expected to be normally about 100 feet in length and 30 feet in beam.

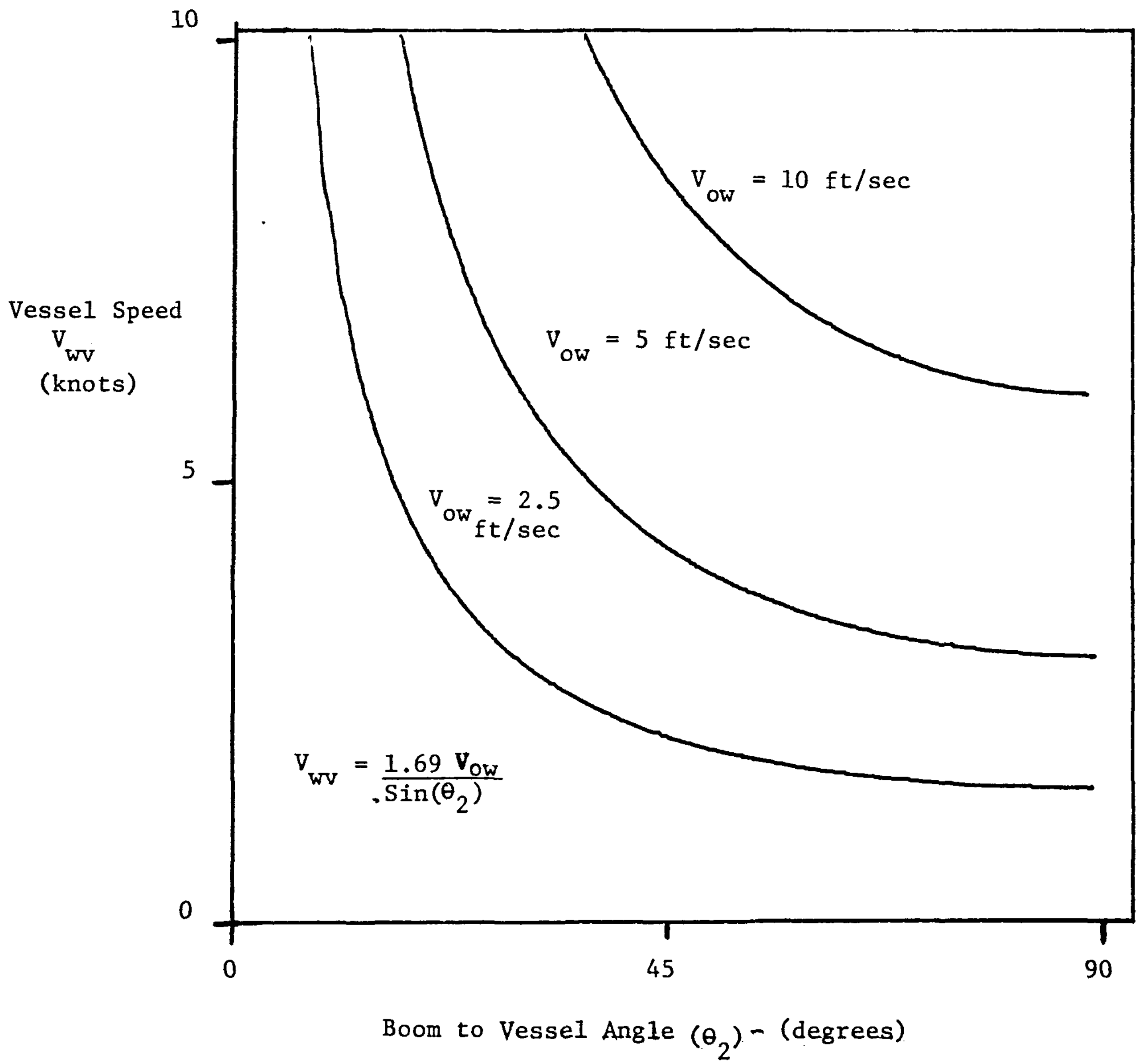


Figure 6

Speed of Advance as a Function of Boom Configuration and Relative Oil to Water Velocity

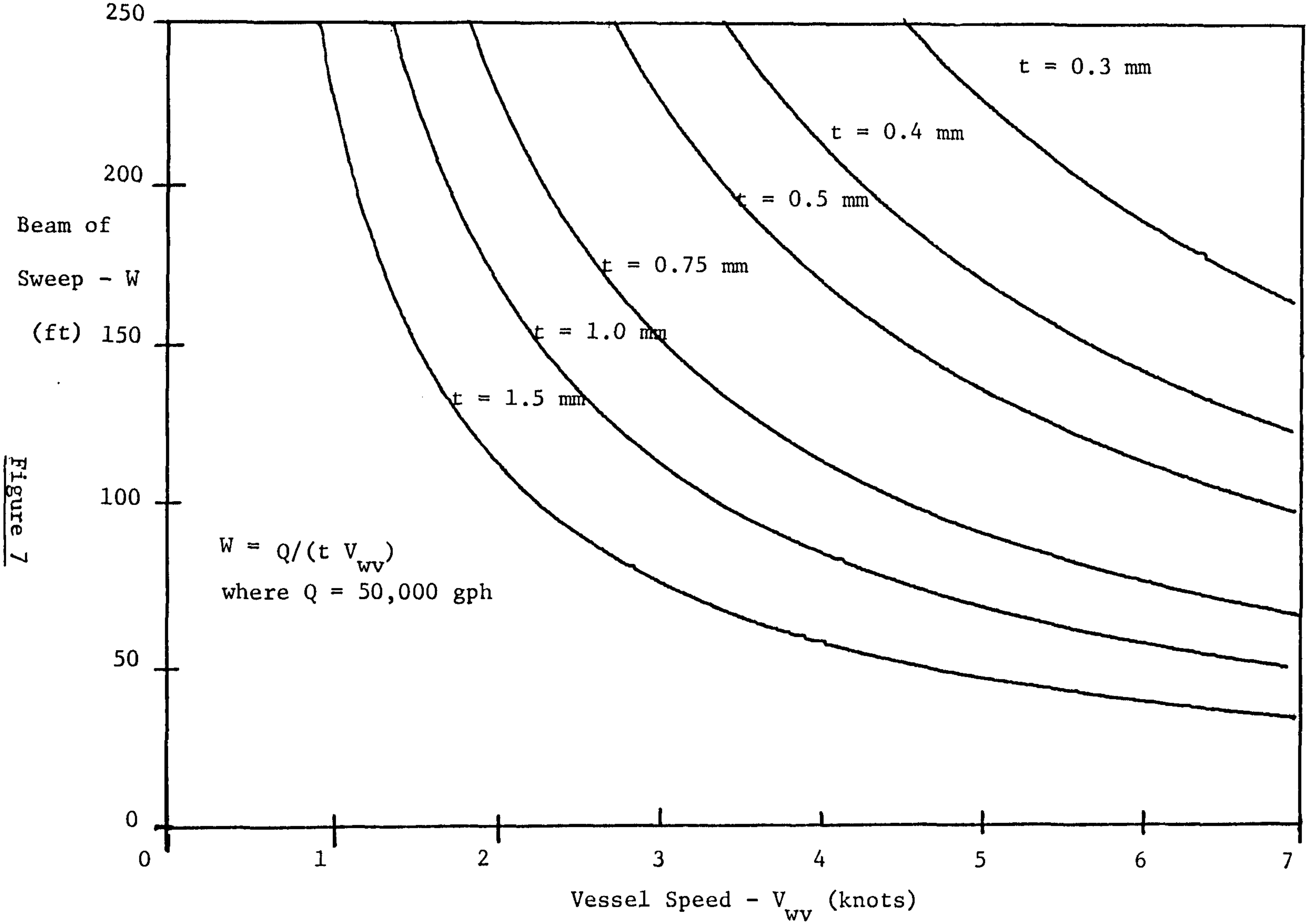


Figure 7
Speed of Advance Required for 50,000 gph 011 Recovery

If the maximum practical boom length is taken to equal the vessel length (to enable proper guy cable support), then the spray boom angulation for oil collection from slicks 1.5 mm and less in thickness, would be limited to about 45°.

Equation (4) and (8) can now be solved to obtain approximate spray flow and pressure requirements as a function of oil to water relative velocity or vessel speed. Equation (10) below expresses the result of these equations using the following assumptions--(see Figure 8 for a graphical expression of equation (10):

C_f = Turbulent friction factor

= $0.74\ Re^{-0.2}$

Re = Reynolds Number

= $D_w V_{ow} L/\mu$

D_w = 1.985 slugs/ft^3

V_{ow} = 5.6 ft/sec for Reynold Number Determinations

L = 10 ft

μ = sea water viscosity

= 2.5×10^{-5} lb sec/ft^2

Area = 10 ft^2/ft of boom

D_o = 1.786 slugs/ft^3

T = 1.5 mm (0.06 inches)

g = 32.2 ft/sec^2

θ_1 = 10°

θ_2 = 45°

$$Q_w(\text{gpm/ft})H_w^{0.5}(\text{psi}) = 67.6\ V_{ow}^2(\text{ft/sec}) \quad \text{or} \quad Q_w(\text{gpm/ft})H_w^{0.5}(\text{psi}) = 78.5\ \text{Vessel speed}^2(\text{kts}) \tag{10}$$

The solution to force balance equation (2), the summation of vertical forces, suggest problems with oil loss resulting from oil slick submergence and subsequent overruning. Since this represents a possible failure mode, it was examined using the same general nomenclature given at the introduction of this section. By inserting the force relations previously developed into equation (2) and algebrically manipulating this result, the following equation results:

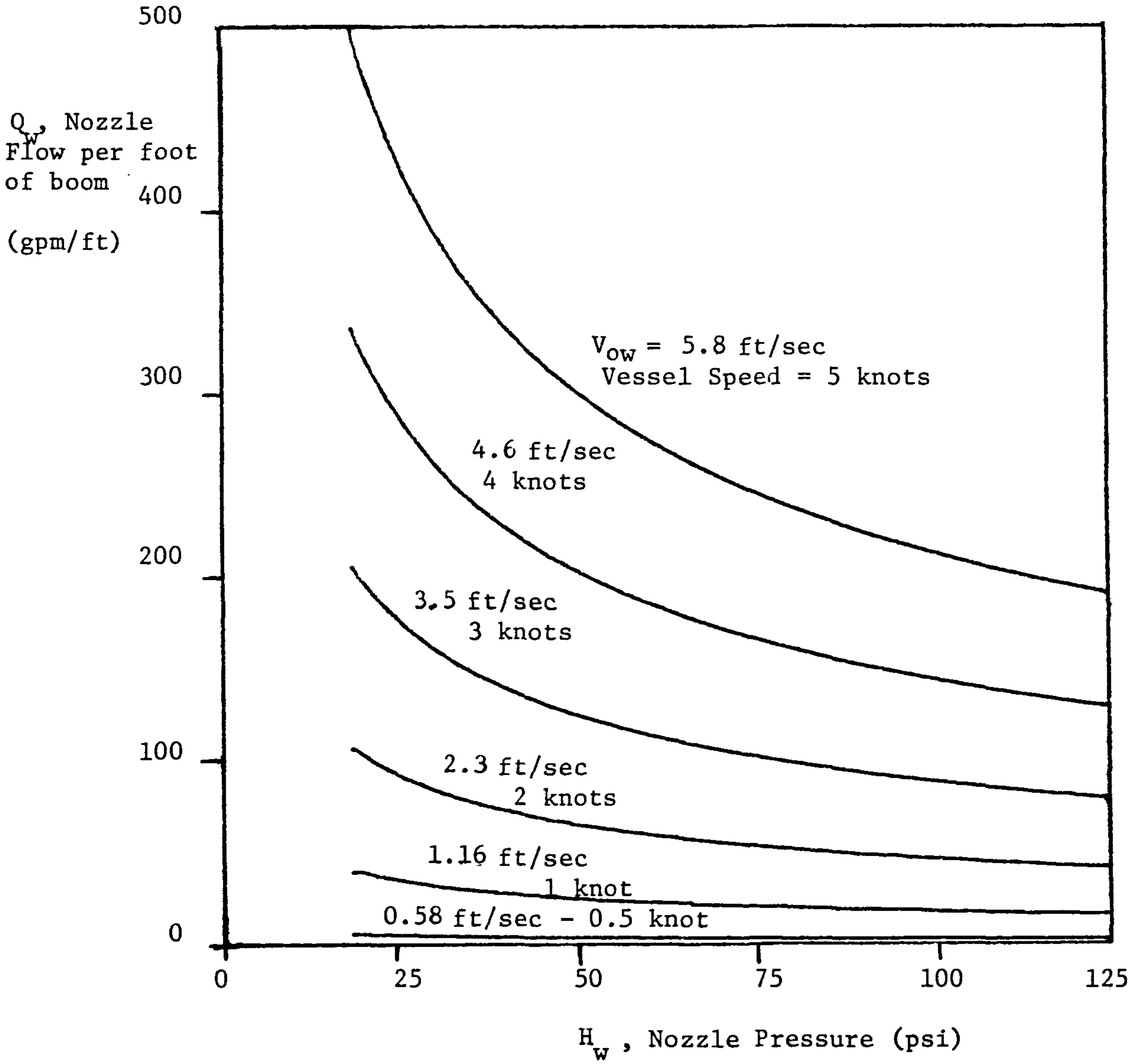


Figure 8

Nozzle Flow and Pressure Requirements as a Function of Speed of Advance

$$\alpha_y = (D_w/D_o)\left[Q_w(2gH_w)^{0.5}\mathrm{Sin}(\theta_1)/(gT\ \mathrm{Area}) - (D_w-D_o)/D_w\right] \qquad (11)$$

where the oil is submerged and being accelerated downward ($\alpha_y \neq 0$).

Overruning an oil slick will occur when the net oil buoyancy (total buoyancy - weight) is overcome by spray forces and when sufficient excess force is present to accelerate the slick to a depth where nozzle sprays are not able to accelerate it horizontally.

As the density of the oil approaches that of water, several limitations on system variables are indicated. A statement of this is given in the following equation where the vertical acceleration is assumed to be zero, but where the oil layer is just stable--any increased downward force would produce oil submergence.

$$(D_w-D_o)/D_w = Q_w(2gH_w)^{0.5}\mathrm{Sin}(\theta_1)/(g\ T\ \mathrm{Area}) \qquad (12)$$

Using this failure criteria, conditions which may enhance oil submergence are indicated as possible system limits.

- As the relative oil to water density approaches zero, system variables become quite limited where either the flow and pressure must be reduced (this implies slower vessel speeds and thus lower recovery rates--assuming equal slick thicknesses) or the spray impingement angle must be reduced to approach zero.

- The effect of variations in impingement angle, for small impingement angles, are quite significant--approximately proportional to the absolute angle change--a change in angle of from 5 to 10° would roughly double the downward spray reaction force component.

- Decreases in oil slick thickness decrease the buoyancy force and thus cause a greater susceptibility to submergence of an oil slick by a given spray condition.

- Decreases in the spray impingement area, such as would be the case if shallow angle nozzles were used or when nozzle height and impingement angles produce reduced areas, cause an increasing tendency to submerge the oil. Wide pattern nozzles may be the preferred type.

The implication of a speed-of-advance limitation as the relative oil-to-water density is reduced is critical and must be further treated. By combining the submergence criteria from equation (12) and the skimming criteria from either equation (4) or (8), eliminating the common spray term, $Q_w(2gH_w)^{(0.5)}$, and using the same assumed variables (but letting θ_1 vary), the following equation results:

$$D_o/D_w = (1-0.009\ V_{ow}^{\ 2}\tan\theta_1)/(1+0.0035\ V_{ow}^{\ 2}\tan\theta_1), \text{ or} \qquad (13)$$

$$D_o/D_w = (1-0.012 \text{ Vessel speed}^2 \tan \theta_1)/(1+0.047 \text{ Vessel speed}^2 \tan \theta_1) \qquad (13)$$

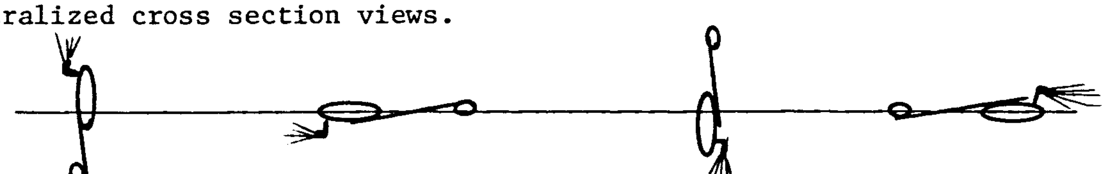
This equation is shown in Figure 9 for given spray impingement angles, thus relating the maximum vessel speeds to a given oil type (density).

BOOM STABILITY AND INTEGRITY

Structural support of a spray header which produces the correct spray effectiveness is required. Continuous rigid floating sections with discretely flexible pivots is the support concept. Floats are suspended as outriggers for additional roll stability. The total boom length is supported at an appropriate angle to the vessel by cables from each boom section to the support vessel bow. At the aft extreme of the boom, attachment to the vessel is made with a free pivot and a lever arrangement to allow for relative vessel to boom surges. The flexible pivots between boom sections are free to rotate only in one plane and not in the other two. Twist from one section to the next is constrinaed. Boom sections are also prevented from forming other than the desired straight length. Figure 10 shows the configuration derived from these constraints.

The several possible hydrodynamic instabilities are considered in the following paragraphs:

Instability No. 1 (roll in the plane of the end view of the boom). Two stable conditions (2,4) and two meta-stable conditions (1,3) are possible in considering this roll possibility as noted below in generalized cross section views.



Condition 1 Condition 2 Condition 3 Condition 4

Condition 4 is the desired condition, applicable during skimming. Condition 3 is possible if the boom front becomes submerged during forward speeds and all counteracting moments (cable force moments, spray force moments and roll stabilizer weight moment) are insufficient to prevent the motion.

Figure 11 and the following discussion indicate how this condition is prevented. The movement due to the spray reaction force is a function of the nozzle flow and pressure characteristic and the moment arm, height from boom center to nozzle. The moment arm is quite short, thus producing a relatively small moment to counteract roll. The roll stabilizer moment is a constant once the floating portions becomes raised out of the water. For this condition it would be the stabilizer weight times the moment arm from center of roll of the boom to center of

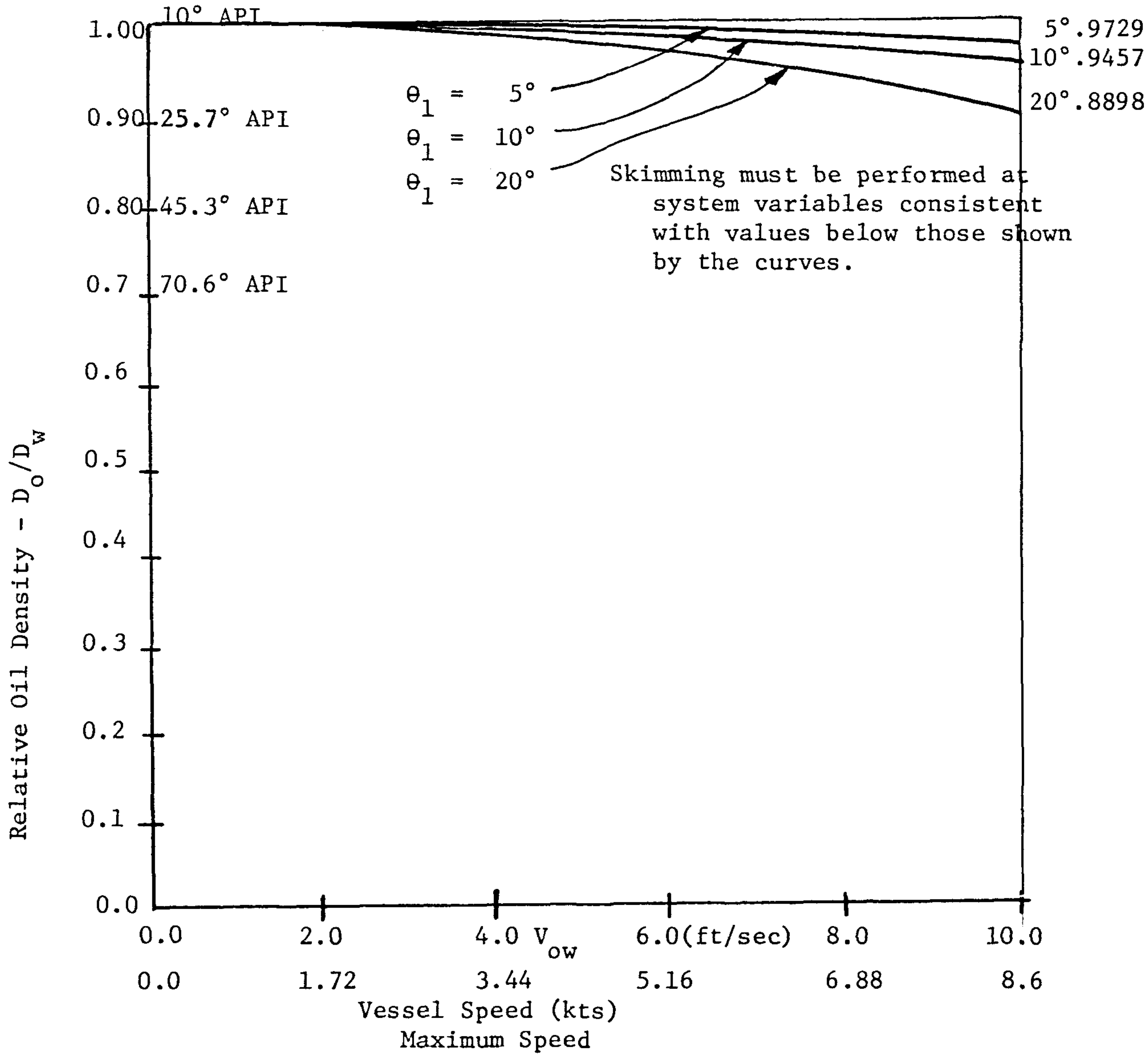


Figure 9

Maximum Skimming Speed as a Function of the Relative Oil Density for Given Spray Impingement Angles of 5, 10 and 20°

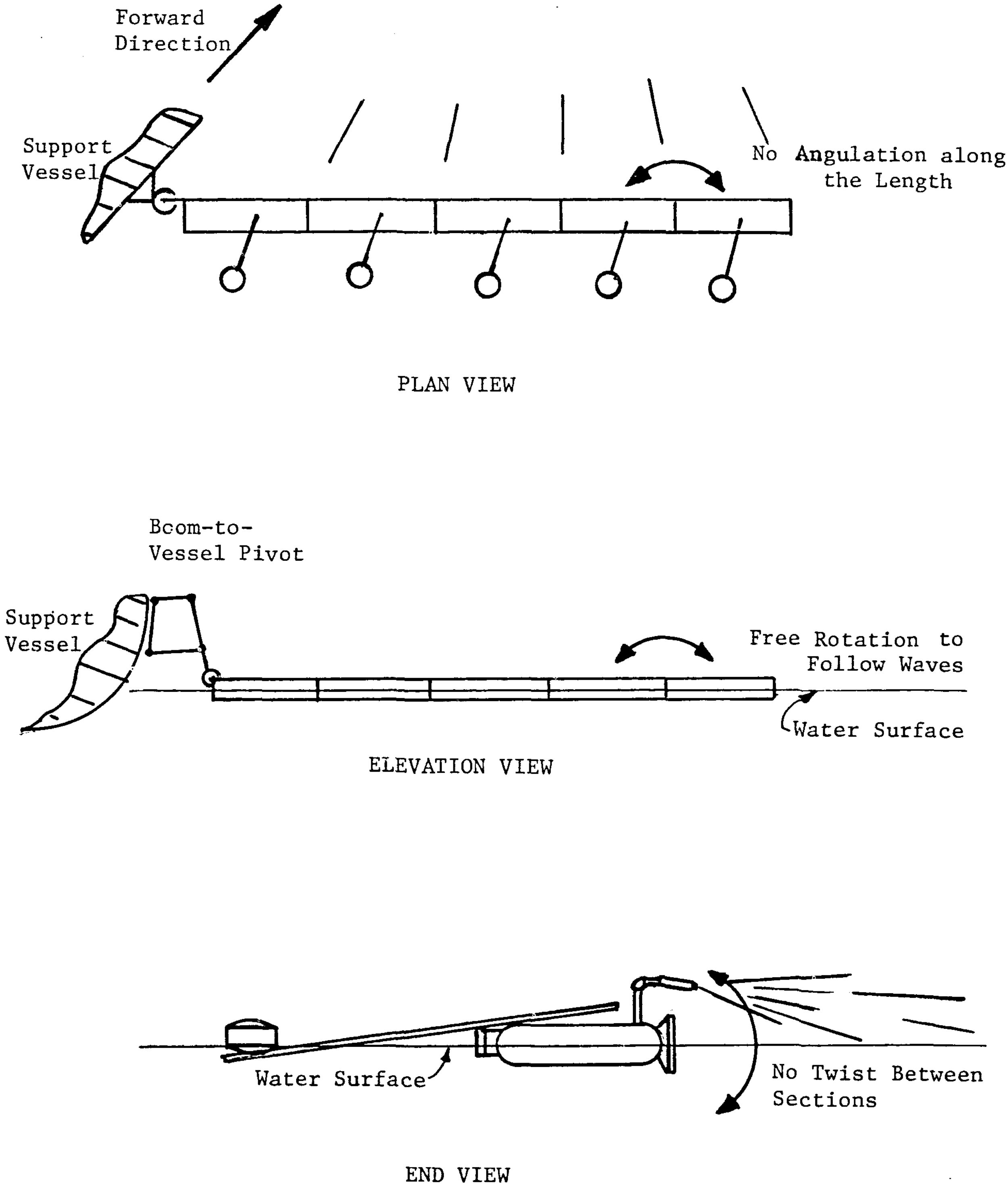


Figure 10

Spray Boom and Pivot Connections

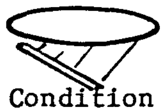
gravity of the stabilizer (quite long). This moment is relatively large. A moment due to the cable forces would be the tension force of the cable times a moment arm which extends from the center of roll of the boom to the cable attachment point and also multiplied by the Sin of the angle between the direction of the cable force and the boom roll position (as seen in the end view). Thus, the cable moment increases with cable forces and with roll angle. The only positive moment which can produce roll is due to drag and wave forces on the boom. The moment due to drag will be a drag force resultant through the center of drag on the boom, the moment arm being the distance from the center of drag to the center of roll, multiplied by the Sin of an appropriate angle (boom roll position to the equivalent direction of the drag force).

By a summation of forces, it is found that the cable forces must be equal to the spray reaction force plus the drag force; therefore cable forces must necessarily exceed drag force. Also, the cable moment arm will be longer than a moment arm due to drag forces. Logically, therefore, a moment due to drag cannot exceed the counteracting cable moment and no exaggerated rolling can be produced when the cables are intact and properly adjusted. The effect of waves produces a similar result with the exception of a rolling inertia which will allow small momentary roll deviations from the equilibrium. Figure 11 graphically expresses this inherent roll stability.

Condition 2 or the upside-down position is only possible if condition 1 or 3 has been encountered first. Although condition 2 is quite stable, considering that condition 3 is unlikely and condition 1 is quite doubtful (no significant moments would be present to cause this condition), the inverted position will not likely occur in even quite harsh wave conditions.

Catastrophic boom roll is considered to be quite unlikely from the preceeding analysis and only small roll angles due to wave effects are expected.

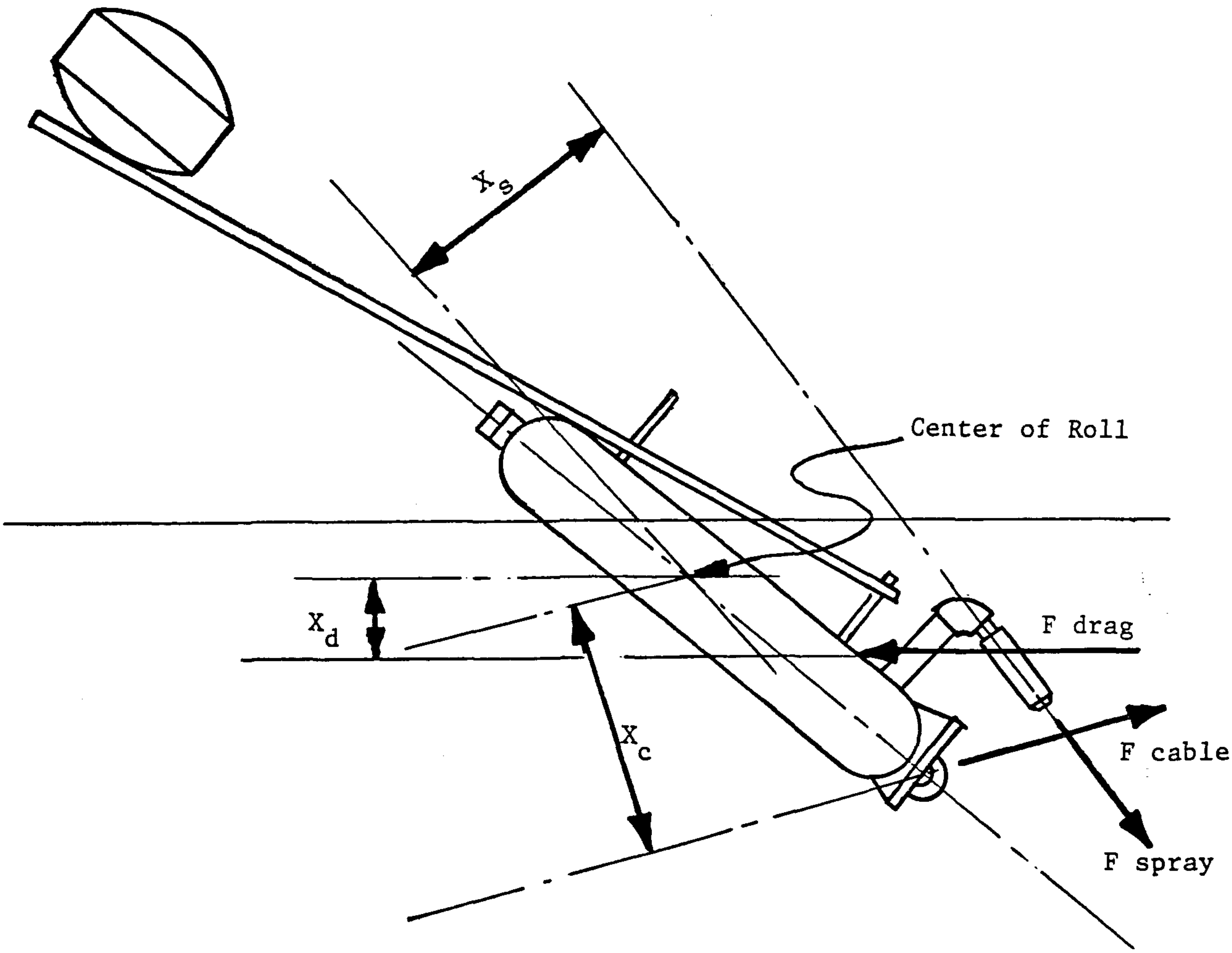
Instability No. 2 (rotation of the boom with respect to the vessel): Two conditions are possible, either the boom is angled and constrained from increased rotation relative to the vessel or forces cause the boom to collapse against the side of the vessel. Condition 1 would be the skimming mode of operation characteristic of approximately 45° angle to the vessel and taunt cables. Condition 2 is a collapsed boom angle with loose ineffective cables.



Condition 1

Condition 2

The cable forces which cause the condition 1 stable configuration are due to spray forces and drag forces. The spray forces are a function of flow and pressure characteristics of the nozzles only, while the force on the boom due to drag is a function of speed of advance and the boom-to-vessel angle (advancing in a straight line) or boom-to-water current



F cable = F drag + F spray
F cable > F drag

Cable Moment = F cable X_c

Drag Moment = F drag X_d
$X_c > X_d$

Therefore Cable Moment > Drag Moment

<u>Figure 11</u>

Spray Boom Moments

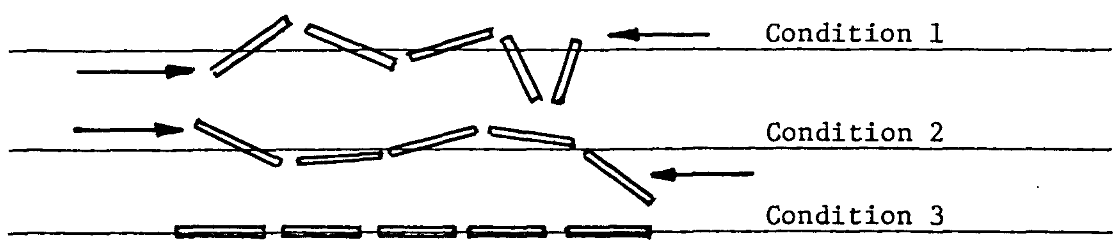
angle (when turning). As the boom-to-vessel angle is decreased, the drag term is likewise decreased. With significant water spray reaction forces, it would be impossible to obtain a condition 2 situation while advancing in a straight line.

In the case of a turning maneuver, the support vessel will pivot about a point 1/4 the vessel length from the bow. The vessel will also have a drift angle, (angle of vessel center line to the direction of travel), similar to a slip angle for an automotive tire during a turn. The stern will drift out on the turn. The following Figure 12 will illustrate the turning maneuver.

When spray booms are attached to each side of a vessel, the boom on the inside of the turn will be pulled sideways by the vessel at an angle relative to the stationary water column. This angle is equal to the vessel-to-boom angle plus the drift angle. The outside boom will also be forced at an angle to the underlying water column. This angle however is equal to the boom to vessel angle minus the drift angle. From these observations, the outside boom would be in jeopardy if the drift angle were to exceed the boom-to-vessel angle (in the absence of spray forces). This could be considered a conservative limit for turning maneuvers when spray forces are present.

When a boom-to-vessel angle of, say, 10°, compared to 45° is used, such as during high speed transport between slicks, smaller drift angles will produce the unwanted instability. However, high speeds result in smaller drift angles thus indicating that high speeds can probably be sustained in most situations. Low speed maneuvers are consistent with large drift angles, making hazardous situations possible. Therefore, during low speed cases with small boom-to-vessel angles or normal skimming angles with no spray present, careful and considered vessel handling would be required.

Instability No. 3 (rotation in elevation view plane due to boom end forces). Forces along the length of a jointed boom will tend to cause it to collapse. The buoyancy and weight distribution of the boom sections will counteract this tendency. As the water level raises and lowers on the boom, the weight and buoyancy produce restoring forces.



Condition 3 will be the equilibrium position in calm waters. Condition 1, though exaggerated, is the correct performance boom shape in a wave situation. Condition 2 would result only from the endmost boom section diving due to a combination of hydrodynamic conditions (waves and current).

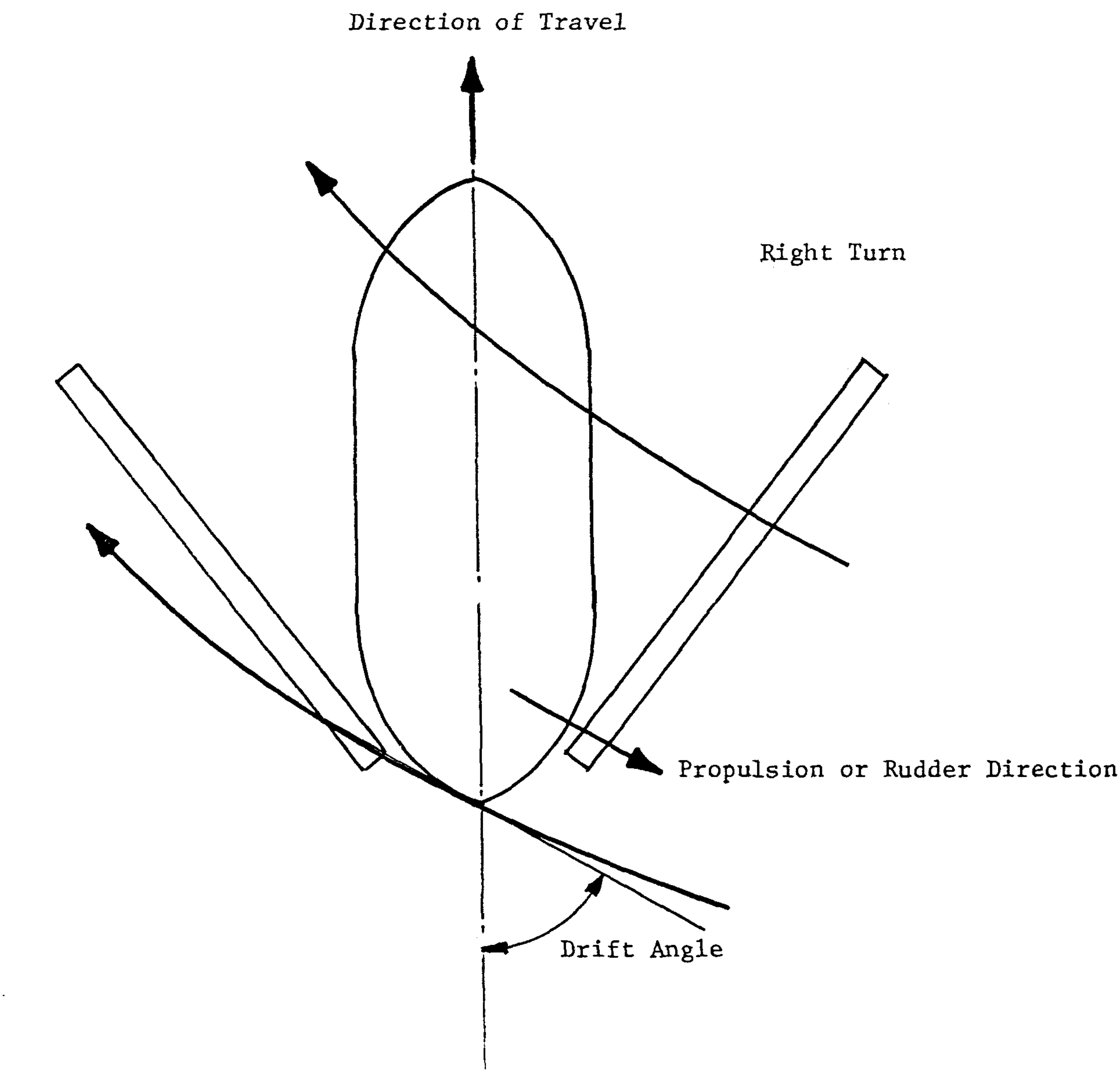


Figure 12

Skimming Configuration During a Turning Maneuver

The boom sections are considered to be approximately half submerged during an equilibrium condition. Total buoyancy will be approximately twice the total weight for a symmetrical body floating half submerged. Such a floating device would act as a spring--a given vertical force applied would cause a displacement which is proportional to the force. The maximum force possible would be either equal to the weight, if the device is lifted from the water, or equal to the net buoyancy (total buoyancy minus total weight) when the device is completely submerged. Consider that equal vertical forces are applied to each end of a boom but in opposite directions. This produces a list or angular deflection and a counter moment. By applying a summation of moments equal to zero (a stable list) and by considering a half submerged object, a list angle can be determined for any value of this vertical force. The following equation is evident:

$$F = \frac{l^2 w \ B \tan \theta}{24} \qquad (14)$$

where:

F = vertical force

l = length of object

w = width of object

θ = list angle of object relative to the water surface (in length direction)

B = either the net buoyancy or the total weight per unit volume

Forces along the length of a jointed floating device will produce alternating vertical force components (force up at one joint and down at the next).

It can be seen that for a given buoyancy or weight per unit volume, stability is enhanced by increases in width and length. As the rotation angle is increased, as is the case for steeper and steeper waves, the instability is worsened.

The end force on the boom is due to several contributing factors; boom drag, spray reaction forces and cable forces. The spray force will tend to reduce the end forces and will dominate (producing tension along the length of the device rather than compression forces) during very slow speeds. The cable force will definitely reduce the end forces--but only on the boom sections at the aft portion of the system. Cables attached to the outward extreme boom connections may have a small component which adds to the end force due to drag. The location of the front vessel, cable mounting and the length of the floating boom will drastically change this effect. The major difficulties which may arise will be from high speed travel, with low spray forces and will be more likely at the extreme inboard joint.

Diving of the end boom is possible and should be considered in the final boom design. Greater buoyancy or hydrodynamic fins may be reasonable preventative approaches.

The above instability characteristics imply that speed of advance in both the skimming and speed modes of travel should be restricted. Trailing of the booms will therefore become necessary above a characteristic speed and in combination with waves which produce large rotation angles.

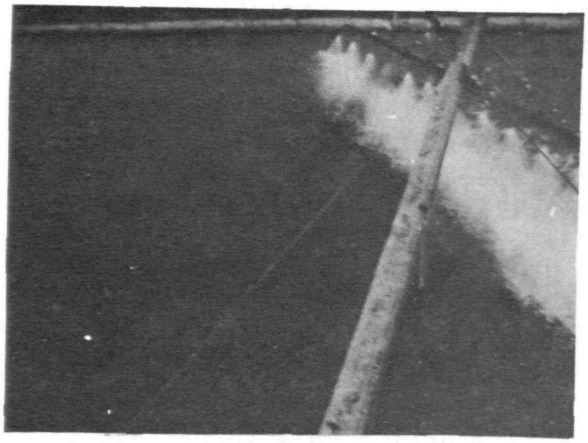
WAVE AND SPRAY INTERACTIONS

Waves will obviously affect both spray effectiveness and the boom motions and stability. The nozzle action on a choppy sea is such that the spray impingement angles vary as a wave passes through the spray impingement area. The significance of this effect is indicated on Figure 9, which shows maximum speed of advance as a function of spray impingement angle which can be sustained without submergence of an oil slick. The dynamic action of a floating boom in waves, producing transient changes in both the relative nozzle elevation above the water and impingement angles due to rolling; surging, is also of consequence. Boom sections should be designed to closely follow the wave profiles which they encounter. Rolling of boom sections from one to the next would be constrained; therefore the boom-to-water surface angle will be at some average value over the entire boom length. Spray nozzle distribution angles should be such as to allow for considerable boom roll and surge and still produce a wide spray impingement area. Longer period (long wave length) waves will have little effect here because of the shallow slopes of such waves. For example, the whole boom assembly can follow a five foot wave which has a 100 foot wave length. The larger the wave, the easier it is for the boom to follow it. The short period "chop" or fresh wind waves will cause the greatest difficulties from both the spray effectiveness and the boom wave following aspects. Model testing should be performed in a "short chop" wave environment.

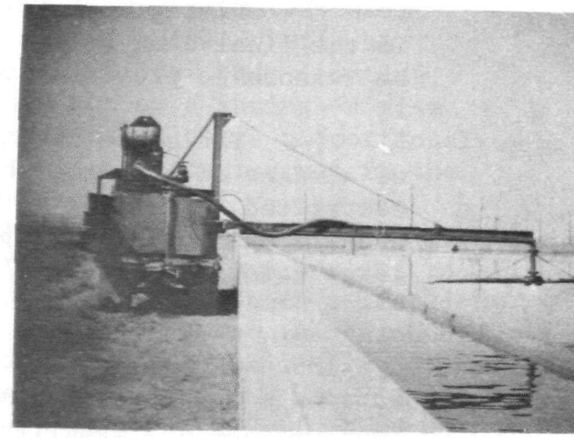
SPRAY BOOM DEVELOPMENT TESTS

Experimental verification and parameterization of spray nozzle characteristics, flows, and pressures on oil slick motion were necessary for a firm design basis of the model system. A spray boom "simulator" was designed and fabricated for this work. The spray simulator as it was called, Figure 13, consisted of a cantilever structure supporting a manifold on which various nozzles were mounted. This structure was supported by a jib crane arrangement from a truck. A pump and tank located on the truck provided pressurized water to the spray manifold.

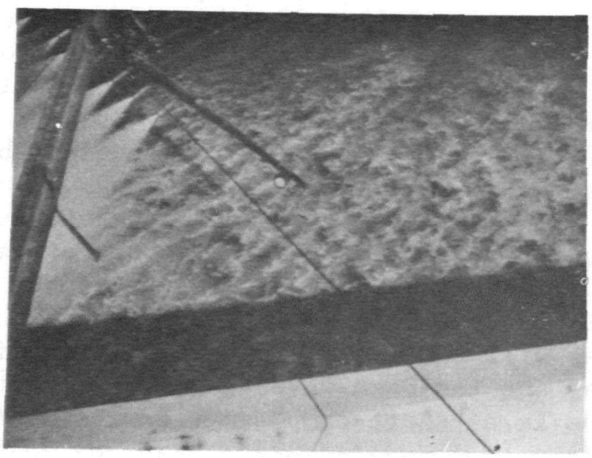
The truck was driven along the test basin wall with the boom overhanging the water adjacent to the wall during the experiment. Water spray from the manifold was directed at floating oil slicks with various combinations of nozzle types, pressures, and flows. A portion



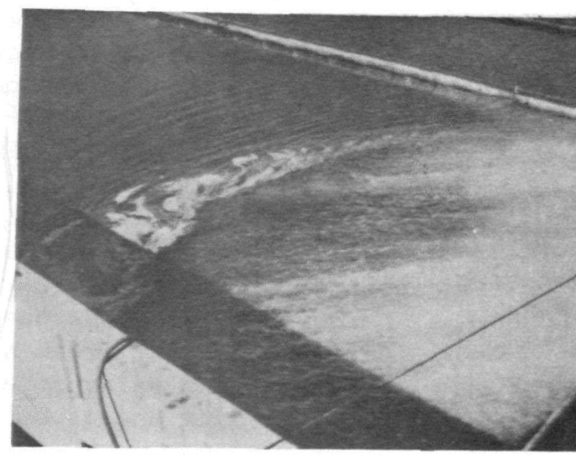
Spray Manifold



Spray Simulator



After Test Run



Before Test Run

<u>Figure 13</u>

Spray Simulator For Spray Nozzle Evaluation of the basin was enclosed by a floating boom and used for testing. The simulator provided for nozzles at six inch centers or multiples thereof for a length of 20 feet. The manifold could be positioned at any desired angle to the direction of travel and the nozzles could be oriented at any desired angle to the water surface or to the manifold. The effect of the water spray on the oil during each run was recorded photographically and the geometrical and hydraulic parameters for each run were recorded. Qualitative visual observations supplemented recorded data.

The search for a viable combination of test parameters resulted in a system judged to be sufficiently effective for design of a scale model prototype.

Table I is a summary of nozzles evaluated using the spray simulator. Figure 14 shows the nomenclature for the various operating components of the spray simulator.

The distance of the nozzles above the water surface was about 30 inches when the simulator was in a level position. Irregularities in the roadway along which it was driven allowed the manifold to vary from ∿36 inches above the water surface to within ∿12 inches of the surface. It was observed that effective combinations of nozzles and angles worked inspite of these height variations.

Basic conclusions drawn from this effect pertain to spray boom effectiveness in moving an oil slick without overruning it. Empirical trials were made for various A, B and C angles (see Figure 14 for definitions). Nozzle types were evaluated and flows and pressures were varied. Runs were made up to 3.0 knots speed of advance, 24 inch significant wave height and different oil types (Texaco Crude Oil 42-44° API and diesel fuel oil).

Conclusions from this phase of the work were as follows:

- Nozzle height had no apparent effect upon skimming efficiency within the range of 12 to 36 inches above the water surface.

- The optimum boom angles appeared to be: A = 67 1/2°, B = 45° and C = 10°.

- The most effective nozzle type for moving surface oil slicks of those tested was the 2HH30350 full jet style (Spraying Systems Co., Bellwood, Illinois).

- Twenty gpm per foot of boom and 100 psi was required to move oil in 24 inch waves and at a 3.0 knot speed of advance.

TABLE I

NOZZLE CHARACTERISTICS

Full Jet Nozzles

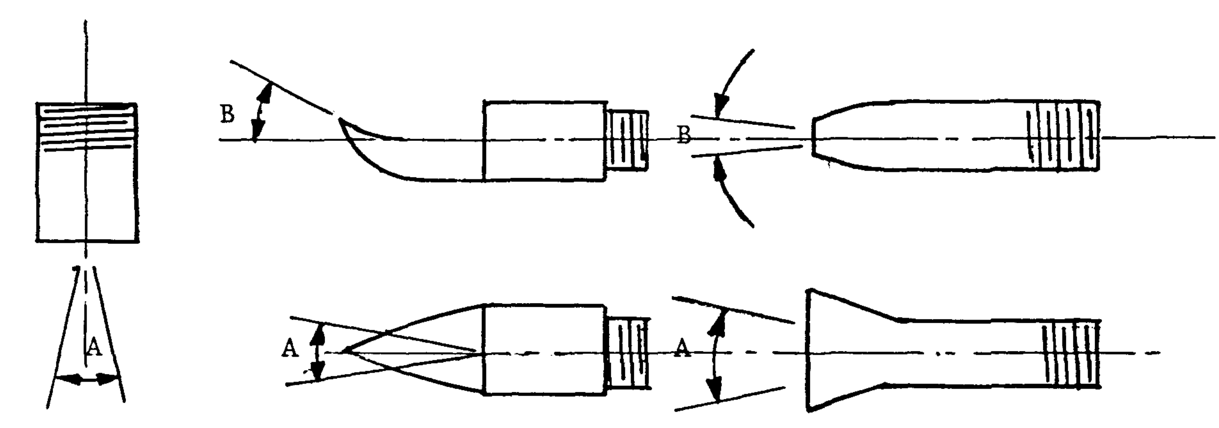
Nozzle No.*	Flow	at Pressure	Spray Angles
3/4 H4	12.4 gpm	80 psi	63°
1 H10	31.4 gpm	80 psi	71°
1 1/4 H14	41.4 gpm	80 psi	73°
2 HH 30350	50 gpm	80 psi	30°

Flat Jet Nozzles

3/4 P35200*	28 gpm	80 psi	40°, 22°

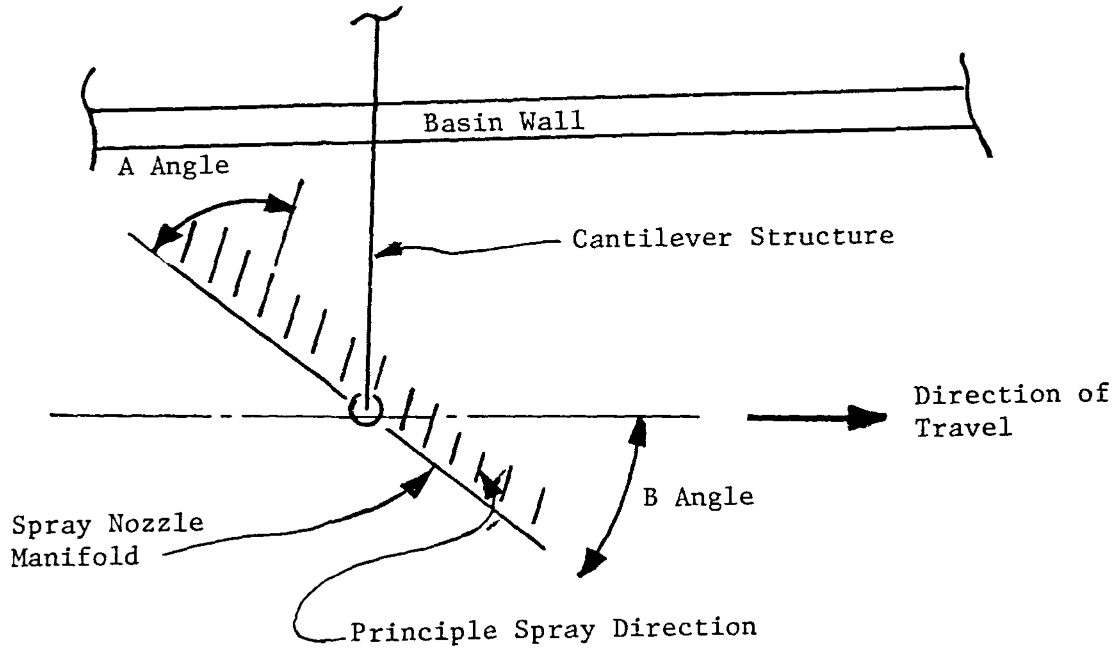
Fabricated Nozzles (flattened pipe couplings)

3/4 A	50 gpm	80 psi	20°, 5°

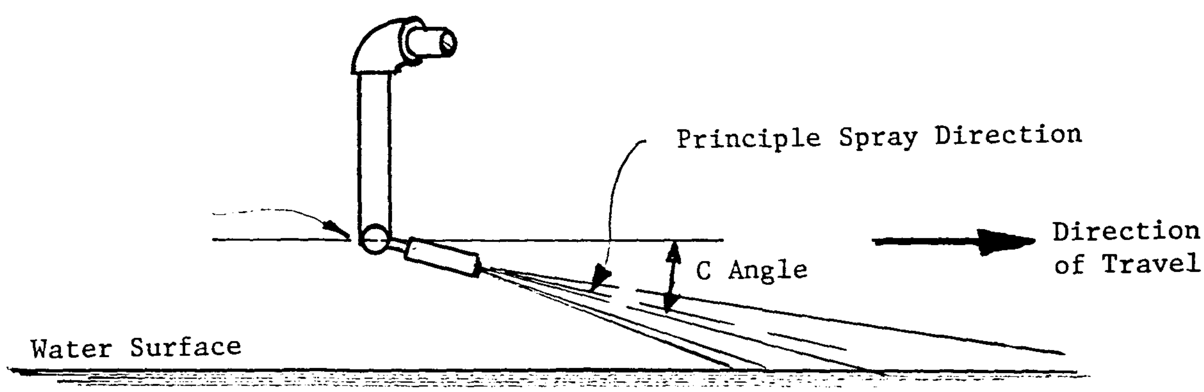


Full Jet Nozzle Flat Jet Nozzle Fabricated Nozzle

* Spraying Systems Co., Bellwood, Illinois



PLAN VIEW



END VIEW OF MANIFOLD

Figure 14

Nomenclature of Spray Simulator Variables

With two exceptions, the nozzles tested were not effective at speeds above 2.8 knots in calm water. The fabricated nozzles were more effective than most nozzle types. However, they produced an irregular spray impingement pattern and required large flows and pressures. Most variation in performance was attributed to the characteristic spray exit angle for the particular nozzle. Flatjets are not appropriate because of their small spray impingement area. Wide angle, fulljets fail because of energy transfer inefficiencies inherent in the wide angle (60°) spray impingement on the surface. The model 2HH30350 has only a 30° spray exist angle in a full cone distribution pattern, thus providing the required surface current without undue turbulence.

The flow and pressure requirements determined from these experiments are based on a cantilivered boom and not a wave following (floating) spray boom. Also the visual observations and photographs of the skimming operation require subjective judgment for interpretation--thus, resulting conclusions should be considered qualitative. Detailed test data are given in Table II.

SPRAY BOOM DESIGN

Spray boom design was performed as several tasks, each representing a performance aspect: hydraulic, hydrodynamic and structural.

HYDRAULIC

Spray boom simulator experiments showed that approximately 20 gpm/foot of boom and 100 psi was sufficient to obtain 80-90% spray effectiveness in two foot waves and speeds to 3.0 knots. These criteria were used in sizing pumps and piping for the model system.

A total length of 40 feet in five 8-foot sections was chosen for the boom model. The water requirements of this boom are therefore 800 gpm total flow with a 100 psi capability for pressure.

Choice of pipe diameter was made from hydraulic pressure drop data for schedule 40 steel pipe. For 800 gpm, a pressure drop of 4.43 psi/100 foot length (5" pipe) or 1.75 psi/100 ft. (6" pipe) can be expected. The choice was made to use two 4-inch pipes interconnected along the boom length. This is equivalent in cross-sectioned area to one 5.65 inch pipe and results in about 1 psi loss within the spray boom length. This is a conservative estimate because of the reduction of flow along the boom length. Vertical uprights at 6-inch centers are provided for the spray nozzle connections, thus allowing for easy changes in nozzle spacing and other piping. Flexible hose connections between boom sections provide for 20 to 30° angular deflection.

A diesel-driven centrifugal pump, capable of 1400 gpm at 120 psi (2400 rpm), was used as the water supply. This pump was mounted on a 35-foot steel hull lifeboat to simulate a support vessel.

TABLE II

SIMULATOR TEST DATA

Test No.	Speed (knots)	Water Spray: Pressure (psig)	Water Spray: Flow (gpm)	Oil: Type	Oil: Thickness (mm)	Nozzle	Angle: A	Angle: B	Angle: C	Effectiveness (percent)
1	5.0	40	270	Crude	.7	3/4 P35200	80°	35°	20°	0
2	1.6	40	270	"	"	" "	80	0	20	0
3	(no data)									
4	2.5	40	140	"	.6	3/4 H4	90	45	20	0
5	1.5	40	140	"	1.2	" "	90	45	20	50
6	1.5	40	240	"	"	1H10	90	45	20	50
7	3.0	40	240	"	1.8	"	90	45	20	0
8	3.0	30	335	"	"	1 1/4 H14	90	45	20	0
9	1.5	30	335	"	"	" "	90	45	20	90
10	3.0	30	335	"	"	" "	90	60	20	30
11	(no data)									
12	(no data)									
13	(no data)									
14	3.5	80	700	"	.7	3/4 A	90	45	10	90
15	2.8	38	316	"	.6	"	45	45	10	70-90
16	(no data)									
17	2.8	50	285	"	1.2	3/4 P35200	45	45	10	75

TABLE II (Continued)

SIMULATOR TEST DATA

		Water Spray		Oil			Angle			
Test No.	Speed (knots)	Pressure (psig)	Flow (gpm)	Type	Thickness (mm)	Nozzle	A	B	C	Effectiveness (percent)
18	2.8	100	400	Crude	1.0	3/4 P35200	45	45	10°	85
19	2.0	100	400	"	"	" "	45	45	10	90
20	1.5	100	400	"	.6	" "	45	45	10	80
21	1.5	100	400	"	.4	2 HH30350	67	45	10	85- 90
22	1.5	100	400	"	.2	" "	67	45	10	80- 90 with 2' waves
23	3.0	40	250	Diesel	.8	" "	67	45	10	50- 80
24	3.0	118	500	"	"	" "	67	45	10	80- 90
25	3.0	80	350	"	"	" "	67	45	10	80
26	3.0	80	350	"	"	" "	67	45	10	80
27	3.0	118	500	"	"	" "	67	45	10	85

Water was supplied to the pump suction from the basin via a bulkhead fitting through the boat hull. Discharge was through twin flexible hoses, 4" in diameter, to connections at the inboard end of the spray boom assembly.

HYDRODYNAMIC

Current and wave forces on the boom sections could only be estimated at this stage in the development effort. For a determination of expected maximum forces, the following was assumed: a single floating boom section 8 feet long, 36 inches wide, and 8 inches deep (rounded ends), a wave characteristic of 3.0 feet (3.9 sec.) superimposed on a 5 knot speed of advance, no wind effect, and a cable rigging which will withstand the forces with little elasticity. With these assumptions, the maximum force due to waves was calculated to be 340 pounds and due to the current, 510 pounds. Superposition of these conditions results in a total maximum force of 850 pounds per boom section due to hydrodynamically induced forces.

STRUCTURAL

Constraints on boom motion and maximum forces are important to the ultimate boom performance and boom interface structures. Each boom section must be capable of withstanding the forces which are imposed under the worse case encountered during its operation. The spray reaction force was found to be 80 pounds per boom section considering the requirement of 20 gpm per foot of boom, 100 psi spray pressure and a nozzle efficiency of 75%. This in combination with hydrodynamically induced forces must be offset by cable forces and the boom to vessel interface pivot.

By making the assumption that cable forces are balanced (no moments are encountered at the connection between boom sections), forces as shown in Figure 15 result.

Considerable compressive force (up to 3300) pounds between boom sections is evident. Cable forces range up to approximately 1000 pounds tension for the balanced force case; 2500 to 3000 pounds should be the maximum requirement of anyone cable as a worst case (unbalanced forces). The front and rear connections to the support vessel will also require considerable strength in resisting the maximum forces.

Unbalancing of the cable tensions will result in bending moments in the affected boom sections in addition to those created by the drag and spray reaction forces. If the outermost cable becomes loose, a bending force is applied at the connection between the outboard boom sections. Inserting the expected maximum forces into appropriate equations produces a maximum moment in the boom section of 660 ft lb at the connection. With balanced cable forces a maximum of only 335 ft lb is reached. Considering the possible problems in rigging, 130 ft lb for bending and 4000 lb compression in each boom section is considered a practical design critera.

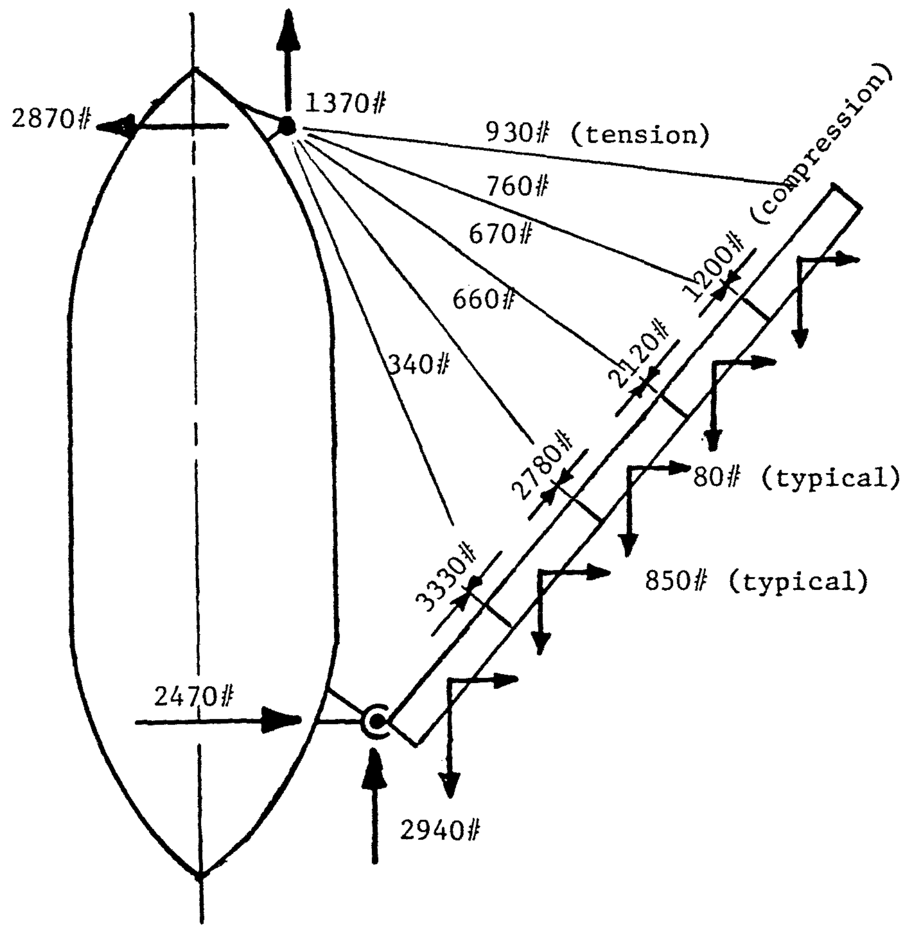


Figure 15

Structural Connections Between Boom Sections
and Between the Boom and the Support Vessel;
Including Maximum Expected Force and Reactions

Other possible forces due to wave action must be considered. A wave could possibly lift a central portion of a boom section resulting in both ends being lifted from the water. The weight of the boom would then produce a bending moment. The buoyancy would produce an upward force at the center and the unsupported ends would produce a downward weight. Forty pounds of force per foot of boom would produce a maximum moment of 160 ft lb in this plane.

Since the boom sections are constrained from relative twist between sections, twisting torque will be randomly applied to the boom sections due to wave action. For design purposes, a 60 pound weight on one stabilizer at a distance of 8 ft from the center of boom roll was assumed to give a maximum twisting torque. The boom length which would be affected must sustain a torque of 240 ft lb.

The boom sections were designed, fabricated and tested for loads in excess of these expected maximum values. Figure 16 is a photograph of the final design arrangement used in concept evaluation tests. Vessel to boom structural connections were made by a lever arrangement which compensates for relative vessel to boom surges.

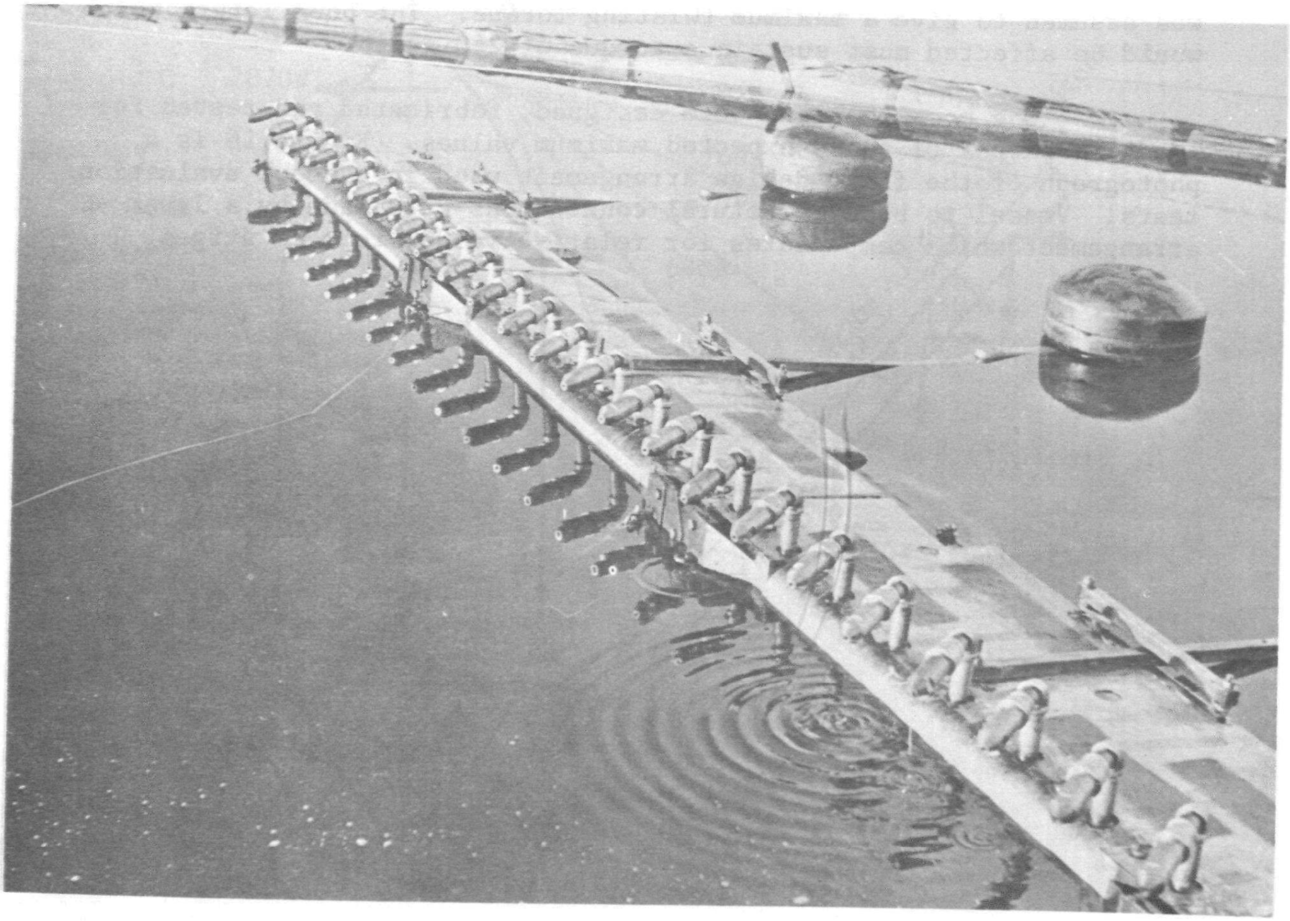


Figure 16

Final Design of Model Spray Boom

SECTION V

COLLECTION CHAMBER DEVELOPMENT

Collection chamber development, as in the case of the spray booms, was performed by analytical treatment followed by model experimentation. Concept evaluation equipment was then designed for system evaluation.

COLLECTION CHAMBER ANALYSIS

Development of the collection chamber concept was based on the environmental conditions in which it must function and the program design goals. Performance factors were classified as effectiveness, stability, and wave following characteristics.

COLLECTION EFFECTIVENESS

Recovery of floating oil which is "swept" by a hydraulic spray boom is not simple. Retrieving a small quantity of oil while avoiding pumping a large quantity of water requires the oil to be concentrated in a stagnant area or stilling chamber. Collection or retention chambers which have open fronts to admit incoming oil and water and then retain only the oil are subject to the phenomenon of underflow and draining. This phenomenon has been extensively studied in the laboratory and attempts have been made to predict analytically the underflow behavior and provide a physical explanation for the effect.[7,8] A side entrance oil collection chamber scheme was employed for concept development to circumvent the difficulty of underflow. The rationale is basically to minimize the quantity of water which must flow into and out of the chamber. For example, in calm water, the only flow of fluid into the chamber is that induced by the spray nozzles. In wave motion, however, there will be a variable flow of water into and out of the chamber as it heaves with the waves. Figure 17 illustrates the collection chamber concept and it is further explained as follows:

- The concentrated oil reaching the inboard boom section is driven into the side entryway of the collection chamber by induced spray current.

- Once inside the chamber, the oil is out of the influence of the free stream flow and is moved forward by a series of internally mounted spray nozzles.

- At the forward most location within the collection chamber (the oil recovery zone), the oil stagnates until oil suction pumps operate to pump the oil on board the support vessel.

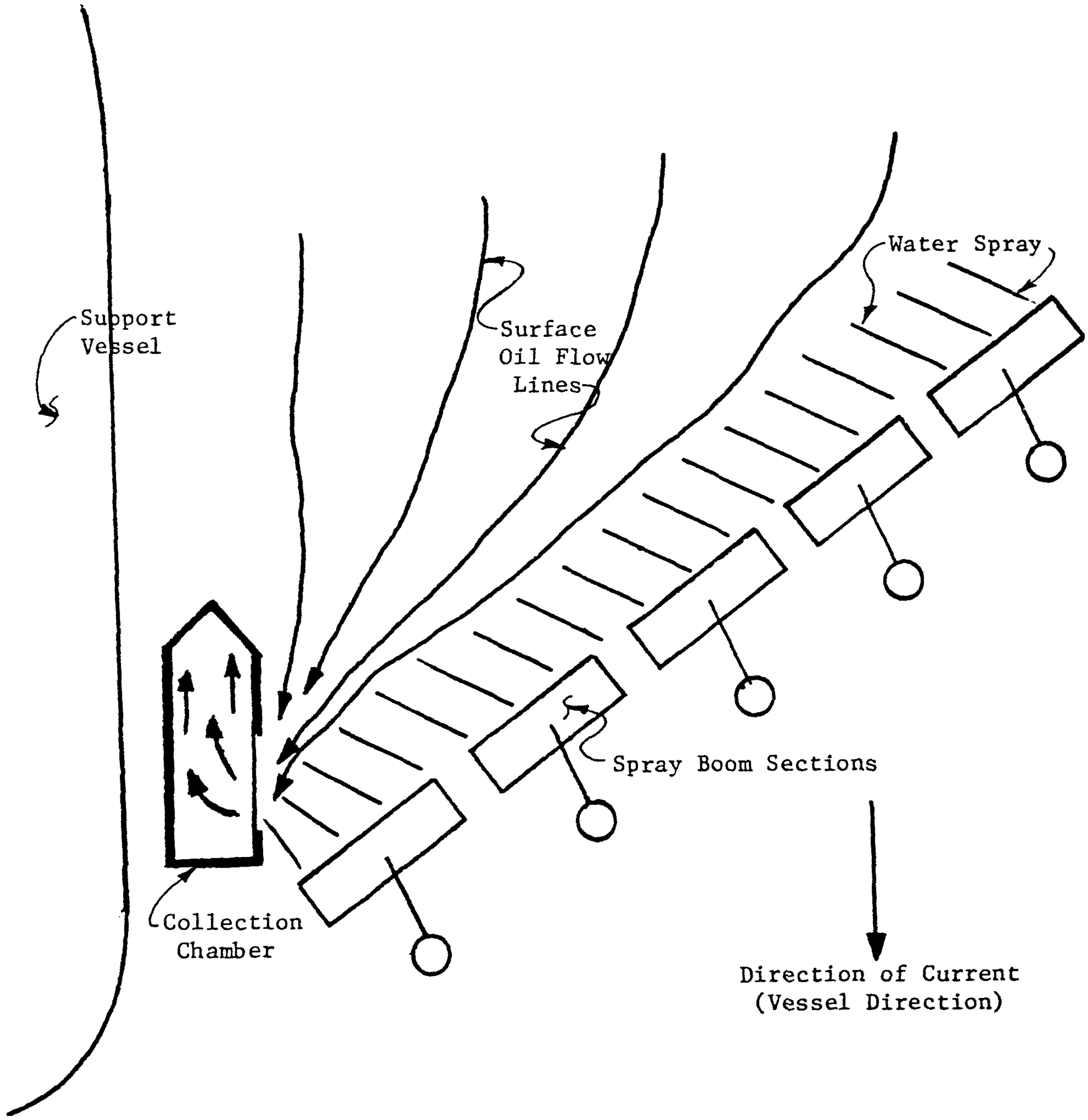


Figure 17

Side Entry Collection Chamber Concept

The flow below the chamber open bottom will cause cells of induced circulation. It was expected that a chamber having a series of internal baffles would provide a controlled liquid circulation pattern within the chamber as it is towed. Correct positioning of baffles and the use of a short bottom plate at the front was intended to prevent oil underflow. The front portion of the chamber is closed at the bottom thus forming a stagnant oil recovery zone. Figure 18 shows the flow patterns expected in this arrangement.

This concept was verified by developmental testing on a model scale. Several spray nozzles were arranged to provide additional impetus to thicken the oil.

CHAMBER STABILITY AND INTEGRITY

As in the case of the floating spray boom, the chamber is subject to all the relative water surface displacements of any floating object. The collection chamber was considered for each instability mode. Figure 19 illustrates the expected induced motions of the collection chamber.

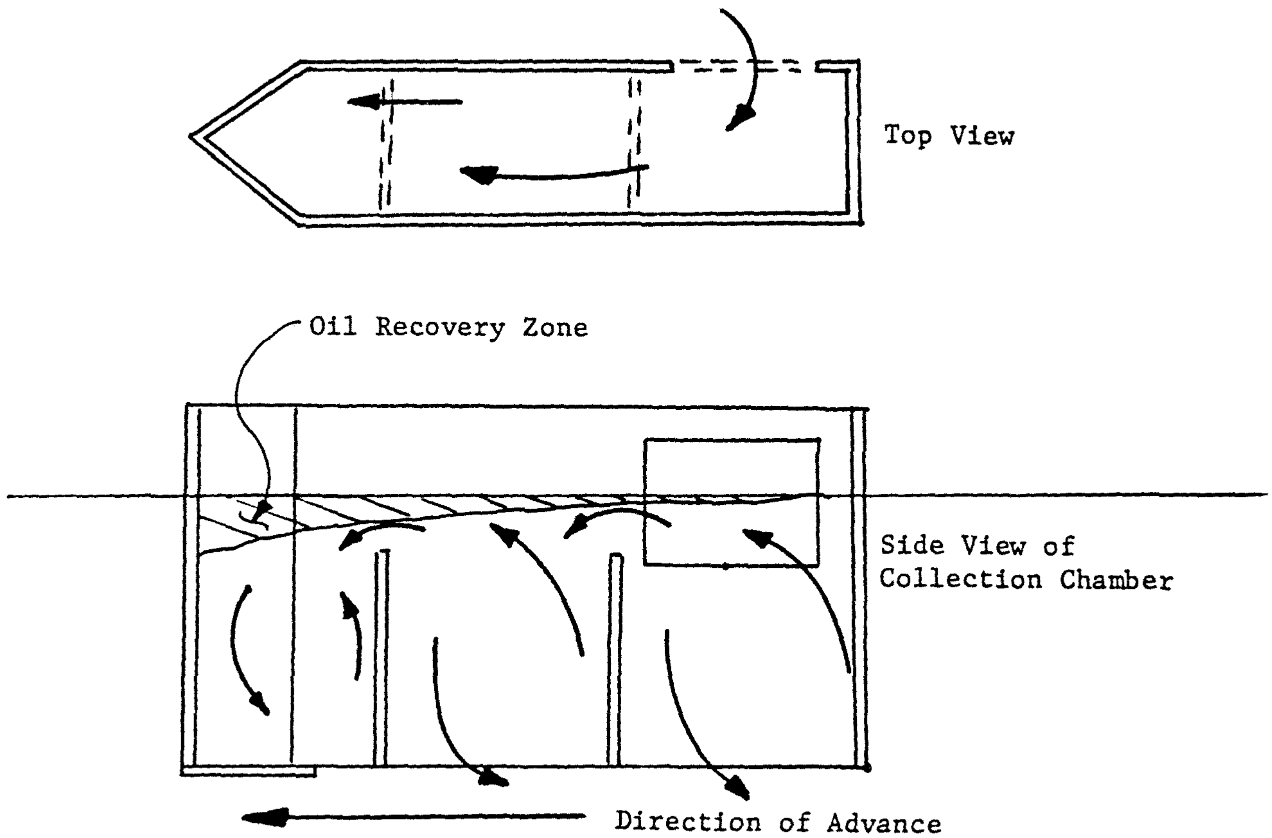
Instability No. 1 (Rotation of Chamber with respect to vessel axis). The relative rotation of the collection chamber must be constrained by the use of an appropriate linkage system. Connections to the vessel are made at fore and aft locations on the chamber. Thus no relative rotation is possible.

Instability No. 2 (Heaving of the Chamber). The connection links between the vessel and chamber will allow for considerable variation of the relative elevations of the chamber and vessel. The relative displacement permitted must be consistent with the expected sea state environmental conditions. The chamber is essentially free to follow encountered wave profiles. To minimize the relative heave of the chamber with respect to the water surface a minimum weight or inertial mass and a maximum feasible buoyancy were desired. By the use of such a design, displacements from equilibrium by a wave will produce large restoring forces. The larger the restoring force, the quicker the response and the smaller the heave.

Instability No. 3 (Chamber Roll). Modeling studies produced a configuration which is much deeper than wide. This shape is sensitive to rolling because there are large areas to produce hydrodynamic side forces but a small distance between floatation cells (width of chamber) to counteract the moments produced. It therefore evolved that the chamber be connected to either the vessel or the first boom section in such a way that the chamber is constrained to roll with these more stable members. A linkage is feasible in producing this constraint while still allowing for correct positioning and debris removal requirements.

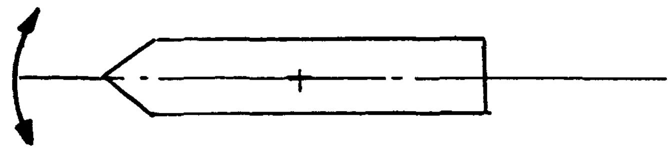
WAVE AND OIL COLLECTION RELATIONSHIPS

The effect of waves on the collection system has been considered and means of compliance to the wave environment have been described.



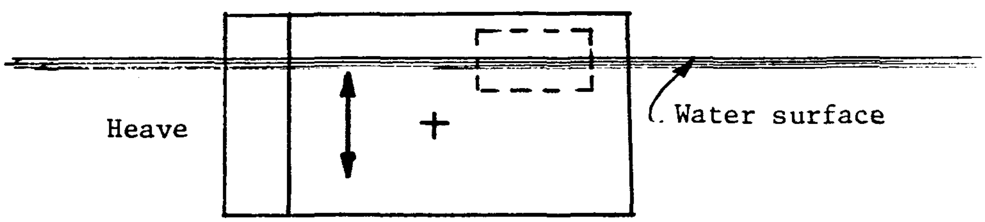
<u>Figure 18</u>

Collection Chamber Internal Circulation Pattern Illustration

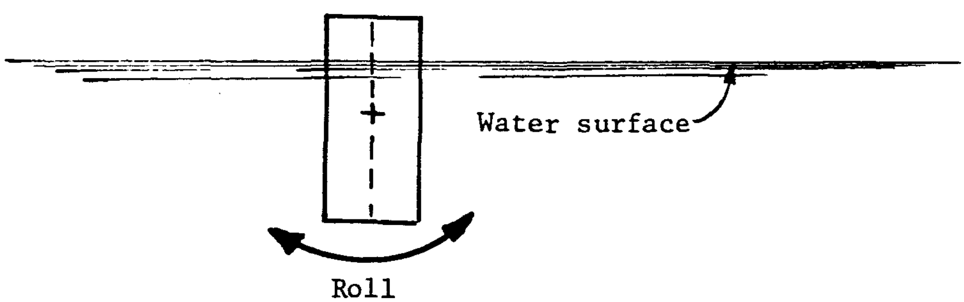


Rotation with respect to vessel axis

Plan View



Elevation View



End View

Figure 19

Collection Chamber Displacements Illustration

The effect of waves on the collection system is manifested both in the oil collection effectiveness and in the chamber motion (stability and integrity).

First, the potential effect of waves on collection effectiveness is due to the water level changes within the chamber. With the fast response of the concept chamber, this will be of little consequence except in waves containing a large, short period energy distribution. This will be the case only for locally active storms producing choppy wind wave conditions. If this situation is encountered, it will cause heaving of the chamber and distortion of the circulation patterns within the chamber. These short period waves are characteristic of smaller waves (on the order of 2 foot significant wave height) and will have little effect on a chamber of greater depth. Another effect of heaving on chamber effectiveness is the resulting flow in and out of the entry door with surge. If the chamber bottom were completely sealed, this effect would produce gross inefficiencies; with the present concept chamber (roughly 80% open bottom) no appreciable in and out flow with heaving is expected. A quick operating control mechanism for recovery of the floating oil in the chamber is suggested, whereby the suction pickup is automatically kept within a small deviation from the surface of the water at the front of the chamber.

Stability and integrity in the presence of waves requires a system which can withstand the expected forces. The present concept affords no major shortcoming or limitations in this respect.

COLLECTION CHAMBER SMALL MODEL EXPERIMENTS

Small model tests were made of the spray boom alone, the collection chamber alone and the boom and chamber together. Larger scale tests to determine full scale nozzle requirements for the spray boom were also made prior to concept model design as described in Section IV.

Scaled models of collection chamber geometries were evaluated in a 24-inch wide by 48-inch deep flow channel. The free stream flow velocity of the channel was regulated by a 20 hp outboard motor mounted on the periphery of a 15 foot diameter circular channel. Fresh water flows past two flow straighteners and through a straight section used for testing. The honey-comb flow straightener reduce turbulence and provide reasonably uniform flow for testing. Surface velocities were determined from pitot tube pressure readings taken 3 inches below the water surface at the center of the channel.

CHAMBER MODEL TESTS

Verification of the concept geometry was by a series of flow channel experiments in which small plexiglas scale models of collection chamber concepts were evaluated. Figure 20 is a photograph of the flow channel with an experimental chamber adjacent to the viewing window.

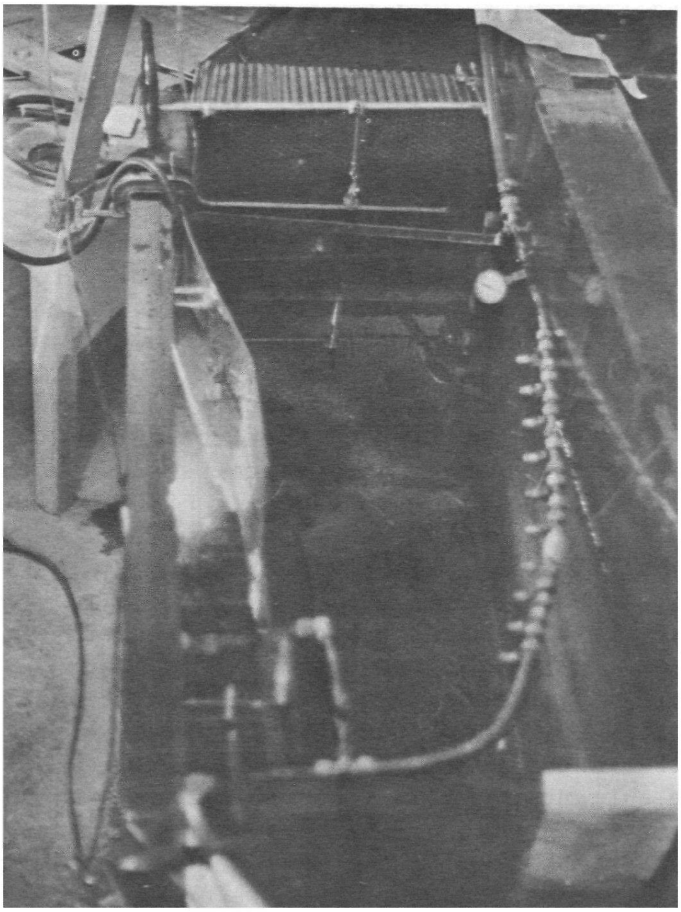


Figure 20

Flow Channel Test Section

Both open front and side entry chamber types were evaluated. It was soon evident that there would be major difficulties in isolating the oil slick from the large quantities of water entering the open front model. The side entry model was therefore chosen early in the development testing.

Testing of this chamber concept showed that oil losses occurred and were attributable to an unwanted circulation pattern within the chamber. This circulation was found to be produced by high stream velocities beneath the open bottom chamber. Incoming oil was entrained in a downward circulation and escaped. As was analytically predicted, the installation of vertical baffles at specific locations along the length and a bottom baffle at the front of the chamber significantly reduced the internal turbulence and provided an essentially calm region at the front for oil recovery. Figure 21 shows the final arrangement.

Effectiveness of the collection chamber was measured by flow channel experiments as the quantity of oil moved to the oil recovery zone divided by the quantity of oil entering the chamber. Experiments were performed with crude oil in which a known quantity of oil (500 ml) was administered at the opening and after equilibrium was reached, the quantity of oil remaining in the recovery zone was measured. Figure 22 shows the result as a function of the free stream velocity. The relatively high internal chamber effectiveness suggest that once oil enters the chamber it is not likely to escape.

COMBINED SPRAY AND CHAMBER SMALL MODEL EXPERIMENTS

The operation of the hydraulic oil recovery system, including the spray boom, collection chamber and oil pickup device, was simulated in small scale model tests. A manifold with 12 small spray nozzles approximated the spray boom for the purpose of visually observing the oil flow patterns and streamlines in the vicinity of the collection chamber side entrance. Oil slick simulation was accomplished by metering a quantity of oil through a linear manifold one inch above the water surface with outlet holes on one inch centers. This configuration allowed oil to spread to a uniform slick before entering the spray region.

Figure 23 shows the floating oil slick being moved into the small model collection chamber by the model spray boom. The view of the oil entrained as a result of turbulence caused by the spray and corresponding surface current impinging on the opposite side of the chamber is shown through the side window of the flow channel. This form of turbulence was prevalent during all of the experiments and was the primary reason for the observed loss of oil out the bottom of the chamber. Once oil droplets entered the chamber, they were moved forward by chamber spray nozzles to the stagnant region. Figure 23 also shows the calm region towards the front of the chamber. The maximum depth of oil contained within this region during experiments was 1 3/4 inches.

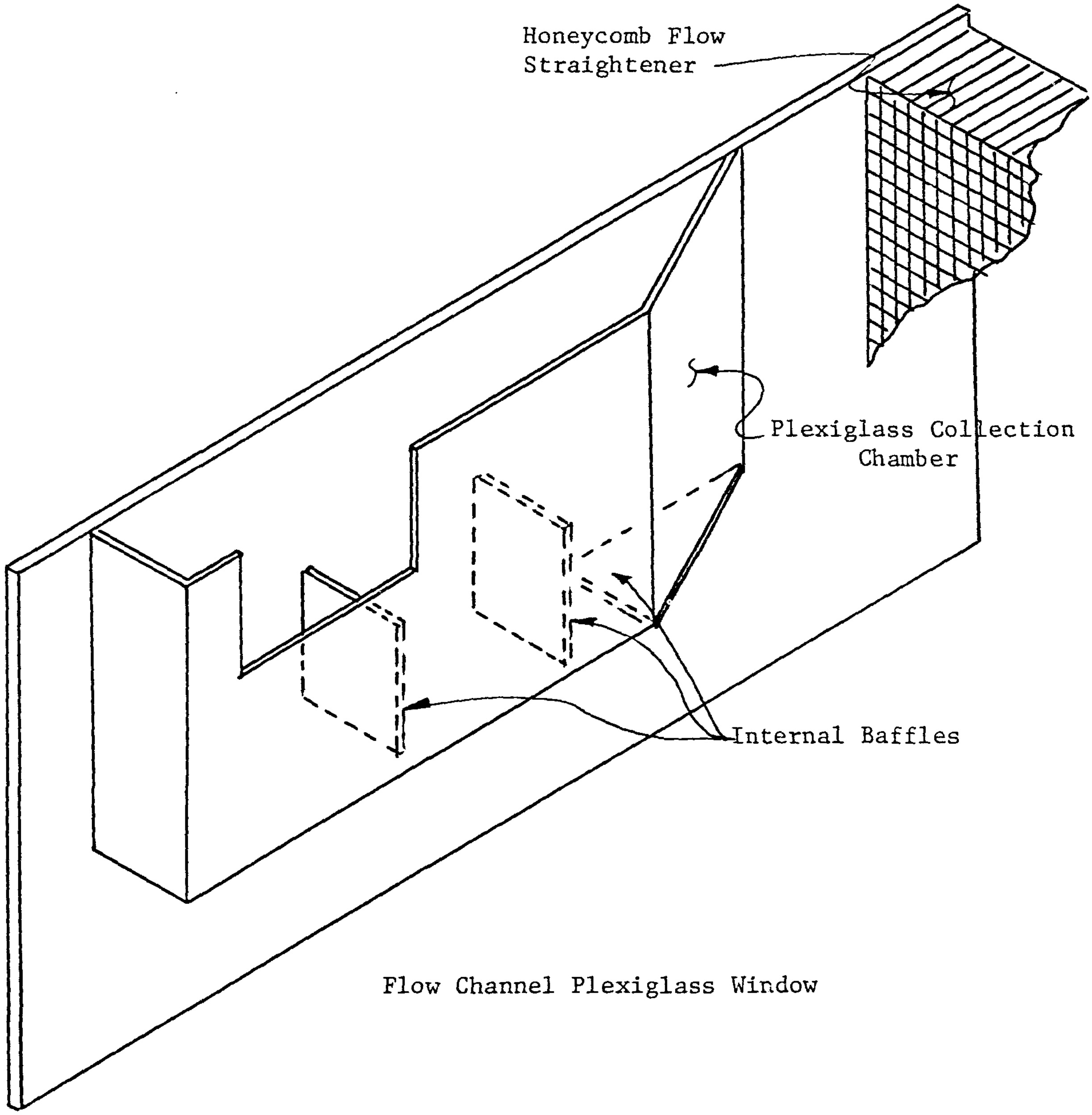


Figure 21

Final Collection Chamber Arrangement

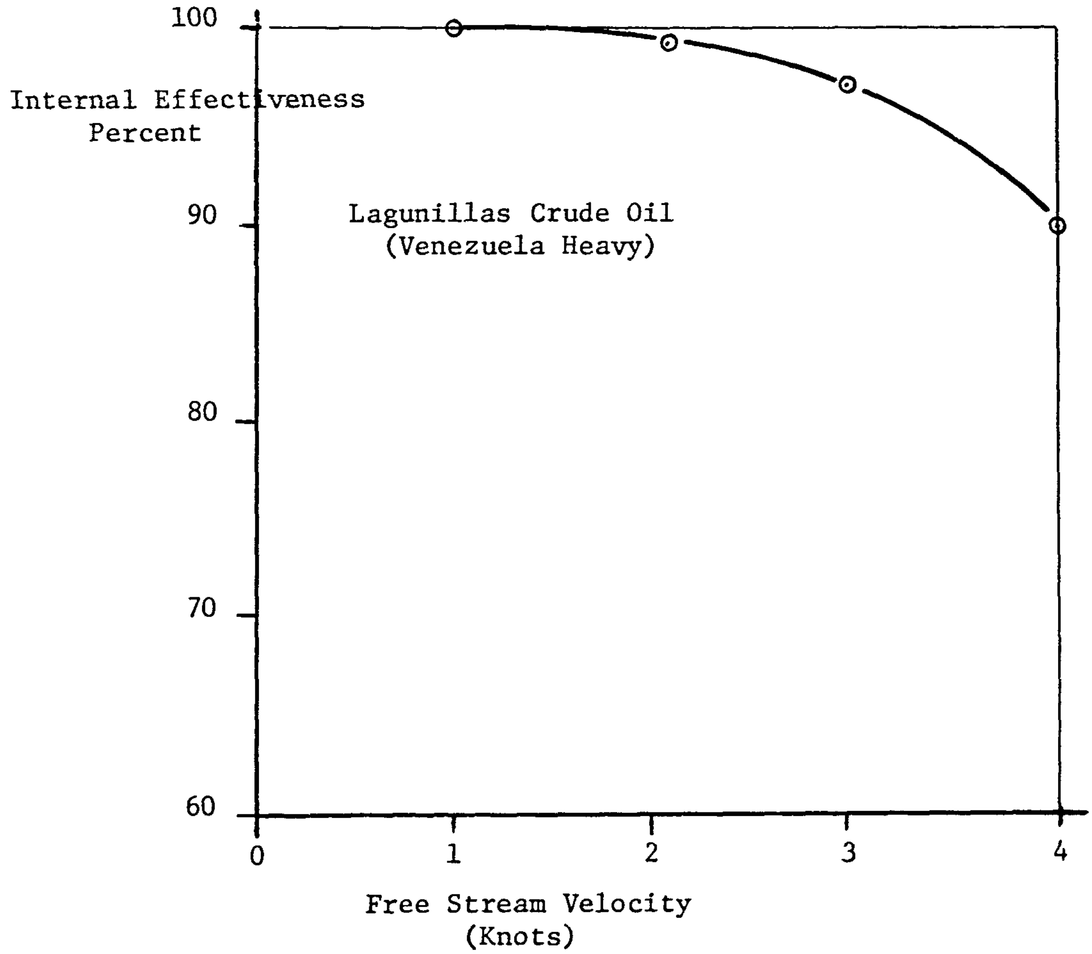
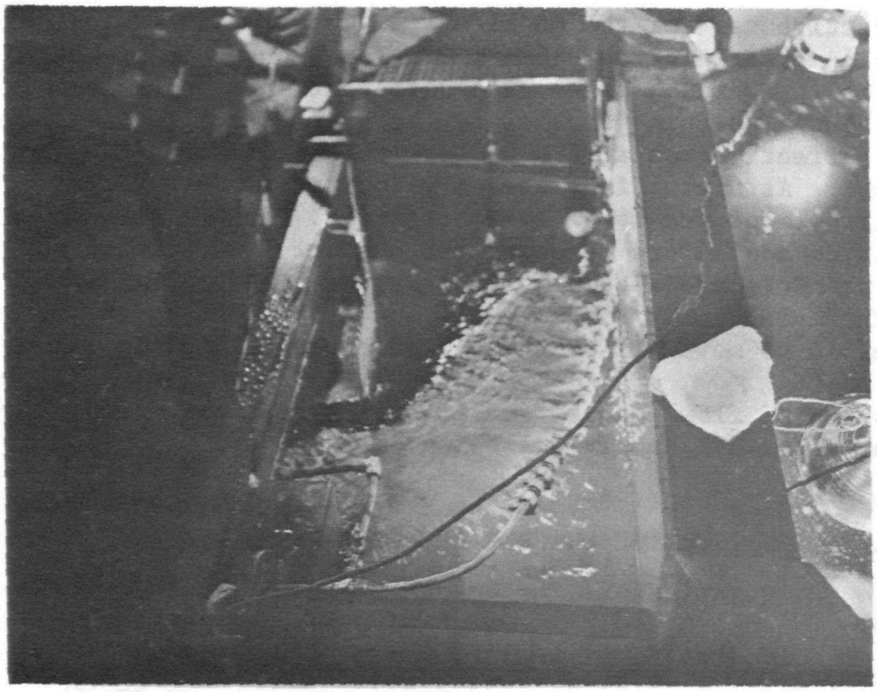
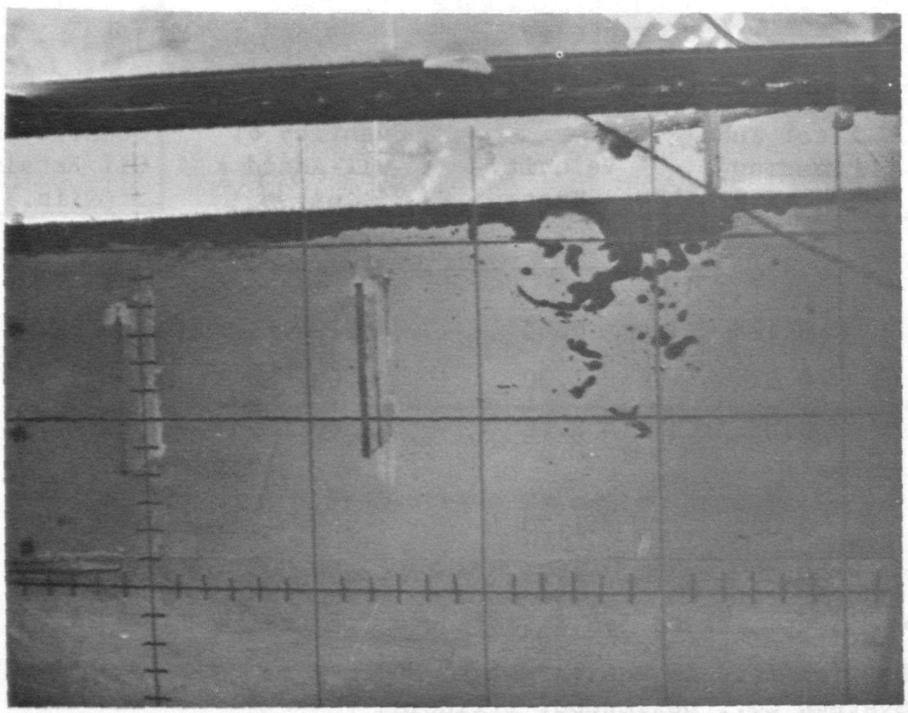


Figure 22

Internal Collection Chamber Effectiveness as a
Function of Free Stream Velocity



Top View of
Test Chamber
showing
Lagunillas
crude being
skimmed into
a simulated
collection
chamber.



Side View of
Test Chamber
showing
Lagunillas
crude oil
entrained at
the wall due
to spray sur-
face velocities

Figure 23

Spray and Chamber Effectiveness Tests

Effectiveness for the model system was defined as the percent of floating oil moved into the chamber and forward to the stagnant collection area. Several nozzles with different spray patterns were tried with a square pattern jet showing the greater utility. As shown on Figure 24, effectiveness at 1.2 knots with the square jet spray nozzles was 100 percent. At higher free stream velocities, the efficiency declined. Flatjets proved to be less effective. It was also noted that oil could escape before reaching the chamber if the model spray boom was not properly positioned. Also, at the higher free stream velocities, the model spray system could not attain the spray pressure and flow required to move all of the oil into the collection chamber.

Results of flow channel small model system experiments are summarized in Tables III and IV following:

TABLE III

SMALL MODEL INTERIOR CHAMBER EFFECTIVENESS DATA

Run No.	Quantity of Oil Added (mℓ)	Quantity of Oil Retained* (in.)	Velocity Knots
1	500	13/16	0.87
2	500	13/16	1.60
3	500	12/16	2.80
4	500	11/16	3.70

TABLE IV

SMALL MODEL SYSTEM EFFECTIVENESS DATA

Test No.	Pitot Tube Reading (in. of oil)	Velocity Knots	Quantity of Oil Added (mℓ)	Quantity of Oil Retained* (in.)	%Eff.
(Flatjet) #1/8P3504**					
5	0.12	0.85	500	12/16	92.5
6	0.31	1.30	500	9/16	69.0
7	0.85	2.16	500	8/16	61.5
(Square Jet) #1/8GG3004**					
8	0.30	1.30	500	13/16	100
9	0.50	1.75	500	12/16	92

Flow = 2.5 gpm, tests 5,6 & 7; flow = 3.5, tests 8 & 9

* 13/16 inches retained is equivalent to 500 mℓ

** Spraying Systems Co., Bellewood, Illinois

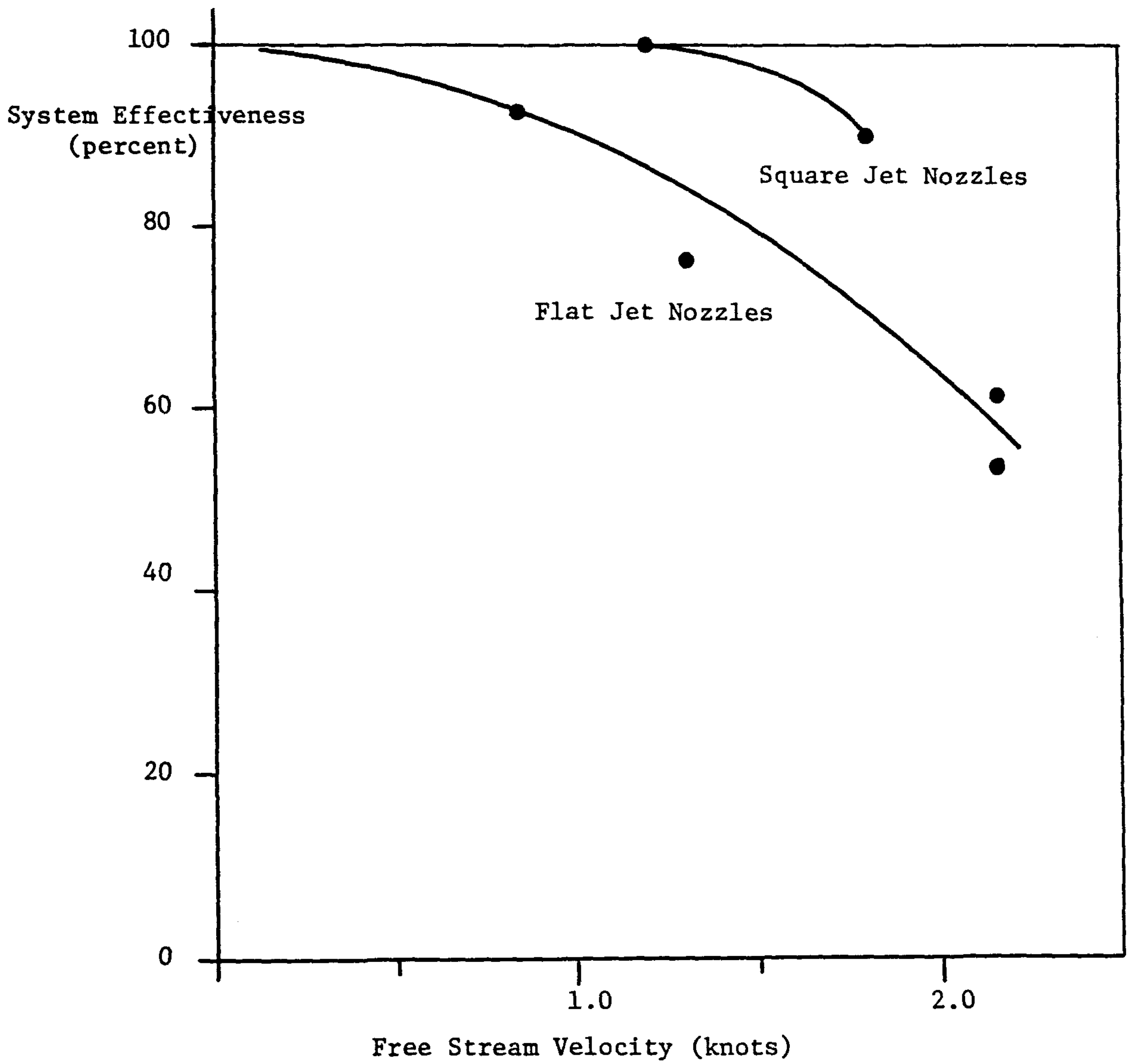


Figure 24

Spray and Chamber Effectiveness as a Function of
Free Stream Velocity
From Small Model Experiments

COLLECTION CHAMBER DESIGN

A large scale model collection chamber was designed and fabricated based on the preceding developmental work.

HYDRAULIC

Spray nozzles were used to induce surface flow toward the forward oil recovery zone of the chamber. Manifolds were designed for orientation, nozzle types, and spray impingement angles consistent with those of the small developmental model. Piping arrangements provided for pressure and flow measurement at the nozzles.

Oil suction piping and recovery pumps were sized for a recovery rate of 260 gpm. To achieve this pumping rate, 3 pumps (diaphram type) of 85 gpm each were employed. Diaphram pumps were used rather than centrifugal pumps to avoid excessive emulsification of oil-water mixtures.

Each pickup pump was provided with an individual suction line (two inch flexible neoprene-lined hose). Each was also attached to a counterweighted recovery device which pivoted at the chamber center and floated in the water in the oil recovery zone of the chamber. Oil could enter any one of the three floating suctions. An arrangement including flotation material and a horizontal baffle provided vertical position control. See Figure 25 for details.

HYDRODYNAMIC

The drag forces on a deep and narrow object, such as the collection chamber are from waves, currents, and the forward motion of the system. These forces were calculated as 765 pounds for a three foot wave (3.9 sec. period) and 285 pounds from a five knot (8.45 ft/sec.) relative velocity (speed of forward motion plus current). By superposition, the maximum frontal force would be 1050 pounds. Since large scale basin experiments were to involve only straight ahead travel, side forces were not determined.

STRUCTURAL

The model test chamber was constructed of plywood with angle iron reinforcement at all corner locations. Buoyancy was provided by closed cell styrofoam held in place by 1/4 inch bolts and large plywood washers. Buoyancy material was positioned in the front and rear for nearly the full depth of the chamber. Additional buoyant material was positioned at and just above the neutral water line to provide large restoring forces against perturbations (waves).

Ballast (220 pounds) in the form of lead bricks was attached to the bottom of the chamber. This reduced the center of mass significantly below the center of buoyancy, therefore enhancing roll stability. The total chamber weight (including ballast) was 440 pounds

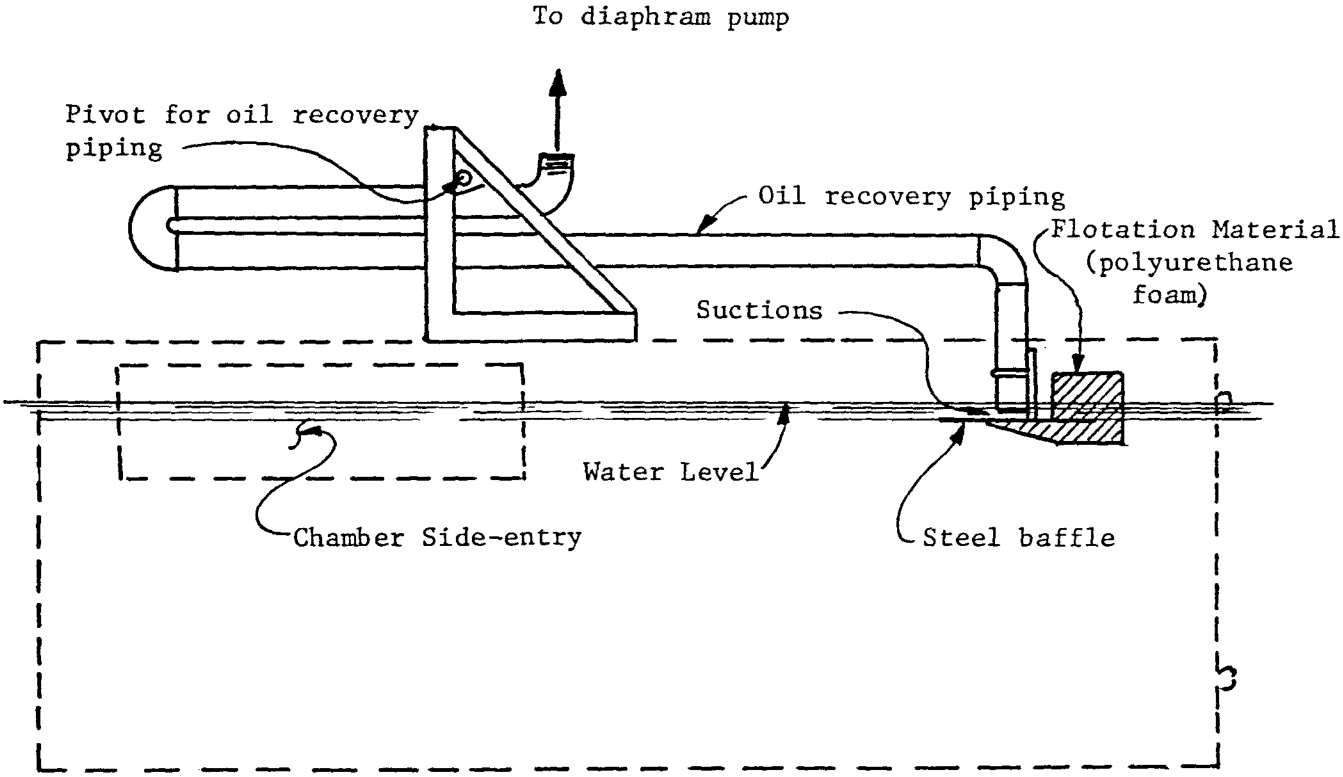


Figure 25

Schematic Showing One of the Three Duplicate Oil Pickup Arrangements and Its Relation to Other Parts of the Collection Chamber and the total buoyancy 880 pounds. Buoyancy was equally divided between material for restoring force and direct chamber weight compensation.

A photograph of the large scale model test chamber as designed and fabricated is shown on Figure 26.

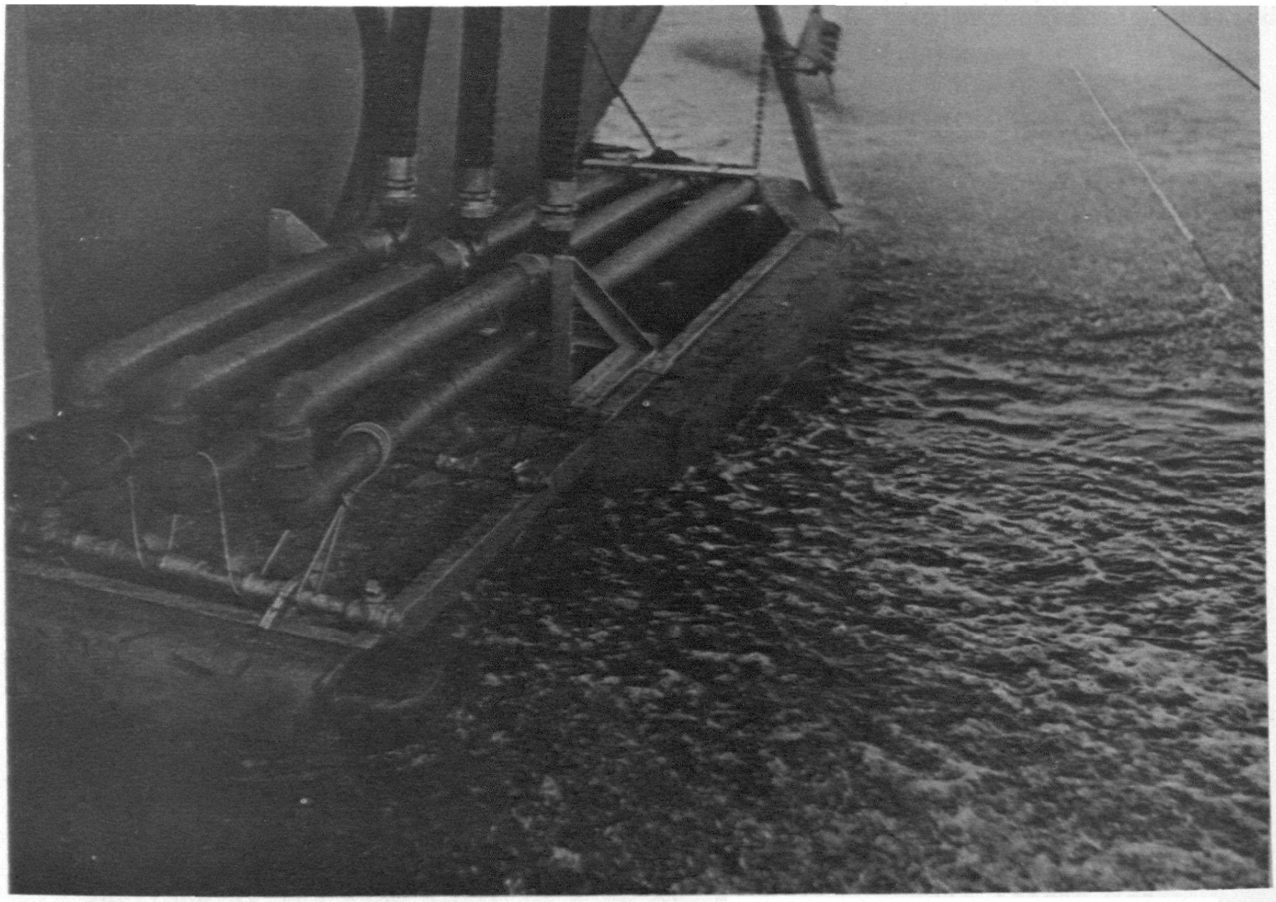


Figure 26

Large Scale of the Model Collection Chamber

SECTION VI

CONCEPT EVALUATION

The basic system components, previously described, were fabricated and combined for experimental evaluation. A thirty-five foot lifeboat was used as the support vessel. It was attached to a trolley that was supported by the test basin wall. A model spray boom, 40 feet long and a 9 foot long collection chamber were attached to the support vessel. The assembly was towed by a tractor driven parallel and external to the basin wall. The system model simulated one-half of a scaled (approximately 40 percent scale) model hydraulic oil skimmer. (See Figure 3 for system arrangement and construction details of the major components--spray boom and collection chamber.) Oil was purposefully spilled in a boomed off area to be swept by the system. During testing, the instantaneous oil thickness was monitored as the area was swept, thus enabling measurement of the amount of oil encountered. Spray flows and pressure and vessel speed were monitored. Recovered oil and water were evaluated for each test to determine system effectiveness and oil recovery rates. During all tests, system integrity and stability was noted.

The main considerations in evaluating concept performance were (a) structural integrity and stability and (b) oil recovery performance.

STRUCTURAL INTEGRITY AND STABILITY

Before oil recovery experiments were attempted, several test runs were made in order to identify any weak design characteristics or system instabilities in waves or under high speed conditions. Minor problems could then be solved before they could impede subsequent performance testing.

HIGH SPEED PERFORMANCE

Several tests were performed in which the support vessel, with the concept system attached, was towed (in the absence of waves) at progressively higher speeds. The collection chamber and boom were separately evaluated. It was initially found that at a speed of three to four knots and the boom angled at 45° to the vessel (no spray), sections of the boom began to dive or "porpoise". This affect was caused by the bow wave formed in front of the boom (estimated as six inches to one foot in height). When these experiments were repeated with the spray system in operation, this effect did not become apparent until speeds greater than five knots were reached. Additional boom-to-vessel cable connections and adjustment of tension in each partially corrected the problem. The roll stability floats for each boom section were adjusted to increase the lift with forward motion. Fifty pounds of additional ballast (per boom section) were also added to each roll stability float. Following these modifications, tests up to and including seven knots revealed no instability or undesired motions.

The speed mode of operation, which might be used for example in moving from one oil patch to another, was evaluated. The boom-to-vessel angle was set at 10° to the vessel centerline and a light spray action was applied to hold the boom in position. One test at a speed of advance of 3.75 knots was made without stability or other problems. A slight tendency toward buckling between boom sections was noted, although it was clearly safe and stable, showing only a few degrees of rotation from one boom section to the next.

No collection chamber instability was noted up to speeds of advance of seven knots. A bow wave occasionally overtopped the chamber front at higher speeds.

PERFORMANCE IN WAVES

Several structural tests were made with waves up to 36 inches (significant) wave height. Initial tests were statically performed. Several minor changes were required in the interfaces between the vessel and collection chamber and between the vessel and boom. See Figure 27 for photographic evaluation of the concept system performance in waves. Experiments were then performed with the system in motion at speeds up to five knots. With the modifications derived from earlier high speed runs, the presence of waves resulted in no inherent difficulties. The boom sections followed the waves quite well even at the higher speeds. The collection chamber also reacted well to waves. The stilling action of the collection chamber resulted in quite small surges in the chamber oil recovery zone (less than six inches). Some of the bow waves overtopped the front of the chamber just as in the earlier tests. No correction was made, although it was noted for change in the event another similar device is built.

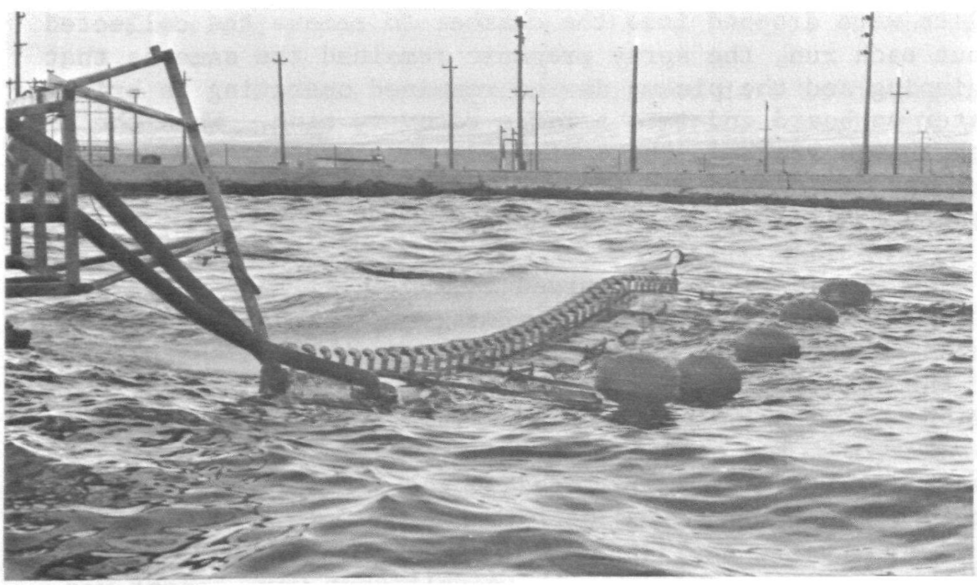
OIL RECOVERY PERFORMANCE

Once the system was found to be structurally sound and stable, oil recovery performance experiments were performed. The system performance was to be characterized with respect to the following criteria:

- oil recovery rate
- system effectiveness
- oil-to-water ratio
- recovered oil properties.

The important system variables were evaluated relative to these criteria in order to determine the system operating characteristics and

Spray Boom Collection Chamber and Support Vessel



Spray Boom and Boom to Vessel Connection

Figure 27

Concept Evaluation Model Operating in a 30" to 36" Wave Condition performance limitations. Three types of oil were used: diesel (No. 2 fuel), crude oil (Texaco, Anacortes - 40-42° API) and Bunker (No. 5 fuel). A considerable range in speeds and several tests with waves were made with each oil type.

As in the integrity and stability tests, the system was towed along the test basin wall by a wheel tractor. The average speed of advance of the model was obtained by timing the travel over the length of a test run. The test area was a rectangle, bounded by booms, approximately 60 feet by 360 feet in length. The performance test length was 203 feet, to accommodate acceleration and deceleration of the system. The effective skimming width was found to be 23 1/2 feet for the 40 foot boom angled at 45° to the vessel and correcting for end effects. The oil thickness was monitored along the test length using a pulse-echo ultrasonic transducer. Thickness was obtained by using an oscilloscope to monitor the time between sound echoes from the oil/air interface and the oil/water interface. The thickness readings were integrated to determine the average slick thickness encountered by the skimmer. A full description of the oil thickness system used in evaluating the oil skimmer concept is appended.

During acceleration (before the test length was entered), the boom spray pressure was adjusted to the value expected to be appropriate during early nozzle development tests. It was maintained at a value which was visually observed to move oil to the correct position adjacent to the collection chamber inlet. Also within this test length, oil suction pumps were started; the inlets at the pickup device in the collection chamber were held manually from contacting the oil and water in the chamber. Once the collection chamber entered the test length, the pickup inlets were dropped into the chamber to remove the collected oil. Throughout each run, the spray pressure remained the same as that set at the beginning and the pickup device remained operating in bringing the oil and water on board and into a large recovery tank. When the end of the test length was reached, the system was decelerated, the spray nozzle pressure was diminished and the suction pickup device allowed to pick up any residual oil left in the chamber.

After each run, data were recorded including all pertinent geometrical relationships as well as nozzle pressures, speeds of advance and oil thickness measurements. An oil sample was taken of the oil at the surface of the recovery tank. This sample was measured promptly for oil, emulsion and water volumes. Later evaluations of these samples indicated the water, oil and entrained air contents. The depth of water, emulsion and oil was also monitored in the large recovery tank and used later in determining system performance.

When tests were made in waves, the significant wave height was manually measured. The significant wave height was the measured peak to trough of the highest 1/3 waves of a random sea. This height was estimated by visual observation of the water height on a meter stick.

Definitions of performance measures and their determination were as follows:

Oil recovery rate is the volume of oil or emulsified oil recovered on board the support vessel (in the recovery tank) per unit time. This represents the rate of continuous oil recovery from the model system under the condition existing during the test.

System effectiveness relates the oil encountered within the skimming area (as implied by the pulse-echo ultrasonic oil thickness measurements) to the oil recovered on board the support vessel (in the recovery tank). A 100 percent effective system would be able to recover 100 percent of the oil encountered under conditions prevailing during a test. Fifty percent effectiveness would imply that fifty percent of the oil encountered is recovered.

Oil-to-water ratio is the amount of oil (and emulsified oil) recovered divided by the amount of free water recovered on board.

Recovered oil properties were from samples taken directly after each test run. After a static holding period for coalescence, the oil, emulsion and water volumes were measured for each sample. Oil concentration in emulsions and entrained air volume were also measured.

Test results are included in Table V following. This Table includes all data relating to oil recovery rates and system effectiveness, i.e., the practical system operating characteristics. Data which relate oil-to-water ratios recovered and recovered oil properties to system variables are also included. Such information is required to delineate the fluid processes necessary for effective stream quality program goals.

Explanation of the tabulated data is necessary for complete understanding of these results. First, experiments were performed at an outdoor facility during the late fall and early winter. In addition to the discomfort to operating personnel, the low ambient temperature of test basin water (32 to 50°F) prevented oil spreading at rates typical of more moderate conditions and considerably influenced other oil properties such as oil viscosity and pour points of Bunker fuel. In addition, equipment freeze-up periodically prevented prompt initiation of experiment runs. Also, when winds occurred, the slick was frequently swept out of the path of the test apparatus against the basin wall. Work was periodically delayed for up to five days. The net result of these environmental difficulties was to slow the rate of experimental evaluation, although such difficulties may be quite likely in actual use of the system. It is believed that considerable knowledge of the possible effects of adverse conditions was gained during this work.

The first twelve test runs were performed with No. 2 fuel oil. During these test runs, data acquisition techniques were developed, operational sequences devised, equipment was run-in, and numerous empirical adjustments were made. The latter entailed relocating the collection chamber position, enlarging its oil entrance aperture, and "tuning" the spray pressure and flow to best correspond to the speed of advance. This tuning was not possible during the performance of a test run(which lasted for only one to two minutes) and had to be done from run to run. This break-in period was much longer than had been anticipated and performance results from the first 12 runs were poor. Effectiveness ranged from 1.5 to 12.8 percent and recovery rate from 60 to 1920 gph. Because of the aforementioned reasons and because of later highly promising test results, the first twelve runs are not considered to be representative of concept system capabilities. Data from the subsequent experiments (13 through 29), are analyzed in the following discussion.

OIL RECOVERY RATE

The effect of changes in slick thickness for the three oil types is shown on Figure 28. Bunker and diesel fuels are little effected, however crude oil tests show a marked increase in recovery rate with increased oil thickness. Figure 29 relates speed of advance with oil recovery rates. Up to 1870 gph was achieved for the speed of advance range of 1.2 to 4.5 knots for Bunker fuel. Crude oil recovery rates as great as 8700 gph were achieved between 1.0 and 4.2 knots and for diesel fuel, 7500 gph up to 3.0 knots. System limitations became apparent especially for the crude oil above 3.0 to 3.5 knots. Oil recovery rates are limited at low speeds by the amount of oil available for recovery, rather than system deficiencies.

A semi-empirical factor which combines vessel speed, oil thickness and spray flow pressure characteristics is used to evaluate this system. This performance parameter (spray flow times square root of spray pressure divided by the product of oil thickness and vessel speed squared, or $Q_w H_w^{0.5}/(T V^2)$ is of similar form to equation (4) or equation (8) in the spray boom performance analysis. The analysis provided the basis for selection of this combination of variables. Data obtained from concept evaluation tests shows a correlation with this empirical factor for the range in variables tested.

Oil recovery rates for Bunker and diesel fuels, are rather insensitive to variation of this factor as shown on Figure 30. Recovery rates of crude oil increased from 3000 to 8000 gph as the empirical factor increased from approximately 15 to 25. A value of 25 would produce 1500, 7000 and 8000 gph oil recovery rates for Bunker, diesel and crude oils, respectively.

SYSTEM EFFECTIVENESS

Effectiveness is defined as the percentage of oil encountered which is collected by the system and brought onboard for processing.

Average slick thickness is plotted against effectiveness in Figure 31. Singular relationships, if they exist, are obscured by

TABLE V

CONCEPT SKIMMING PERFORMANCE TEST RESULTS

Test Run*	Time/Date	Spill Material	Slick Thickness (mm)	Wave Condition (height/period)	Speed of Advance (knots)	System Effectiveness (%)	Oil Recovery Rate (gph)	Oil/Water Ratio	% Water (air) in Recovered Oil	Empirical Factor $Q_w H_w^{0.5}/(T V^2)$ gph/ft psi$^{0.5}$/(mm kts^2)
1	11:30/12/3	Diesel Fuel(#2)	.8	calm	.5	7.2	140	.05	--	488
2	12:10/12/3	"	3.8	"	.9	12.5	1920	.52	--	36.3
3	10:30/12/4	"	.8	"	1.3	7.4	520	.12	8	72.2
4	12:00/12/4	"	1.3	"	2.0	9.8	910	.40	22	25.4
5	1:30/12/4	"	.6	"	2.9	9.4	590	.05	56	34.8
6	2:30/12/4	"	.9	"	0.8	2.5	60	.03	60	67.7
7	11:15/12/5	"	2.3	"	3.3	1.5	430	.03	77	7.9
8	12:00/12/5	"	1.4	"	3.6	2.1	360	.03	38	11.6
9	1:00/12/5	"	.8	18"/2.5 Sec.	1.4	12.8	530	.10	30	51.9
10	2:30/12/5	"	.8	24"/3.0 Sec.	2.6	5.3	390	.03	50	32.4
11	9:30/12/8	Bunker Fuel(#5)	1.5	calm	0.8	3.0	130	.03	(25), 7	61.3
12	10:30/12/8	"	1.9	"	1.4	4.2	480	.05	(17), 7	20.1
13	2:00/12/8	"	1.1	"	2.1	10.4	1870	.12	(36)	27.3
14	9:00/12/9	"	1.3	"	2.7	6	1170	.34	(25)	17.3
15	10:00/12/9	"	2.4	"	3.0	12	1420	.16	(4)	9.2
16	10:00/12/10	"	2.1	"	1.4	13	820	.07	(27)	25.9
17	11:00/12/10	"	0.5	"	4.5	6.5	1500	.20	(12)	27
18	10:00/12/11	"	1.1	28"/3.0 Sec.	1.2	8.7	420	.06	(12)	47.2
19	11:30/12/11	"	1.4	28"/3.0 Sec.	2.8	30	1380	.08	(13)	14.0
20	11:30/12/12	Crude Oil (40-42° API)	1.2	calm	1.6	84	7700	7.7	70	34.8
21	1:00/12/12	"	1.7	"	3.0	55	8700	2.4	67	11.1
22	2:30/12/12	"	1.7	"	4.2	24	3000	.6	64	9.2
23	11:00/12/13	"	1.0	"	2.0	40	4670	6.8	13	20.3
24	12:00/12/13	"	1.6	14"/3.5 Sec.	2.0	97	6800	7.5	3	15.0
25	1:00/12/13	"	1.0	14"/2.5 Sec.	1.0	100	4900	2.3	3	69.8
26	11:30/12/14	Diesel Fuel(#2)	3.0	calm	1.5	56	7500	1.5	1.5	19.6
27	12:00/12/14	"	2.5	30"/3.5 Sec.	2.0	39	6700	1.2	3.1	14.3
28	1:00/12/14	"	2.5	calm	3.0	41	6640	1.2	6.9	7.3
29	2:00/12/14	"	1.5	30"/3.5 Sec.	0.9	81	6810	4.9	3.2	53.4

* Test runs 1 through 12 are not considered to indicate system performance; but were made to determine necessary modifications.

Test runs 13 through 29 will be considered to indicate system performance for the particular arrangement tested. It does not indicate optimum performance of basic concept.

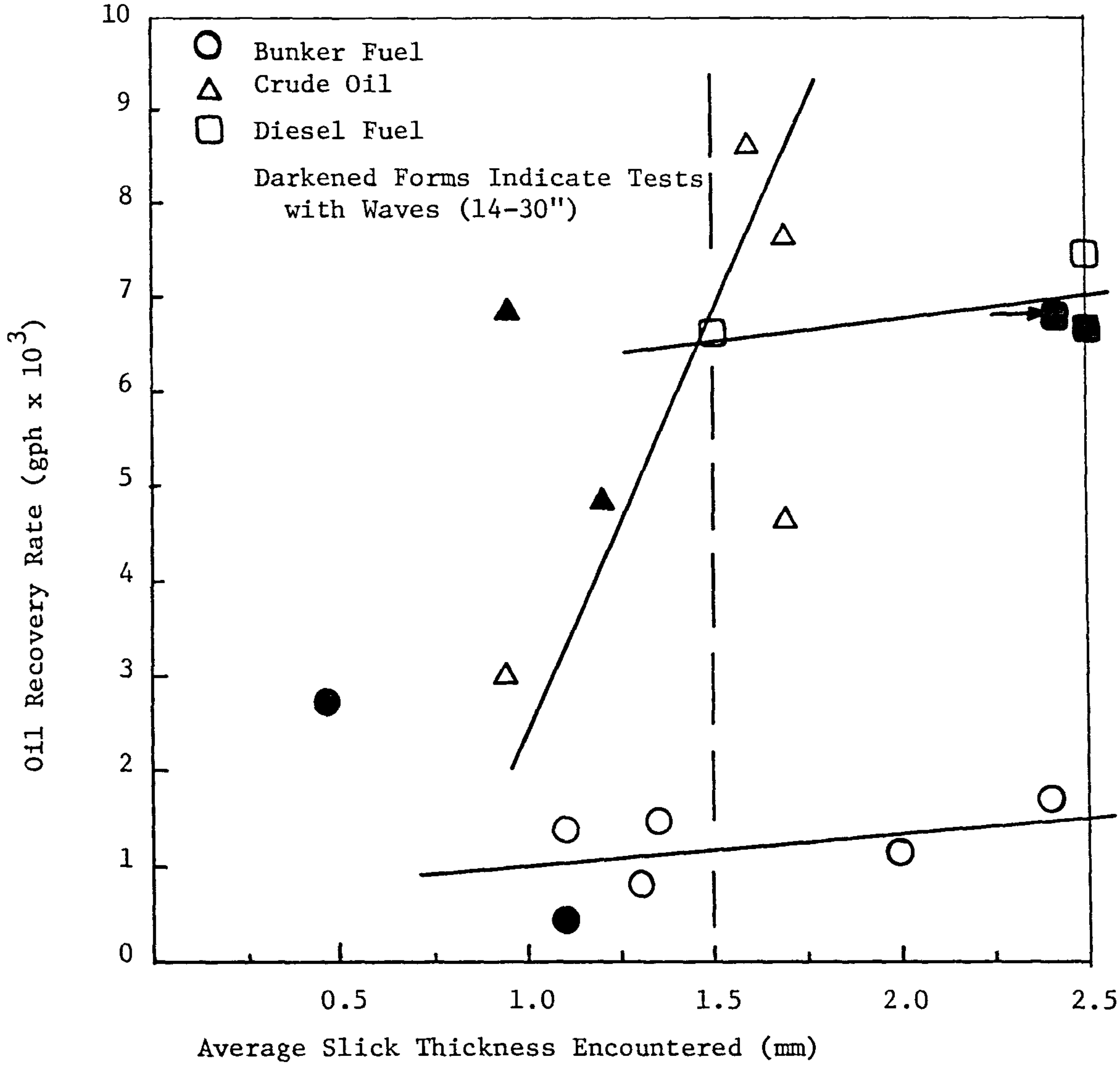


Figure 28

Oil Recovery Rate as a Function of Slick Thickness

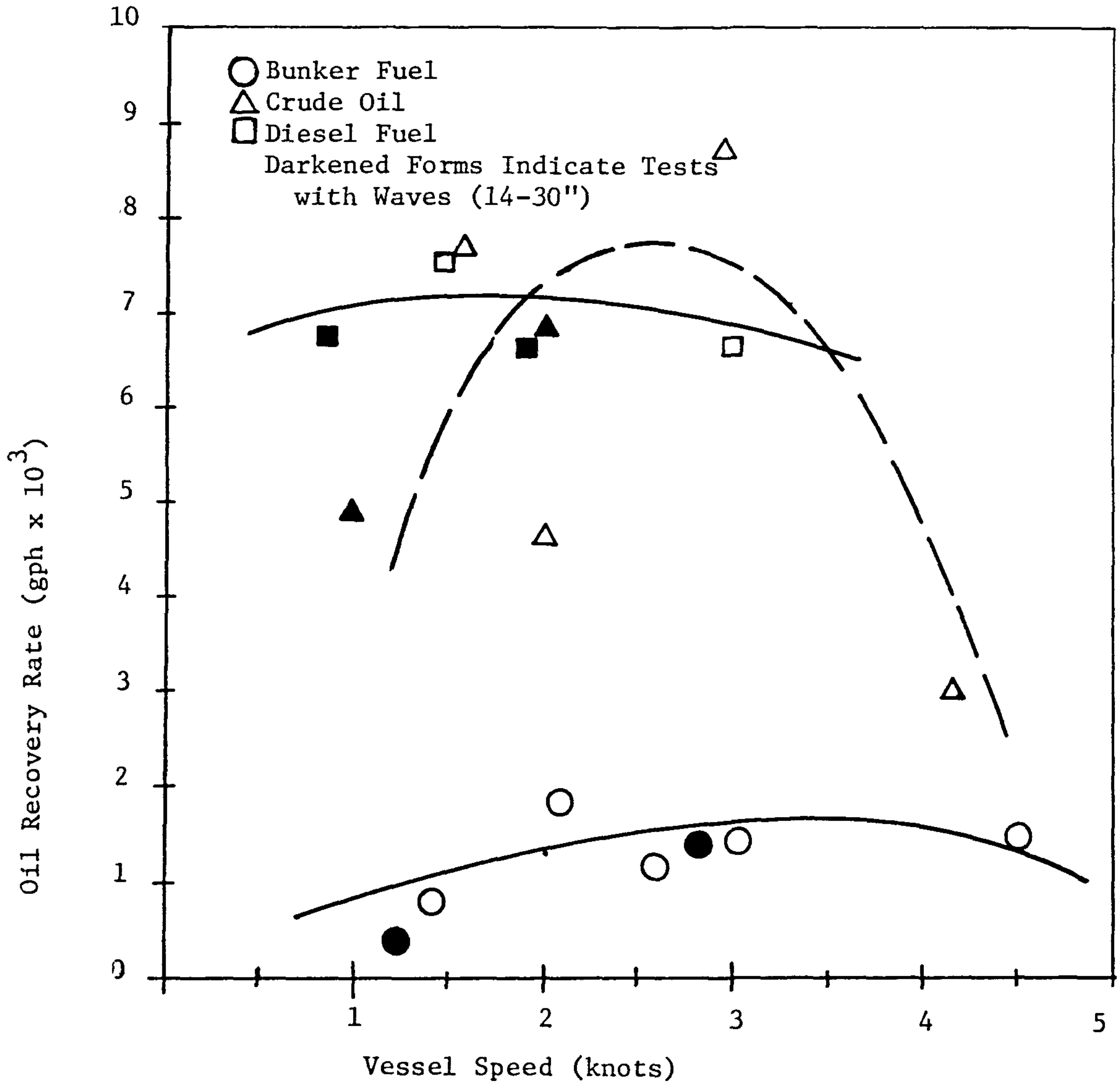


Figure 29

Oil Recovery Rate as a Function of Speed of Advance

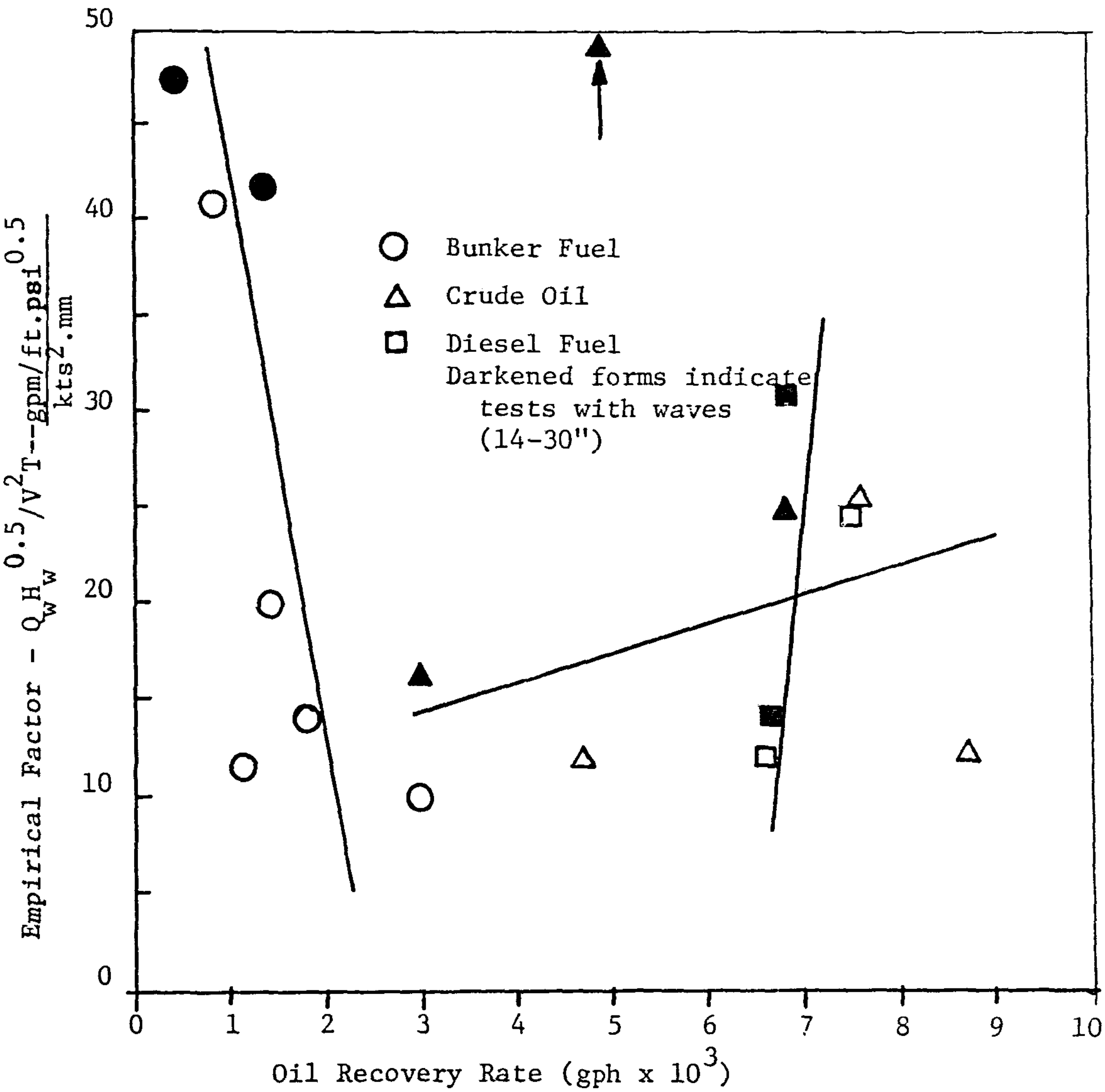


Figure 30

Empirical Factor as a Function of Oil Recovery Rate

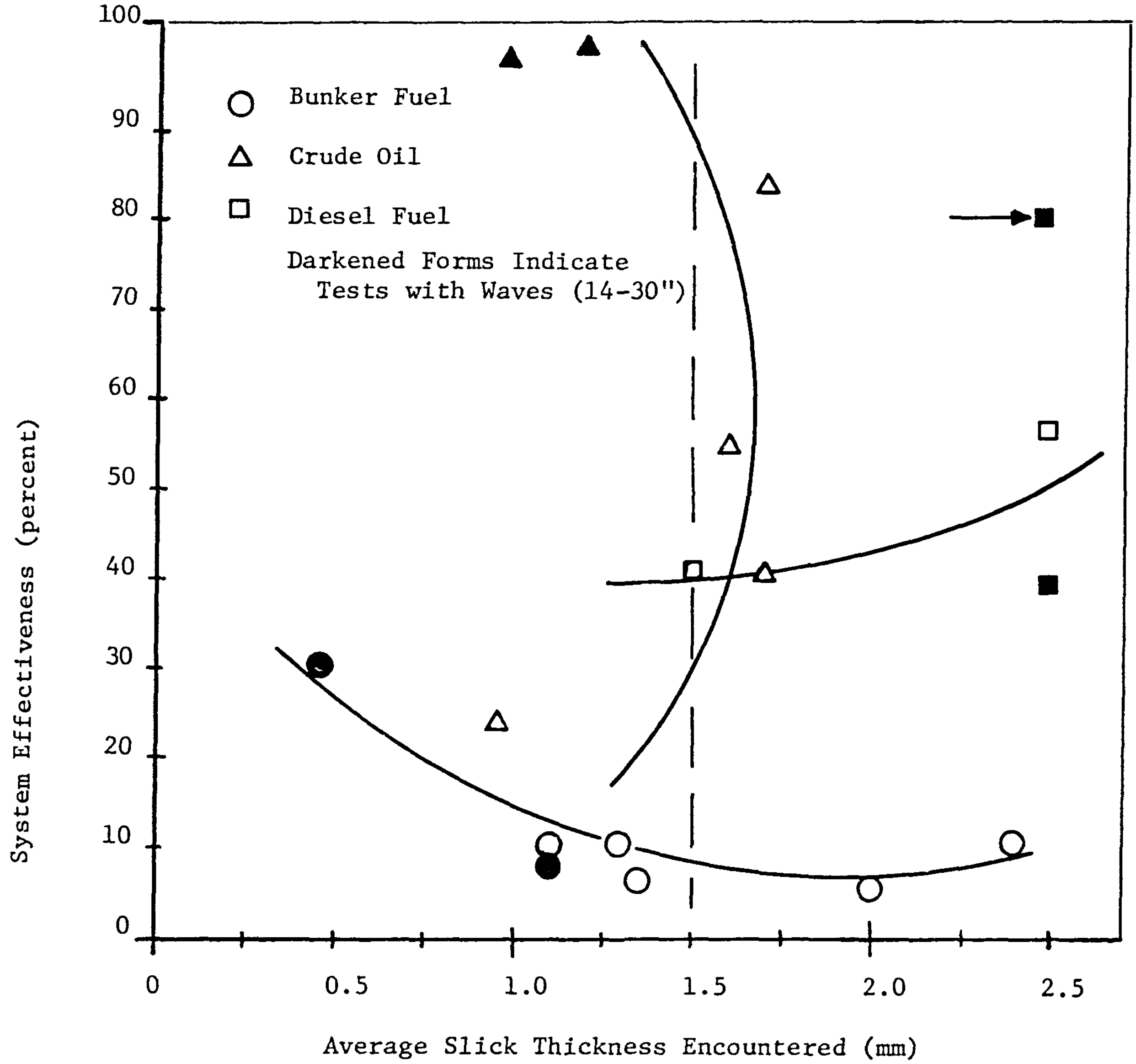


Figure 31

Model System Effectiveness as a Function of Average Oil Slick Thickness such variations as the emulsification of the oil by recycling from run to run and nonuniformities in slick thickness. As is expected, system effectiveness decreases with increases in speed of advance (see Figure 32). This is a result of both inefficiencies in skimming at higher speeds and limits in system variables such as spray flow and pressure at increasing speed. Bunker fuel showed relatively poor system effectiveness. During evaluation tests, low temperatures caused this material to congeal so that it did not physically resemble the slicks of the other materials. It appeared very sluggish and tended to roll along near the surface rather than flowing on the surface as did the other material. Several possibilities exist for improving performance on Bunker fuels. The most attractive is to provide the capability for adjusting the height of the spray nozzles so that spray water exits just at the water surface. Such a reduced spray impingement angle would be expected to substantially improve effectiveness on heavy oils. This conclusion is supported by the spray boom performance analysis in consideration of the submergence phenomenon caused by spray impingement on heavy oils.

Figure 33 shows system effectiveness as a function of the previously defined empirical factor. The correlation defined in Figure 33 is consistent for the three oil types. An empirical factor of approximately 25 is required for recovering 100 percent of crude oil encountered. Extrapolation of the diesel test data shows a value of 40 for 100 percent recovery.

Bunker fuel tests also show a correlation, but at a lower range of effectiveness. Extrapolation far beyond the experimental parameter range should be done with caution. Considerable increase in the empirical factor is necessary in order to increase system effectiveness for Bunker fuel to the levels observed for the lighter materials. Approximately 20 percent system effectiveness was obtained at an empirical factor value of 40. Changes in the system would be expected to change the performance correlation.

OIL-TO-WATER RATIO

The relative quantities of oil, emulsified oil and water recovered on board the model test support vessel varied considerably. Since the oil recovery pumps (3) were all operated continuously for each full test run at their maximum pumping rate (no attempt was made to optimize the oil to water relative pickup rates), variations in the quantities of oil, emulsion and water recovered occurred. Experiments were performed over a broad range of speeds of advance, over varying slick thicknesses, with different oils (pumping Bunker fuel would be slower due to viscosity effects). With waves, some pumping of air occurred (the suction device would frequently raise above the surface and momentarily pull in air). All of these would affect the relative quantities of oil (and emulsion) and water being recovered by the pumping system.

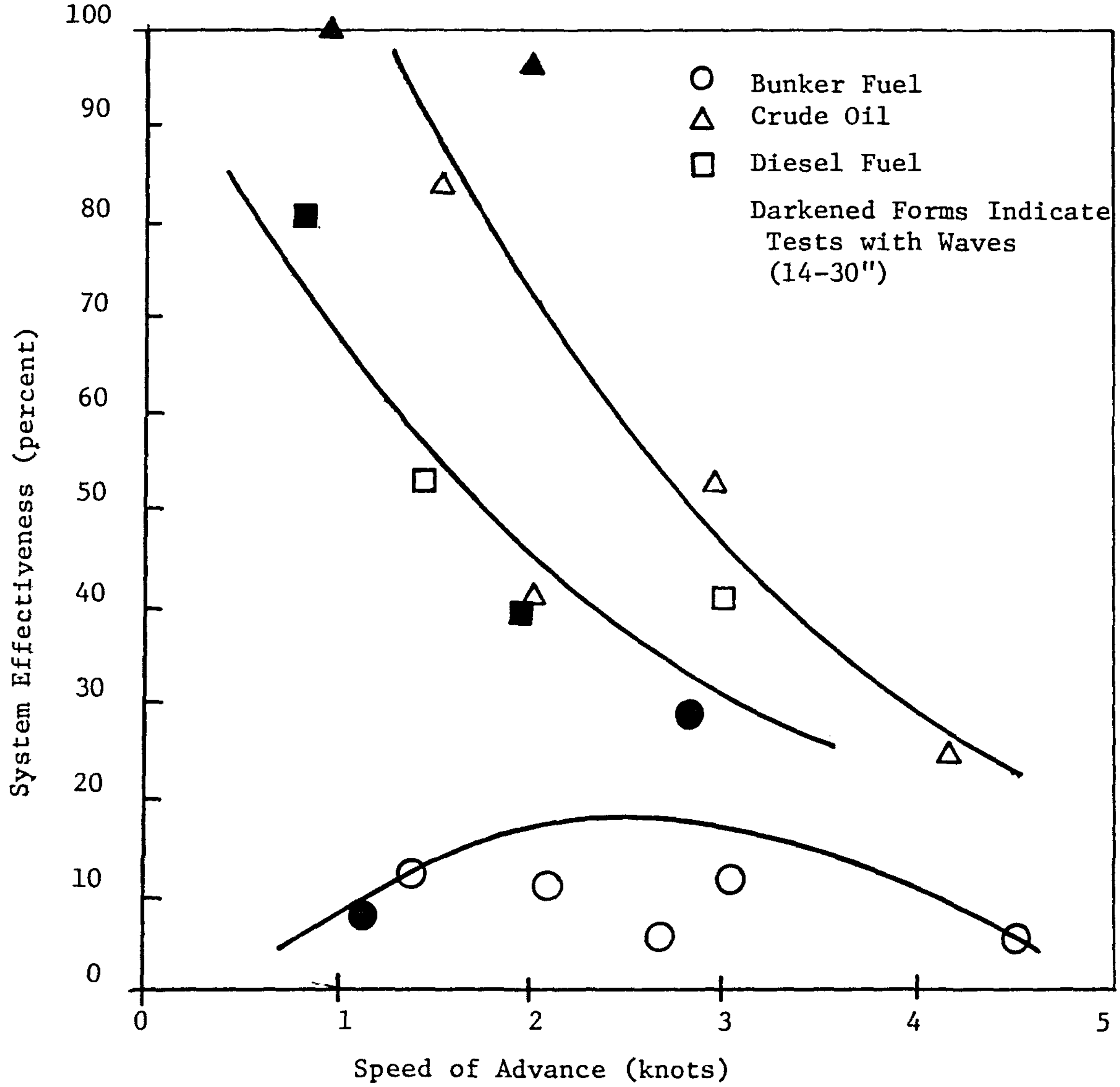


Figure 32

Model System Effectiveness as a Function of Speed of Advance

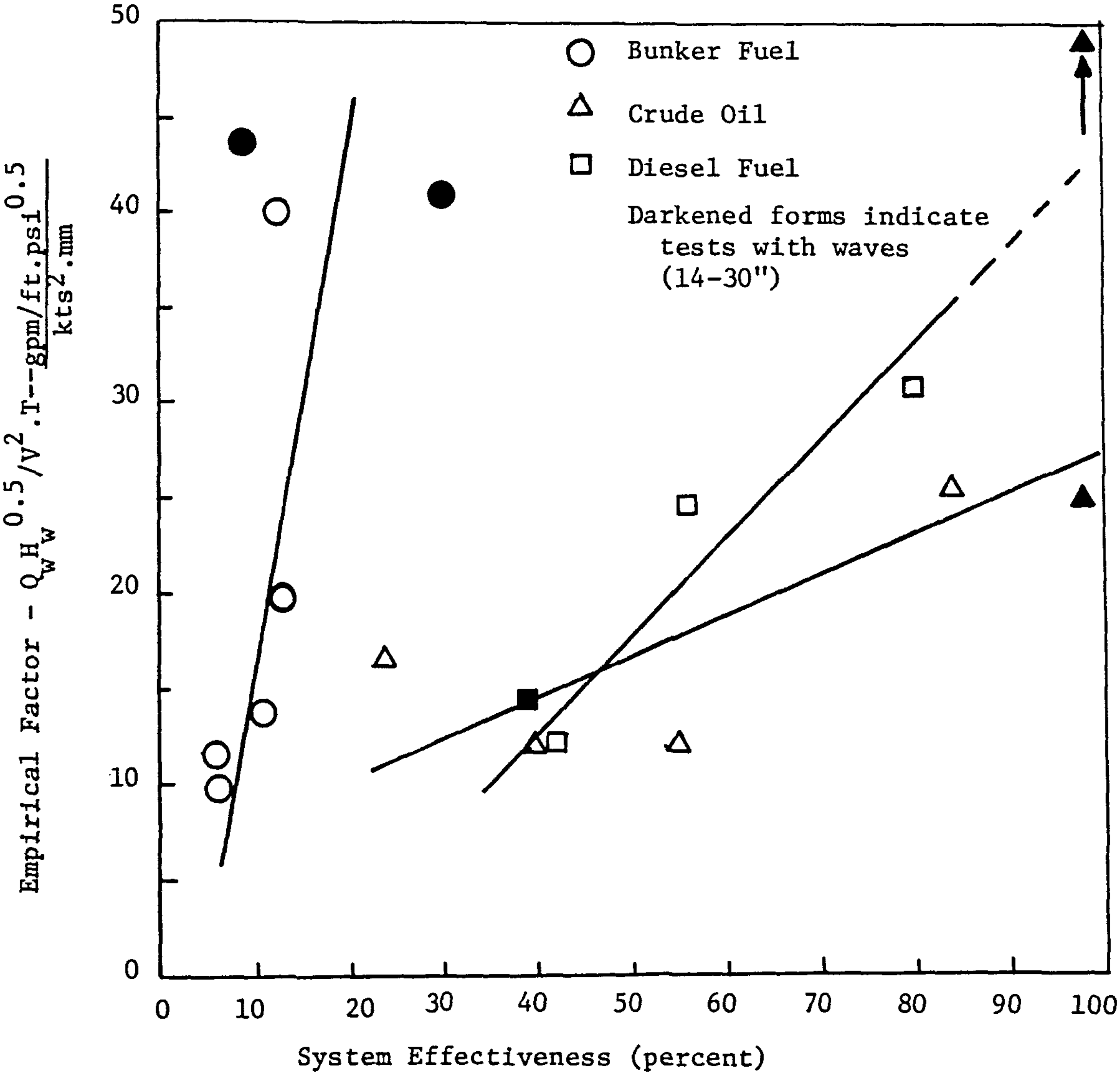


Figure 33

Empirical Factor as a Function of Model System Effectiveness

With continuous operation of a large prototype system, the rate of pumping of the oil recovery pump system could be readily controlled. Approximate maximum oil-to-water ratios for Bunker fuel, crude oil and diesel fuel were found to be 1/3, 20/1 and 4/1, respectively. It is also probable that frequent and appropriate "tuning" of the system would achieve oil-to-water ratios on a continuous basis as were obtained during the best test runs. Bunker fuel oil-to-water ratios would possibly be increased from the 1/3 value for continuous operation. Greater ratios would be possible if recovery rates were increased or pumping rates reduced. Here, continuous operation implies oil recovery over a time period on the order of an hour rather than the short duration test runs of one to two minutes.

RECOVERED OIL PROPERTIES

Characteristics of recovered oil were implied by sampling recovered oil and allowing the constituents to coalesce. Thus, a determination of the extent of emulsification and air entrainment was possible.

Bunker fuel (No. 5, P.S. 300 grade) showed no tendency to emulsify. Volume was found to decrease with time, however. This decrease was observed to be caused by air entrainment in the spraying and pumping operations. Air entrainment varied from 4 to 36 percent in the recovered oil product for the test runs evaluated, averaging 19 percent over the seven tests. This represents a decrease in effective density of on the order of 19 percent, i.e.,Bunker of density 1.0 would have an effective density of 0.81.

Both diesel fuel (No. 2) and the crude oil (40-42° API) samples showed varying degrees of emulsification, primarily water-in-oil type. Water concentrations ranged from three to 70 percent and 1.5 to 9.6 percent for crude and diesel fuel, respectively. Crude oil samples averaged 37 percent water, while diesel oil samples averaged only 3.7 percent. For both fuels, it was impossible to distinguish free oil from emulsified material in the samples when initially examined.

Crude and diesel oils showed no tendency to capture entrained air, probably due to their relatively low viscosities. Bunker fuel, on the other hand, was quite viscous, almost to the pour point of the material, and showed no emulsion with water.

Continued cycling of the oils resulted in added emulsification from one test to the next, as was noted in the initial 12 test runs with diesel fuel.

SYSTEM PERFORMANCE ASSESSMENT

The following paragraphs compare the measured or extrapolated concept system evaluation test with design goals as specified in the request for proposal.

(1) <u>Skim in 5 foot waves with 20 mph winds and 2 knot currents superimposed</u>

Skimming with the complete system at approximately 40 percent of full prototype dimensions was performed in random waves of three feet height with little or no degradation in system performance. Waves in the area covered by surface oil slicks were suppressed to about 30 inches in height. It is believed that the short chop waves encountered by the concept system during testing are probably more detrimental to performance than longer waves of the 5 foot size. This is because of the ability of the floating components to follow the longer wave profiles. Component interfaces will be designed to be compatible in displacement and strength to the expected environmental effects of a five foot sea.

The effect of wind on performance (structural and stability) was not determinable during the high wind conditions periodically experienced during model testing. These winds did, however, force the oil slick against the test boundaries and out of the skimmer path, thus making it impossible to test for skimming performance during such periods. All exposed components are of a low profile to the wind and the sea. It is therefore believed that winds of 20 mph will have little effect other than to cause a surface oil movement with respect to the water column.

Currents of 2 knots are assumed to be relative velocity values between the system components and the water column. Since skimming was quite successful at greater values than 2 knots, this was met.

(2) <u>Capable of 8 knot speeds in 10 foot waves and 38 mph winds and capable of 12 knot speeds under the condition of (1) (not while skimming)</u>

The configuration of the system in this mode of travel would be such that the booms would be towed in a trailing position. The low profile of the booms and their ability to follow the sea surface are expected to make them quite suited to towing. The outrigger floats are expected to present some resistance to such speeds. However, with adequate design of the connection to the booms, these floats will handle 8 or 12 knot travel. Problems may arise at the joints between boom sections and between the boom sections and the support vessel. Design of these interfaces must make provision for expected environmentally induced forces. Total travel for the vessel boom interface must be suited to the wave heights encountered. Quick breakaways or other similar devices might be necessary for protection of the vessel and personnel under severe storm conditions.

(3) <u>Storage of 1,000,000 gallons of oil</u>

Storage requirements were beyond the experimental phase of this concept development program although pillow tanks are presently available and capable of filling this demand.

(4) Able to recover oils ranging from light diesel to Bunker C

Test runs with diesel fuel (No. 2), Bunker fuel (No. 5) and with a crude oil (40-42° API) showed capability for handling each type. The recovery rate for Bunker fuel was at about one sixth the rate for crude oil and diesel fuel recovery. Test runs involving Bunker fuel showed that the spray jet tended to aerate this material so that it exhibited a lower density than it would have otherwise. This enhances the ability of the system to recover heavy fuels as compared to concepts involving only gravity.

(5) Capable of recovery 50,000 gallons per hour under design environmental conditions as stated in (1)

Recovery rates of 50,000 gph can be accomplished by a prototype recovery system based on the concept developed in this program. Test data show that 1500 gph of heavy oil or 7000 to 8000 gph of light oil (crude oil or diesel fuel) can be recovered by the concept model which covered a 23.5 foot sweep width. Simple scale-up shows that 50,000 gph can be recovered using a skimmer boom combination which has a 140 foot sweep width for light oils and 780 foot for heavy oils. As previously mentioned, flexibility for optimal placement of nozzles closer to the water surface, should enhance performance for heavy oils. Further tuning of the spray pressure and boom-to-vessel angles may also improve on these scale-up predictions. Concept evaluation tests were performed on contained slicks. Linear extrapolation to the prototype system would be expected to be conservatively in error because of the boundary effects associated with boomed areas as contrasted to large unrestricted slicks.

(6) Operate on slicks of 1.5 mm in thickness or less

The concept system recovered oil throughout the range of oil slicks employed in evaluation tests (0.465 to 3.75 mm).

(7) The recovered oil shall not contain more than 10 percent sea water and the effluent water shall not contain more than 10 mg/liter of oil

Additional equipment, such as centrifugal separators, coalescers, or settling tanks, will be required to meet these goals. The development of these was beyond the scope of the present program. Features of the proposed concept which tend to enhance the oil-water separation process are: (1) the entrainment of air in the heavier oils makes them more buoyant (air floatation may be a natural process in the system); (2) water effluents from separation processes may be recycled through the pressure spray system and; (3) recovery pumping rates can be "tuned" to produce a consistently high proportion of oil in the recovery product pumped from the collection chamber.

SECTION VII

ACKNOWLEDGMENTS

Experimental analysis and design phases of the study were performed by a team from Battelle Memorial Institute's Pacific Northwest Laboratories at their hydrodynamic testing facility in Richland, Washington. Acknowledgment must be given to those organizations which assisted in this effort. The assistance of the Texaco and Shell Oil Companies in providing test oils is greatly appreciated. Local material fabrication contractors and equipment purveyors also must be given credit: Keltch Construction Company, Metalfab Company, R and N Inc., W I and M Fuel Company and Felton Oil Company are but a few who made contributions.

The authors gratefully acknowledge the support and guidance given by personnel from the Water Quality Office of the Environmental Protection Agency, specifically, Mr. John J. Barich, III, who served as project officer and Mr. Harold Bernard and Mr. Kurt Jakobson of the Agriculture and Marine Pollution Control Branch.

Mr. John R. Blacklaw
Mr. Blaine A. Crea
Mr. Roy C. Kelley
Dr. E. Roger Simonson
Mr. P. C. Walkup
Battelle Northwest

SECTION VIII

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SECTION IX

APPENDIX

Ultrasonic Oil Thickness Measurement Device

An ultrasonic system was assembled and used during concept evaluation tests of the floating oil recovery system employing a spray boom and side-entry collection chamber. It was operated in waves varying from essentially calm conditions to 3.0 foot short chop waves and in currents up to 4.5 knots. Considerable difficulty was experienced with the system as assembled at the maximum environmental conditions experienced.

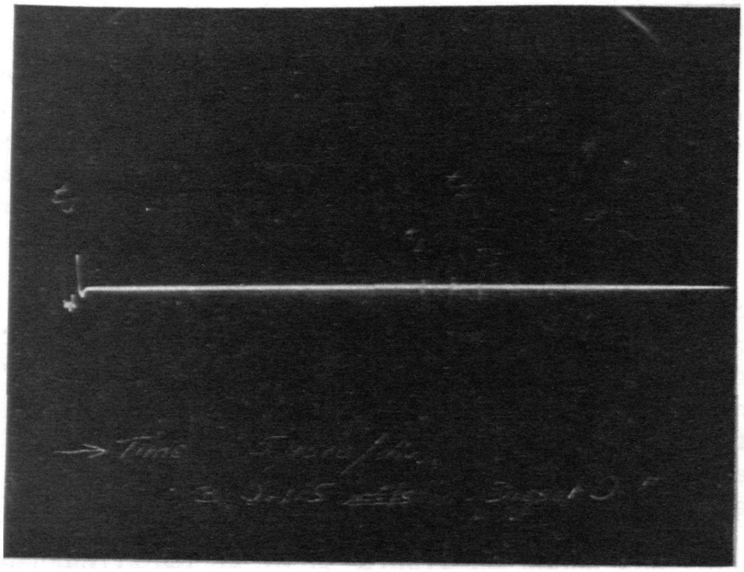
The concept involves a specially designed ultrasonic transducer which obtains oil/water and oil/air interface signals for further processing. Detection of the two interfaces is accomplished by using a pulsed ultrasound signal and monitoring the return reflected pulse. The time delay between return pulses is an indication of the presence and thickness of an oil slick. All that is necessary to cause a reflected pulse is to have a significant abrupt density change at an interface.

The photographs shown on Figure 34 of an oscilloscope trace of the pulse-echo signal train for diesel fuel on tap water illustrates the ultrasonic technique. In the first photograph, t_0 denotes the transmitter pulse or time '0', t_1 represents the reflected sound energy from the water-oil interface, t_2 represents the oil-air interface, and t_3, t_4, ... represents the reflected trapped sound in the oil layer. The time between t_1 and t_2 and t_3, etc. is directly proportional to the oil thickness. Calibration of the instrument would involve determination of the velocity of sound in oil, thus, the time measurement may be converted directly to oil thickness. The second photograph represents near the minimum thickness (near 10 mils) which can be measured with commercially available ultrasonic instrumentation.

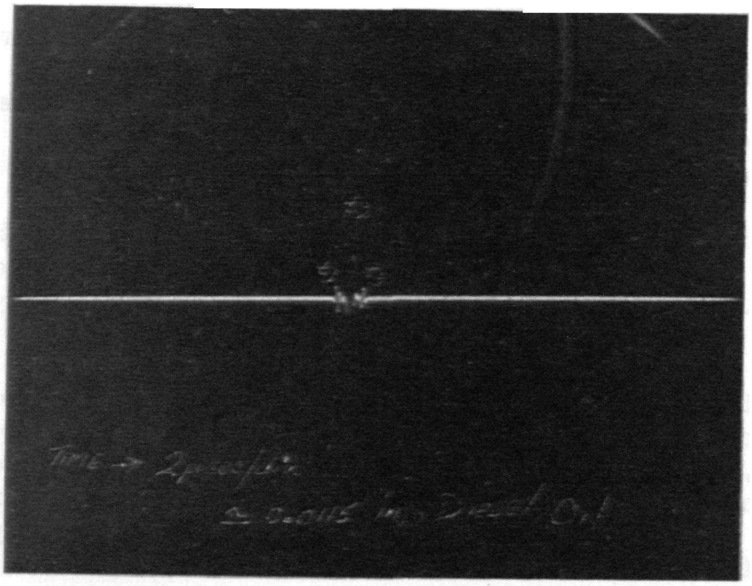
A support must be provided to hold the transducer within a given distance of the surface. A floating catamaran pontoon was used as the support principally because of the wave following capability of such structures.

Processing of signals can be by many approaches depending upon the required accuracy and the wave conditions present. With any appreciable waves, a time delay, a pulsing system and electronic gates are employed so that only the time difference between signals from the two interfaces is monitored. This method and monitoring of compressed signals was used in the work described herein.

High accuracy measurements or measurements of very thin slicks require high quality signal processing equipment and appropriate transducers. Testing was accomplished with a thickness accuracy of approximately 1/16 inches. Equipment presently available may be assembled to measure down to 1/100 inches and further refinements may make a resolution of 1/1000 inches possible.



Diesel Fuel (No. 2) 3.0 mm thick, on tap water



Diesel Fuel (No. 2) 0.3 mm thick, on tap water

Figure 34

Oscilloscope Trace from Slick Thickness Measuring Device

BIBLIOGRAPHIC:

Pacific Northwest Laboratories, Battelle Memorial Institute, Concept Development of a Hydraulic Skimmer System for Recovery of Floating Oil, performed for the Environmental Protection Agency, Water Quality Office, Program Number 15080 FLT 4/71, April 1971.

ABSTRACT

Efforts are being directed to develop effective countermeasures against floating oil slicks. Mechanical recovery methods, which do not cause additional environmental insult, are most attractive. Such a concept, a hydraulic skimmer, was investigated.

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Experimental work was directed toward component development and evaluation of a large system model in a simulated environment. A 35 foot support vessel, a 40 foot spray header, and a 9 foot collection chamber provided the 23 1/2 foot model sweep width. Speeds of advance to five knots, random waves to 30 inches significant height and three oil types were used in evaluating this system. Other equipment such as an ultrasonic oil thickness gauge, process pumps and tankage were also used.

Model experiment results showed, for light oils, 80 to 100 percent effectiveness and oil recovery rates of 6600 to 8700 gph. Results with Bunker fuel were not as great, being on the order of 1300 to 1800 gph and 12 to 30 percent effective in recovering oil from the water surface. However, program time constraints did not permit experimental verification of modifications expected to increase performance on heavy oils.

Further development of the concept, including additional model testing with heavy oils plus open sea evaluation of a prototype system was recommended.

ACCESSION NO.

KEY WORDS:

Concept
Equipment Development
Oil Skimmer
Open Sea
Evaluation
Oily Water
Separation Techniques
Technical Feasibility

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1 Accession Number	2 Subject Field & Group	
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5 *Organization*

Pacific Northwest Laboratories of Battelle Memorial Institute

6 *Title*

Concept Development of a Hydraulic Skimmer System for Recovery of Floating Oil

10 *Author(s)*

Blacklaw, John R.
Crea, Blaine A.
Simonson, E. Roger
Walkup, Paul C.

16 *Project Designation*

21 *Note*

22 *Citation*

Environmental Protection Agency, Water Quality Office, Program Number 15080 FWP 4/71, April 1, 1971, 88 pp.

23 *Descriptors (Starred First)*

Evaluation*, Oily Water*, Separation Techniques*, Technical Feasibility*, Efficiencies, Hydraulic Systems, Hydrodynamics, Jets, Mathematical Studies, Testing, Water Pollution Treatment

25 *Identifiers (Starred First)*

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