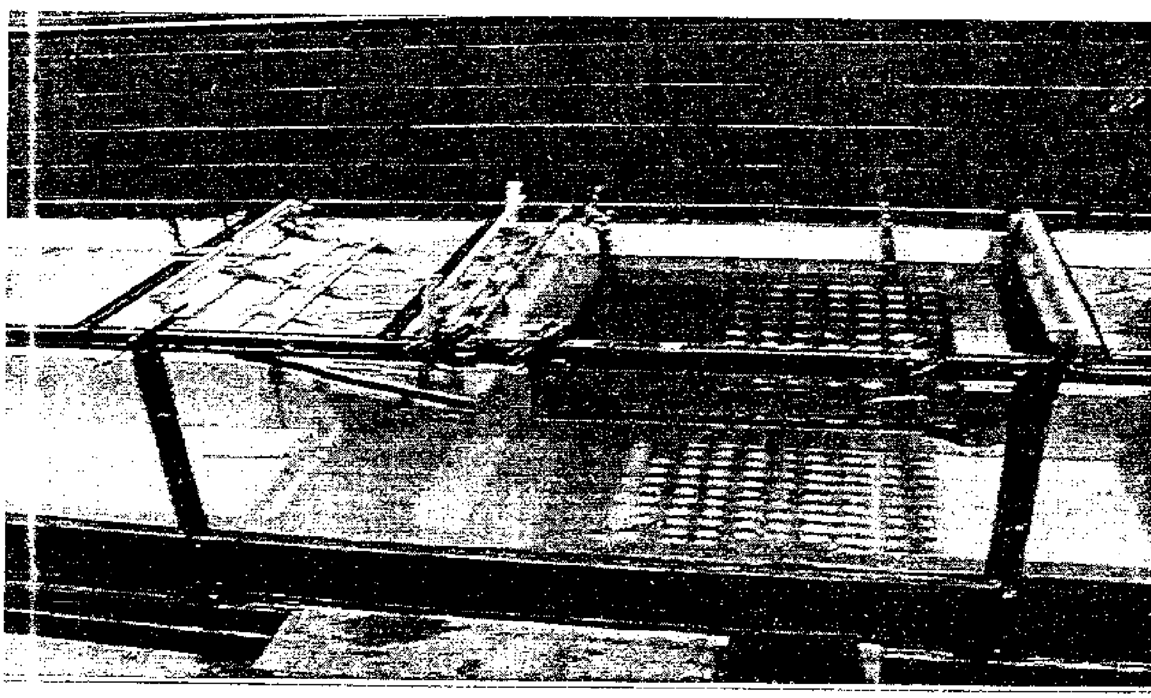
B.I.O.C.

Bow for Improved Oil Collection



Tech 797: Ocean Projects
Senior Design Project
2000 - 2001

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Date Submitted:
April 20, 2001

Sea Grant
New Hampshire/Maine

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Bow for Improved Oil Collection
on the Hydrofoil/Fast-Sweep

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Acknowledgements:

"This work is the result of research sponsored in part, by the National Sea Grant College Program, NOAA, Department of Commerce, under grant #NA16RG1035 through the University of New Hampshire / University of Maine Sea Grant College Program."

We would like to thank the following people, for supporting us and answering our questions throughout the past year:

Dr. M. Robinson Swift, for assisting us with every aspect of this project from start to finish. Sharing your knowledge of the topic helped make this project successful, and is greatly appreciated.

Robert Steen, for helping us conduct flume tests for every single model, for answering any questions we had, for loaning us tools and equipment, and for providing valuable advice.

Brett Fullerton, for helping us run flume tests, for shutting of the tank when we couldn't get there in time, and for your general tips.

Donald MacPherson and Barbaros Celikkol, for spending parts of several of your afternoons helping us come up with possible bow alternatives.

John Scott, for helping us manage our finances.

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Abstract

Oil collection capabilities of Hydrofoil/Fast-Sweep, an oil skimmer designed for towing alongside a buoy tender, gradually decline at speeds above 2 knots due to the turbulence created at the bow of the design. The straight, cylindrical bow of this design induces turbulent flow on the water as it passes by, thus mixing up the oil slick at the water's surface. Once mixed, the oil is less likely to travel down the submergence plane and into the containment region.

The purpose of this project was to develop a new bow for Hydrofoil/Fast-Sweep that is able to reduce the bow turbulence and improve oil collection at speeds higher that 2 knots. Considerations made while developing new bow designs included reducing the bow turbulence prevalent in the original design, and containing the oil that had been exposed to that turbulence. Bows were designed to satisfy these criteria, with 1/5-scale models of the most promising bow designs being constructed.

The UNH flume tank provided testing grounds for the 1/5-scale bow models. Oil skimming conditions were simulated in the flume tank, and the performance of each model was evaluated. The water speed used for each test was around 2.2 ft/sec, which is equivalent to a full-scale model speed of about 3 knots. For comparative purposes, a 1/5-scale model of the original Hydrofoil/Fast-Sweep bow design was tested and evaluated. Several of the new models were seen to outperform the original model. Results showed the benefits of both reducing the bow turbulence by bringing the bluff front float above the waterline, and containing the mixed oil by adding a shroud underneath the submergence plane. The most successful bow alternative tested in this project, the

extended plane decreased exit shroud model, incorporated both of these criteria. The extended plane model with no shroud showed a substantial improvement in performance over the original model, yet would still be easy to fabricate and implement.

I. Introduction

Purpose:

Oil is a very slick, hazardous, and crude substance, and yet it is this world's most popular source of energy. Millions of gallons are pumped from the oil wells in the Middle East and other parts of the world. Massive oil tankers are used to transport thousands of gallons of oil across the ocean and waterways. If, for some unseen reason, one of these tankers has an accident and the hull is punctured, thousands of gallons of crude oil could be spilled out onto the open ocean or coastal waters consequentially, polluting the natural habitats for many living creatures.

Oil spills must be cleaned up quickly and thoroughly. Oil may spread out and encompass a large area and endanger any wildlife in the location of the spill. It may take decades to recover from the impact of oil spills. Conventional oil booms deployed by the U.S. Coast Guard alongside buoy tenders during oil spill sweeping operations are very limited by the speed at which they may operate. Depending upon the type of oil, it has been documented that these booms are rendered ineffective at speeds faster than 0.6 to 1 knot (Delvigne 1989). Therefore, an increase in the speed at which these devices effectively operate would allow faster clean up of the spill as well as easier maneuverability of the ship towing the device.

With the above limitations of the standard oil boom being taken into account, new devices are being designed to replace the standard oil boom and improve oil collection. Devices, such as the "Hydrofoil/Fast Sweep" and the "Bay Defender," employ the submergence plane concept to collect the oil. "Hydrofoil/Fast Sweep is a device that rides alongside a ship and mechanically sweeps up the oil. "Bay Defender" is a stationary flexible oil barrier that collects the oil in a containment area as it travels downstream with the current. These devices greatly increase the percentage of oil captured at higher speeds compared to conventional booms. There are some limitations to the speeds reached with these devices. One limitation is the formation of bow turbulence caused by the submergence plane. This turbulence breaks up the oil slick, which in turn will limit the amount of oil collected. If this limitation could be lessened, these devices could operate at much faster speeds and therefore reduce the cleanup time and increase the volume of oil captured.

The goal of this project is to design, develop, and analyze several scale model submergence planes in order to reduce the amount of bow turbulence generated. Each model is subjected to a qualitative dye test and a quantitative bead test for the purpose of comparison. This data set is then interpreted to identify the best bow configuration.

Previous Work:

The U.S. Coast Guard uses standard oil boom in its oil spill recovery operations in a device named the Vessel of Opportunity Skimming System (VOSS). As shown in figures 1 and 2, the boom can be rigged on either side of a vessel and used to mechanically sweep up the spill. A skimming pump then pumps the oil to the towing ship.

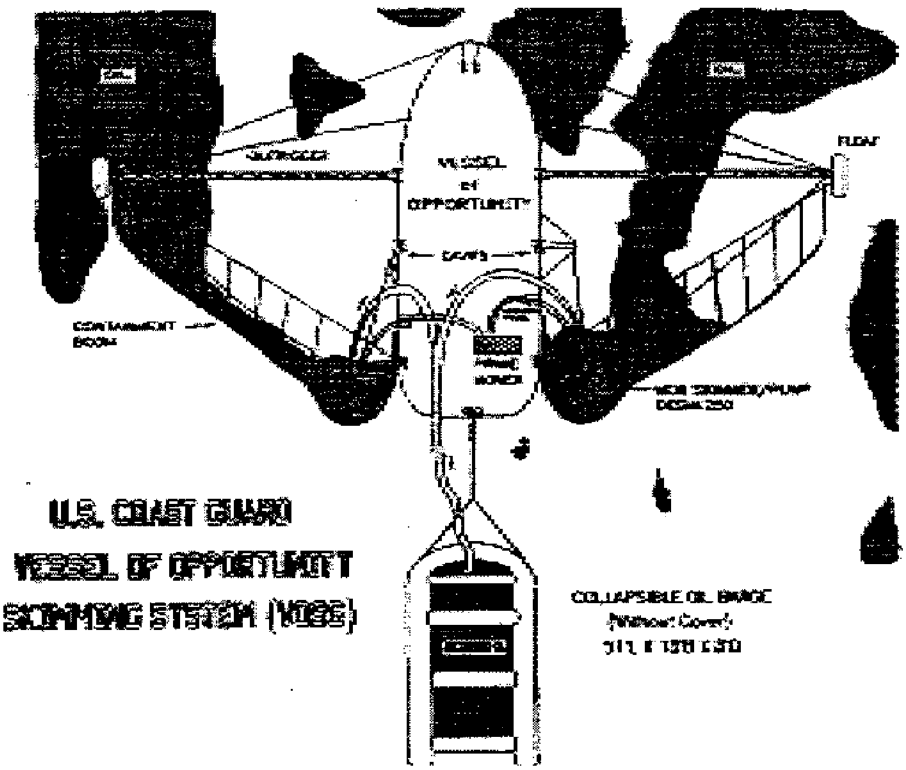


Figure 1: VOSS in operation

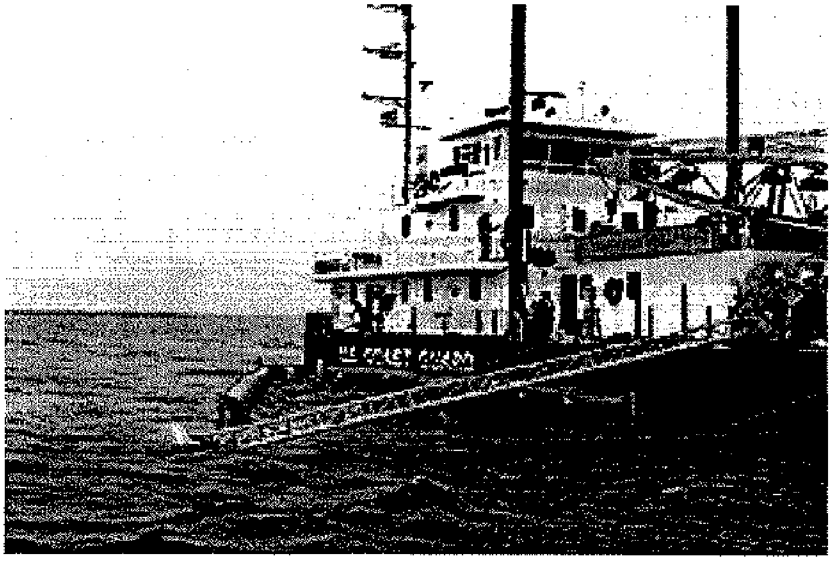


Figure 2: VOSS deployed on buoy tender

The boom consists of three basic components (see Figure 3), including (1) a flotation device at the top, (2) a flexible curtain to contain the spill, and (3) a weight to keep the curtain taut.

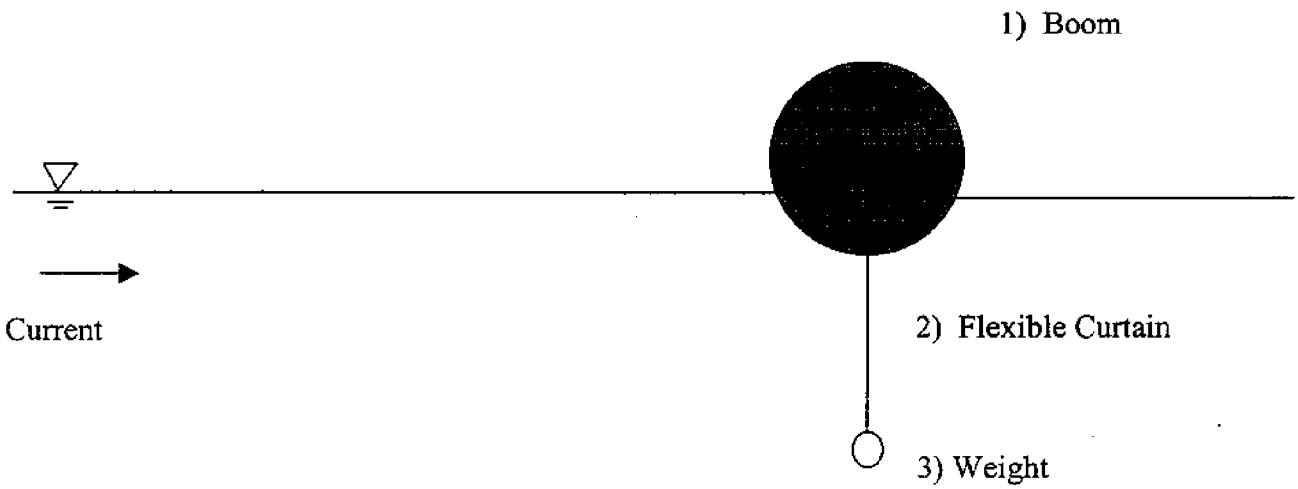


Figure 3: Diagram of conventional boom

In operation, the vessel travels through the oil slick, while the oil collects against the boom's skirt, and is pumped into a storage device. The performance of the oil boom greatly diminishes as the perpendicular component of current exceeds a critical value. This critical value is between 0.6 – 1.0 knots depending on the oil properties (Delvigne, 1989). When this value is reached, oil tends to travel underneath the curtain causing leakage. Since most vessels need to operate at or above one knot for ease of steering and maneuverability purposes, an operating speed below one knot hampers the ships handling as well as reduces the amount of oil that may be collected in a given amount of time. If the boom is anchored as a stationary collector, leakage is a severe limitation of the device, since natural currents in rivers and tides often exceed this critical value.

Delvigne (1989) has done much research on the types of failures of oil booms depending on the type of oil. The five basic failures for booms are entrainment, drainage, splash-over, submergence, and planing. These failures occur when the boom is still intact and are not associated with structural failures.

Entrainment failure is when the oil is carried by the flow under the boom in droplets. This happens when turbulence occurs at the downstream side of the waves on the oil/water interface, hereafter referred to as the headwave, which is built upstream of the boom, and causes oil droplets to break away and become trapped in the moving water and pass under the boom. Unless the headwave is a considerable distance upstream from the boom the oil droplets will not have the time to re-surface to be captured by the boom. The amount of oil lost in the headwave failure depends on the water velocity and specific gravity of the oil. If the oil droplets lack buoyancy to rejoin the slick, they will be carried under the boom. The lighter, lower viscosity oils have been shown to fail in this fashion (Coyne, 1995).

Critical velocity occurs when the headwave becomes unstable and droplets of oil are stripped off and entrained in the water streamlines and flow underneath the boom. The component of water speed perpendicular to the boom is the critical velocity. It is this critical velocity that determines how fast a boom may be towed or the maximum current it may be deployed in. Currents and waves contribute to critical velocity such that waves cause the oil particles to have an additional velocity component added to the current velocity.

Another more severe form of entrainment is failure by critical accumulation. This failure seems to only occur with high viscous oils. As the incident velocity increases, the thickness of the oil along the skirt increases in depth. At a certain velocity the thickness increases rapidly and the whole slick is carried under the current. This critical velocity seems dependant on the type of oil being contained.

Drainage failure occurs as oil collects at the boom face. It increases in depth and finally flows down the skirt and travels underneath to the other side. Water at the skirt is accelerated downward to keep up with the flow underneath the skirt. Increasing the curtain depth increases the distance the water must travel which causes drainage failure to occur at a lower critical velocity. The critical velocity at which drainage failure occurs depends on curtain depth, oil viscosity, specific gravity, and the depth of the oil being retained by the boom. This velocity is greater than the critical velocity for entrainment failure. Splash-over failure occurs in choppy seas when oil splashes over the boom. Most booms will have splash-over failure if the length to height ratio of the wave falls below 5:1.

Submergence failure occurs when the boom is deployed or anchored in a fast current or if the boom is towed at a high velocity. The tendency to submerge at a given velocity is an inverse relationship to the boom's reserve buoyancy. That is, if the boom has large reserve buoyancy it is less likely to suffer submergence failure.

Planing failure is when the curtain lies flat on the surface of the water. This may occur in a strong wind and a strong current moving in opposite directions. This failure may occur if the boom has improper ballasting.

With these failures of the conventional boom, much research has been done in finding alternative ways to recover oil. The submergence plane, shown in Figure 4, is one concept that has been shown to contain oil at speeds above two knots (Bianchi and Henry, 1973). The submergence plane protects the containment area from the perpendicular flow of the current. This allows the oil to be pumped out of the containment region, and it also allows for faster currents and operating speeds for vessels. Two devices that utilize submergence plane theory are the "Bay Defender" and the "HydroFoil/Fast-Sweep".

In operation the oil slick encounters the bow and is forced down the submergence plane where it encounters the inlet gap. The gap is the distance between the horizontal baffle and the end of the submergence plane otherwise referred to as the bite. Since oil is less dense than water, it will rise up into the opening and enter the containment area. Excess water will leave through the exit holes at the bottom of the baffle, while the back boom contains the oil. As stated above, this system protects the containment region from the incident current.

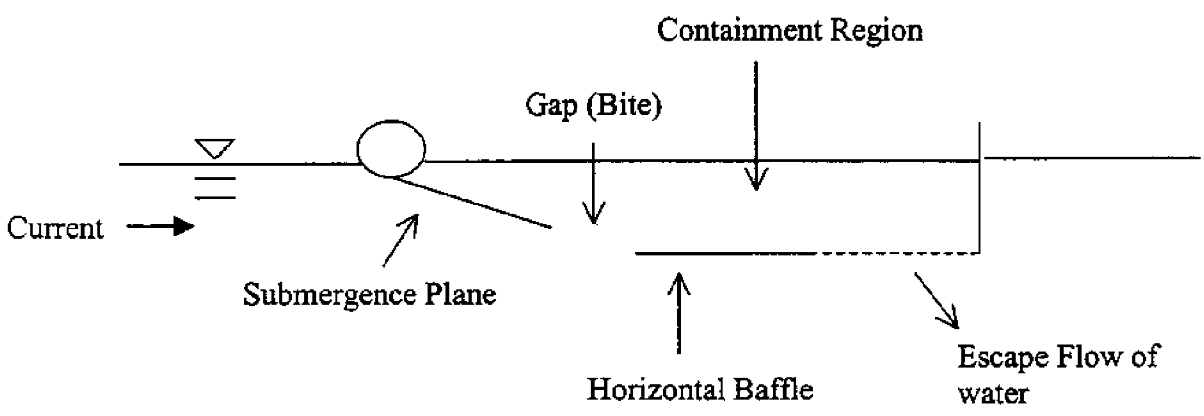


Figure 4: Side view of submergence plane in operation

One problem encountered by submergence planes is the formation of bow turbulence. An extreme example of the bow wave created by the submergence plane is found in Figures 5. This turbulence breaks up the oil slick, causing the slick to mix vertically in the water column. This mixing causes a percentage of the oil to miss the gap depending on the speed at which the system is operating. At speeds above about 2 knots, the system begins to lose its effectiveness, and much of the oil will fail to enter the containment area at speeds above 3.5 knots.

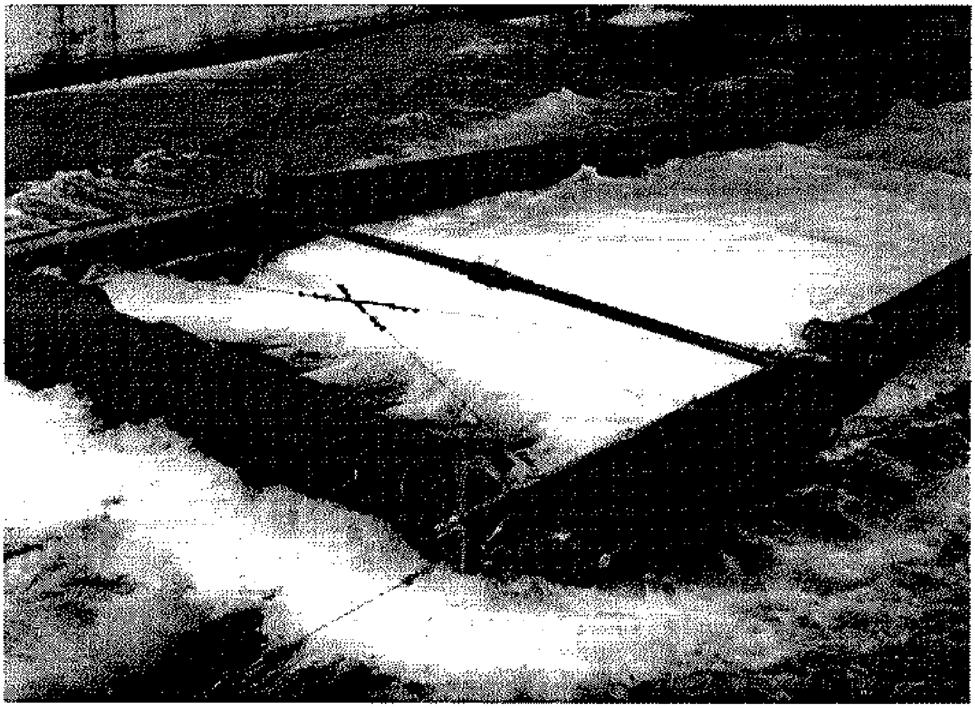


Figure 5: Bow turbulence created by Hydrofoil/Fast-Sweep at 6.5 knots

"HydroFoil/Fast-Sweep" (See Figures 6 and 7) is a flexible skimming system that employs a hydrofoil as well as a submergence plane. It is designed to be deployed alongside a U.S. Coast Guard buoy tender. The system uses a Fast Sweep inflatable oil boom as the aft perimeter barrier. One problem with the submergence plane is the lift forces associated with it. As the speed increases, the system's bow tends to rise up. This is counteracted by the use of a hydrofoil mounted transversely below the submergence plane with a negative angle of attack, hence the name "Hydrofoil/Fast-Sweep." This device uses the foil to provide a downward force to counteract the upward rise of the submergence plane. Both the lift force and the downward force provided by the hydrofoil are dependent on speed. The two forces will neutralize one another at any speed at which the vessel travels.

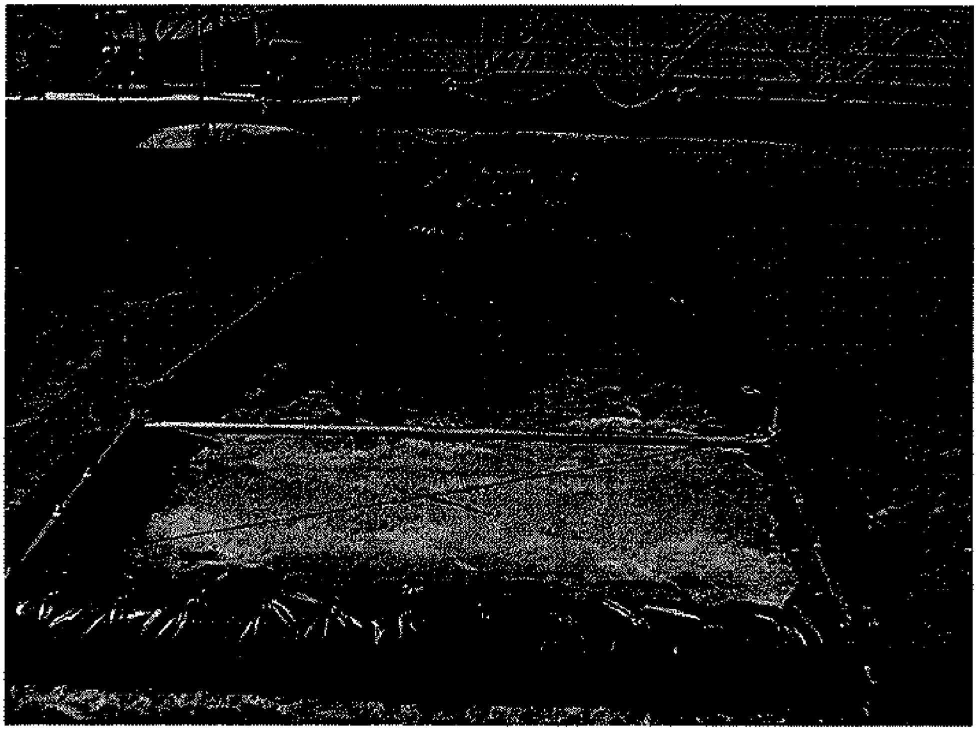


Figure 6: Hydrofoil/Fast-Sweep being towed

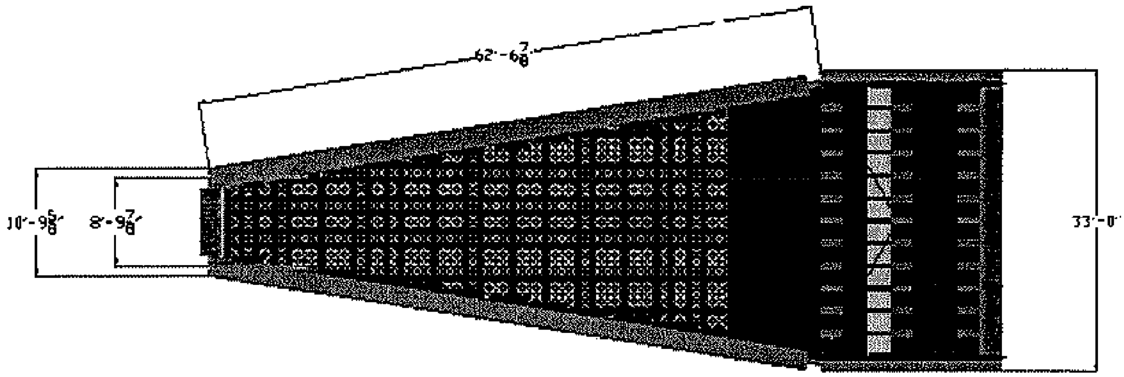


Figure 7: Full scale model of Hydrofoil/Fast-Sweep

"Bay Defender" as shown in Figure 8, is a flexible stationary device that collects oil by means of a submergence plane. It is intended to be anchored in current to intercept oil slicks. Bay Defender, in fact, uses standard booms as lead-ins in its deployment. The boom funnels the slick into an apex, where it is forced down the submergence plane of the Bay Defender. In this configuration, the critical velocity of the boom is not reached and thus no leakage occurs at the boom.

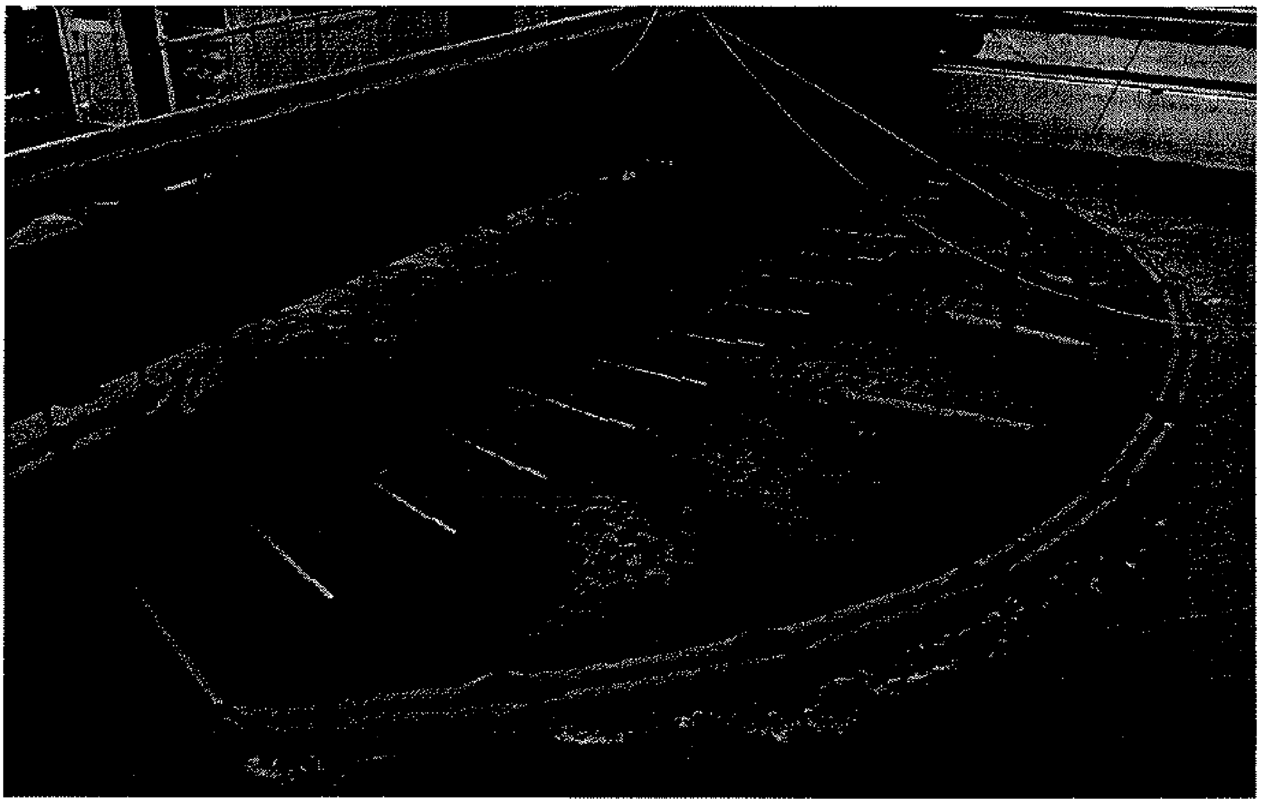


Figure 8: Bay Defender in oil testing

Objectives:

Our specific objectives were as follows:

1. Develop bow designs that reduce the amount of turbulence and increase the retention of oil.

2. Perform comparative bead and dye tests on the original model as well as six other bow designs.

3. Identify the best design and any design improvements that can be easily implemented.

Approach:

To start this project several meetings took place with various experts in naval architecture, fluid mechanics, as well as Ocean Engineering. From these meetings, an understanding of the interaction between oil, air, and water was arrived. With these theories of the how the turbulence was formed, many theoretical designs were roughly sketched out to address each problem. A decision to eliminate designs that relied on power or control systems was made. Each theoretical design was critiqued and from these meetings our final designs were developed.

Six two-dimensional models of bow designs that could be used for "HydroFoil/Fast-Sweep" were constructed. The model of the existing submergence plane was included for comparison. The new designs all address the problem of bow form turbulence from different perspectives. The new designs include a model that removes the front flotation device and extends the submergence plane out of the water, a model with a plane in front of the front float, and a model with a shroud beneath the original submergence plane that will contain the vertical mixing, and a model combining the extended plane and the shroud. The final two models changed the orientation of the shroud on the original model.

Retention tests were done using plastic beads instead of oil. This avoided the hazardous handling as well as clean-up time for the tests. The beads chosen have a high specific gravity similar to Sundex oil, a standard oil employed in equipment evaluation in experiments. A known volume of beads was added to the tank at a specific model speed, and retention results were compared among the models. The dye test was used to visually observe the amount of vertical mixing in the water column to indicate which model generates the least amount of turbulence.

II. Design Considerations

After evaluating the limitations of the Hydrofoil/Fast-Sweep profile, it was clear that improvements could be made in order to reduce the wave created at the bow of the design. Designs that were considered for this project all attempt to overcome the adverse effects that the bow wave has on oil collection. The sole purpose of this project was to improve the bow of the Hydrofoil/Fast-Sweep model. No other facet of the original model was changed.

There were several specifications that the design of the Hydrofoil/Fast-Sweep had to meet. The specifications of the system pertain to the model's size, dimensions, durability, ease of packing, ease of deployment, and the materials that the design is constructed from. However, these issues were not relevant to the goals of our project. The improvement of the bow shape was the primary concern in our work. Only specifications relevant to the bow, such as submergence plane angle of attack and gap geometry, were considered for this project. Previous work on the submergence plane concept had provided proper values for dimensions related to the bow of the Hydrofoil/Fast-Sweep. Dimensions of the Hydrofoil/Fast-Sweep model that were relevant to our study can be seen in Figure 9. Note that these are the dimensions of the full scale system.

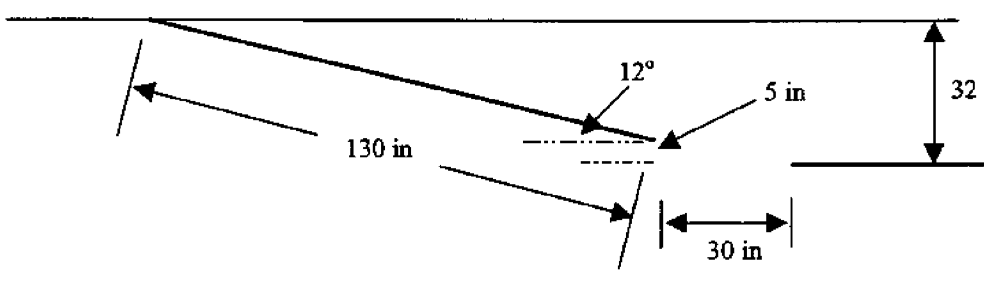


Figure 9: Relevant dimensions of full scale system

The primary concern with the bow that is currently used for the Hydrofoil/Fast-Sweep is the turbulence created at the bluff flotation body at the front edge of the model. This bluff body creates a rotational wave at the front edge of the system. At speeds above roughly two knots, this bow wave breaks up the oil slick and disperses the oil in a downward direction. In the absence of this turbulent bow wave, the oil would be less likely to break up, and more likely to travel smoothly down the submergence plane and into the containment region. Any bow designs that might help limit the harmful effects of the bow wave were evaluated and possibly tested.

Three general criteria for new bow configurations were considered as possible designs were brainstormed. The first criterion involved the development of a bow that doesn't expose the incoming oil to a bluff floatation body at its front edge. This would greatly limit the turbulence that is created at the bow of the original model, and ultimately collect oil more effectively. The second criterion involved diverting the oil away from the front float of the original bow design, in order to limit the mixing of the oil. Finally, the third criterion that involved containing the oil that is broken up when exposed to the bow wave. In other words, the bow would somehow limit the area that the oil could spread into after it is broken up by the bow wave. Bows that implement some combination of these design criteria were also considered as attempts were made to improve the original bow.

Besides the aforementioned design considerations, another factor that comes into play when evaluating possible bow designs is practicality. In terms of ease of implementation, the simpler bow design is a more practical alternative than a more complex design. A bow design that has rotating parts or needs a power source in order to function is a less attractive solution to the problem, simply because it adds more possibilities of a part failure. In addition, designs that are more complicated are generally more difficult and expensive to manufacture. In the case of this project, the problem that existed was one that had more of a geometric solution, rather than a mechanical solution. Unless there was strong evidence that some type of mechanical bow system had distinct advantages over a simpler bow configuration, the simpler bow design would take precedence.

III. Design Alternatives

After evaluating the criterion that would help to improve the bow of the original Hydrofoil/Fast-Sweep, several new bow designs were conceived. The first criterion for new bow designs involved eliminating the incoming oil's exposure to the bow wave created by the bluff flotation body. The second criterion involved diverting the incoming oil away from the bluff cylindrical bow. Finally, the third criterion attempted to contain the oil after it is broken up by the bow wave. Many of the new bows that were considered take one or more of these criteria into account.

In this section, several new bow designs will be introduced and discussed. Because of the comparative nature of this study and the 2-dimensional shape of the prototype bow, it's important to look at each design's cross section. When testing the design alternatives, the width of each of them will be the same, but will be constructed at a reduced scale. Two-dimensional modeling will allow the performance of each configuration to be compared to one another. As long as the width of each design is the same, two-dimensional analysis can provide as much insight into a design's performance as three-dimensional analysis. For this reason, the figures of all design alternatives are two-dimensional side views. The original bow design that is currently used for Hydrofoil/Fast-Sweep can be seen in Figure 10. The inclusion of the original model is for purposes of comparison.

Original Design:

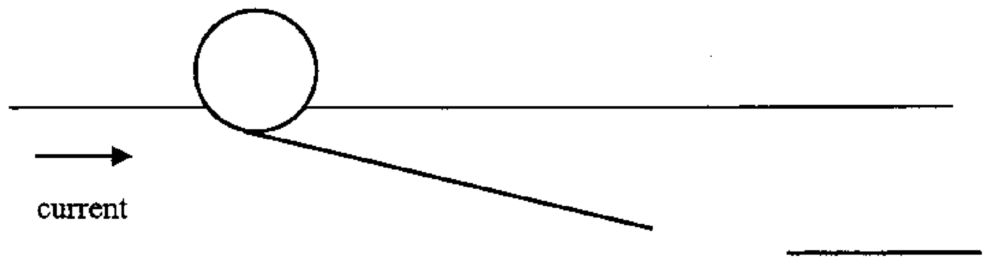


Figure 10: Side view of original design

From Figure 10, it is clear that the incoming oil is exposed to the bluff flotation body at the front edge of the bow. Because of its exposure to the turbulent bow wave that is created by this body, the incoming oil mixes up. As the oil mixes up with the turbulent water, it is diverted downward and away from the submergence plane. For this reason, the mixed oil is less likely to travel down the submergence plane and rise up into the gap. The alternative shapes that are discussed in this section all attempt to improve upon this original bow design.

Extended Plane Design:

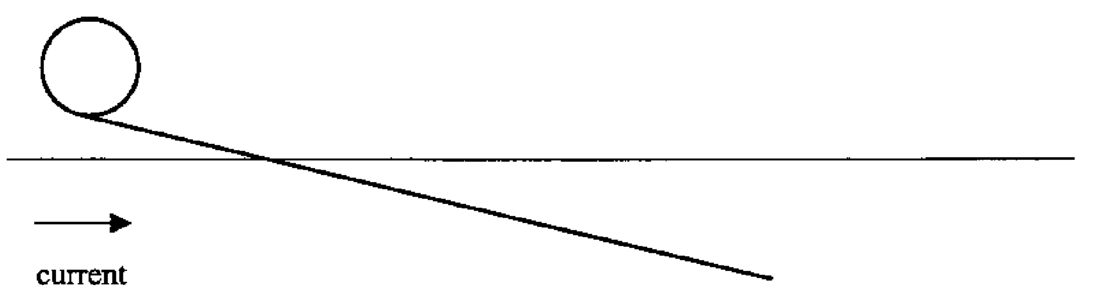


Figure 11: Side view of extended plane design

As seen in Figure 11, the extended plane bow design is very similar to the original design. The only difference between the two designs is the location of the waterline. In the original design, the incoming oil is exposed to the bluff flotation device at the front of the bow. However, in the extended plane design, the incoming oil is exposed to a smooth 12° submergence plane, while the reserve buoyancy is above the waterline. The idea of the extended plane model is to limit the mixing that is created by the bluff body. The reserve buoyancy will still be located at the front of the system in the case of severe wave conditions, but the incoming oil is not exposed to it under normal operating conditions. Limiting the mixing at the bow should ultimately lead to more efficient oil collection.

Preceding Plane Design:

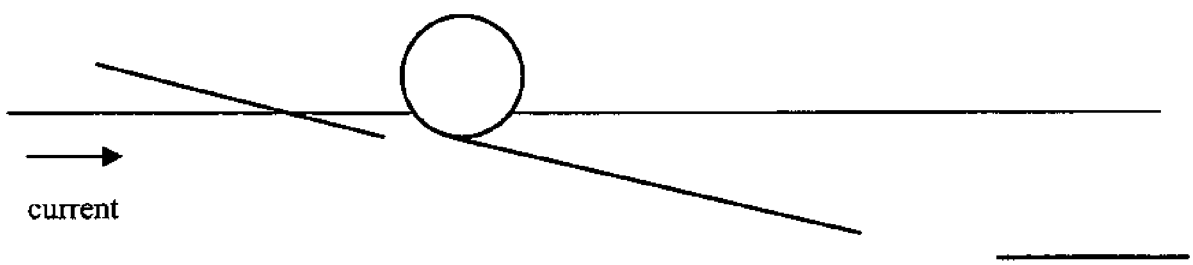


Figure 12: Side view of preceding plane design

The preceding plane design is shown in Figure 12 above. Every aspect of this design is the same as the original model, except it incorporates a 12° plane in front of the bluff flotation body. The idea is to divert the incoming flow away from the bluff float that it would otherwise be exposed to. The preceding plane creates a more benign bow wave, as in the extended plane design, due to the small incline the incoming oil is exposed to. With limited mixing due to a smaller bow wave, the oil would be more likely to travel down the submergence plane and into the gap.

<u>Shroud Designs</u>:

Three different shroud designs, seen in Figures 13, 14, and 15, were considered for evaluation in this project. The shroud designs all incorporate a shroud beneath the submergence plane, in an attempt to contain the oil after it's exposed to the bow turbulence. The difference between the three designs involves the placement of shroud relative to the submergence plane. The first shroud design has parallel planes, the second design has a smaller inlet gap and a larger outlet gap, and the third design has a larger inlet gap and a smaller outlet gap.

Parallel Plane Shroud Design:

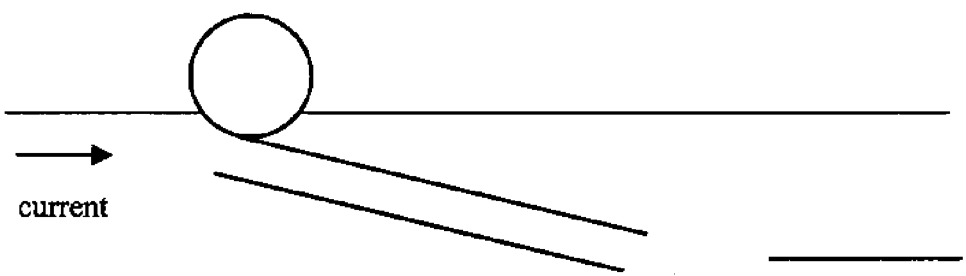


Figure 13: Side view of parallel plane shroud design

*Shroud Design (Entrance gap ~ 0.5*Exit gap):*

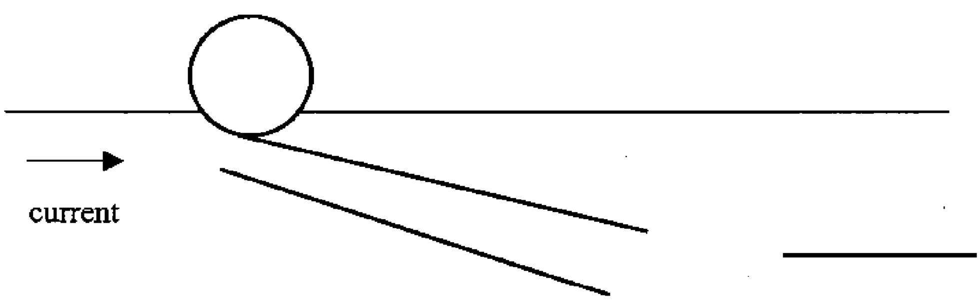


Figure 14: Side view of enlarged exit shroud design

Shroud Design (Exit gap ~ 0.5 Entrance gap):*

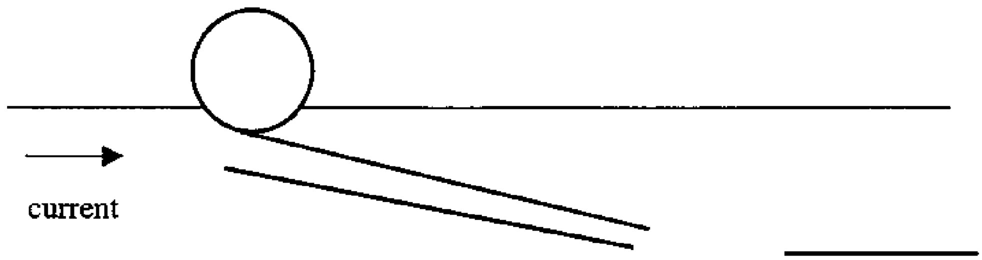


Figure 15: Side view of decreased exit shroud design

The parallel plane shroud design is the most basic of the three. Its sole purpose is to limit the spreading of the oil so that more oil can be collected. The shroud design that has a smaller inlet gap and larger outlet gap would operate slightly different than the parallel plane design. Because the flow rate in the gap between the submergence planes is constant, the water speed will slow down as it travels through. Because oil will rise faster in slow moving conditions, this decrease in water speed could help the oil to rise into the gap. The increase in gap size could prove to be detrimental, however, since it allows more vertical spreading of the oil traveling down the plane.

The third shroud design has a larger inlet gap and a smaller outlet gap. The shroud is angled in such a way that the oil is directed toward the gap. Although the decrease in gap size will provide an increase in fluid velocity, the oil is so tightly contained at the exit gap that vertical spreading is not severe. One possible negative feature of this design is the creation of too much energy in the containment region. This could occur if the shroud directs all of the water traveling through into the gap.

Preceding Roller Design:

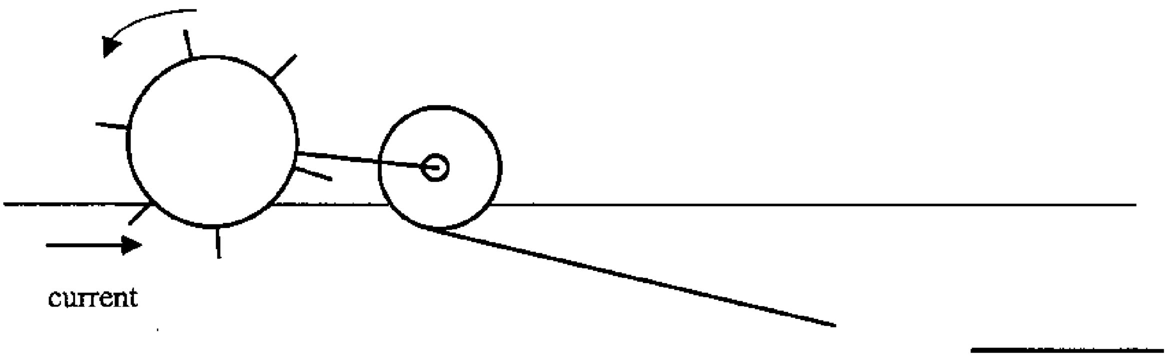


Figure 16: Side view of preceding roller design

The preceding roller design, as seen in Figure 16, is the first of two design alternatives that involve rotating parts. The roller that precedes the bow of the original design would be hinged in such a way that it is allowed to rotate freely as it is exposed to a current. Paddles would be located periodically around the circumference of the preceding roller to allow the current to provide the energy. Instead of seeing a bluff, rigid body, the incoming oil would now see a freely moving, rotating body. The intent of this design is to direct the incoming oil down the submergence plane with the roller, and also to limit the bow wave. Note that this design needs no power source.

Dynamical Inclined Plane Design:

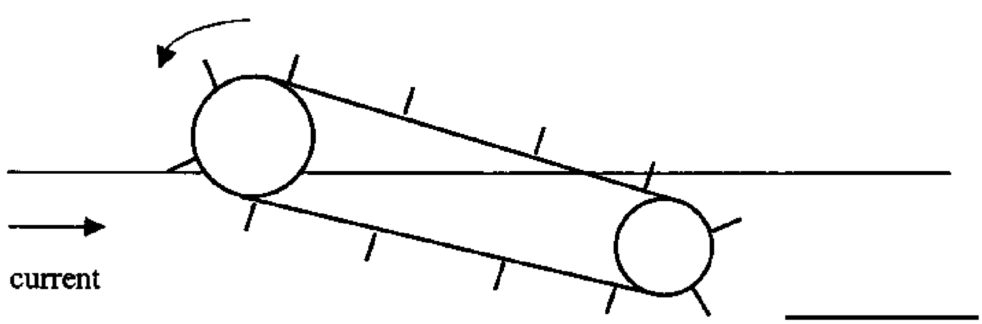


Figure 17: Side view of the dynamical inclined plane design

The dynamical inclined plane design can be seen in Figure 17. Like the preceding roller design, the dynamically inclined plane design has paddles on its rotating part to allow the current to provide the power. However, instead of using a roller that precedes the original front float, this design uses a rotating submergence plane. The submergence plane in this configuration wraps around the original front flotation body as well as an added underwater cylinder. The setup of the submergence plane is much like a conveyor belt. The motion of the submergence plane would help to lead the oil slick into the gap. Because the plane wraps around the front float, the water would effectively see a rotating body, as in the preceding roller design. The rotating body would limit the bow wave in comparison with the bluff body of the original design.

Saw Tooth Design:

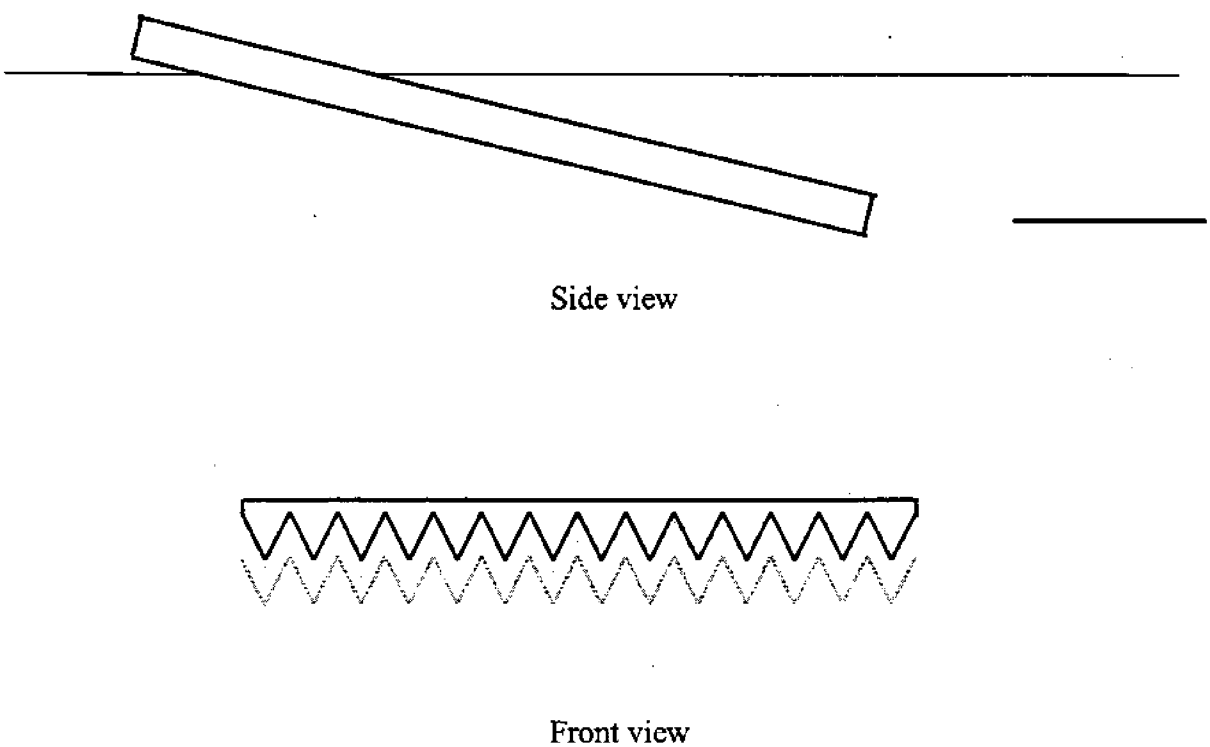


Figure 18: Saw tooth design

The saw tooth design, seen in Figure 18, still relies on the submergence plane to drive the oil down into the gap. However, instead of offering a bluff body or a flat plane as resistance to the incoming oil, it would have the 'points' of the teeth. This design attempts to lessen the initial bluff area the oil faces. It then attempts to channel the water down the submergence plane in between each point, and into the entrainment region. This is the only design that actually changes the submergence plane geometry. Due to the more complex submergence plane geometry, stretched fabric construction (as used on the original design) may not be as practical as some of the other designs.

Designs Tested:

After evaluating the good and bad features of all of the design alternatives, six alternative designs were chosen for testing. The original design was included also, so that the performance of all the design alternatives could be compared to the performance of the original bow. Five alternative designs are listed below:

1) Extended plane design
2) Preceding plane design
3) Parallel plane shroud design
4) Increased exit shroud design
5) Decreased exit shroud design

The final alternative bow that was tested was a combination of the most effective shroud configuration mounted on the extended plane design. Because the level of performance of the extended plane design was expected to be greater that that of the original design, the best shroud configuration would be added to the extended plane model to further increase oil collection. The three shroud configurations were tested on the original model to see which works best.

The major concerns while choosing which designs to test were ability to lessen the adverse effects of the bow wave, and ease of manufacturing. None of the designs chosen incorporate moving parts in the system, and they are all geometrically simple. Designs such as the preceding roller design, the dynamical inclined plane design, and the saw tooth design weren't chosen for testing due to their lack of simplicity. The simpler design is always the more attractive design unless there's strong reason to believe that the more complex design will be more effective. Since none of the complex design alternatives were more promising than the simpler ones, they were not chosen for testing.

Along with their simple geometry, each design alternative chosen for testing attempts to deal with the adverse effects created by the bow wave. The extended plane model brings the bluff flotation body above the waterline, therefore exposing the incoming oil to a mild 12° decline rather than a bluff cylindrical body. The preceding plane model attempts to divert the incoming oil away from the turbulence created by the bluff body. The shroud models all attempt to contain the oil after it is broken up by the turbulent bow wave. The best shroud configuration on the extended plane model would also contain the broken up oil, but the oil would be less mixed up because it's not exposed to the bluff body as in the original shape.

The types of tests that were performed were identical for each model, allowing for comparative evaluation of the designs. The performance of the original bow design was the basis for all comparison. Besides the type of tests performed, the scale of each model was also the same, and depended on the size of the testing facilities available, as discussed in the Experimental Method section.

IV. Experimental Method

Testing Facilities:

All model tests were performed in the re-circulating dirty flume (see Figure 19) at the Jere Chase Ocean Engineering Building at the University of New Hampshire. The dirty adjective refers to the fact that oil may be used in the flume, but for these experiments beads were used to avoid the messy cleanup of oil. As seen in Figure 19, the overall length of the flume is forty feet. The flume is forty-eight inches tall by forty-six inches wide. The water level may be set at a maximum level of thirty inches above the separation baffle. The near side of the tank is clear to allow visual observation of any models placed in the flow. Two propellers powered by two electric twenty horsepower motors drive the water current. A variable frequency driver governs the water speed generated by the motors with inputs to the driver in hertz.

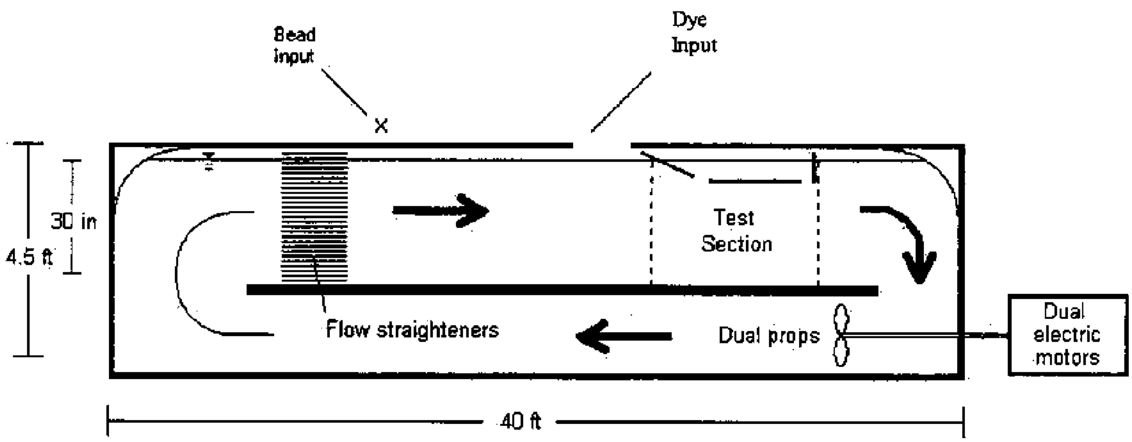


Figure 19 Diagram of flume

Model Construction:

One-fifth-scale models were built to scaled dimensions of the HydroFoil/Fast-Sweep bow and each of the alternative designs. The submergence plane, for each model, was made out of sheet of low-density polyethylene (LDPE). A truss system was used to provide strength and support to the models. The trusses were made out of 1x2 inch pine and connected by drywall screws. The reserve buoyancy float was made out of eight-inch diameter PVC pipe. The pipe was then sealed to the submergence plane by use of Liquid Nails.

Scaling:

The dimensions of the flume at UNH determined the scaling factor for our models. A consideration of naval architecture is the effect of blockage on the fluid flow around a body in an enclosed area. The principle states that if the draft of the body occupies more than one-third of the depth of the tank, the data may be skewed due to the increased velocities, waves, or boundary layers. Therefore for a model to be placed in the UNH flume it must have a draft of less than ten inches. The draft of the HydroFoil/Fast-Sweep is listed at thirty-two inches; thus a one fifth scale model has a draft of 6.5 inches. This falls well within the criteria of a one third draft clearance. Model test parameters were assumed to obey Froude scaling laws, which are detailed in the appendix.

Test Preparation:

For each experiment that was performed, the horizontal baffle was placed at a depth of 6.5 inches as shown in Figure 20. From this depth, the model placement in the flume had consistent gap geometry for each model as well as for each test. The bite, or vertical separation between the end of the submergence plane and baffle, for each test was one inch and a gap length of six inches. Great care was used to ensure these dimensions were accurate since these had significant effects on the amount of bead retention. These dimensions are the one-fifth scale dimension for the HydroFoil/Fast-Sweep. For each test the submergence plane angle must be kept at 12 degrees for each test for comparison purposes. The cylinder in the original model must be set up with a two-inch depth in the water for each test, whereas the extended plane model must have a three-inch rise out of the water. The preceding plane model must have the preceding plane one-inch from the leading edge of the cylinder and set at an angle of 12 degrees. The various shroud models require the same set up as the original model or the extended plane. The shroud is attached to the bottom of the model. It does not interfere with the setup of any model. See Figures 21 through 27 for dimensioned drawings of the setup of each model.

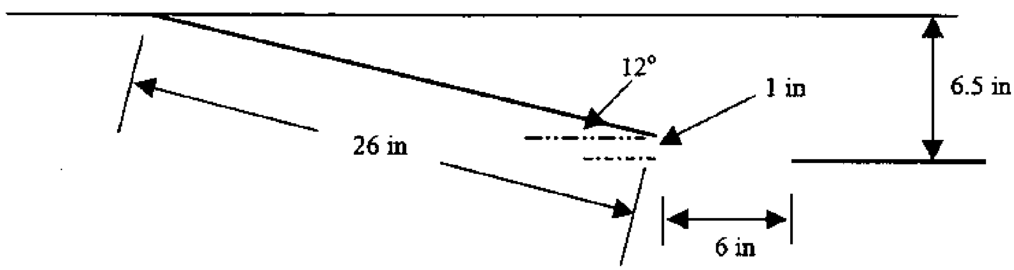


Figure 20: Gap geometry of one fifth scale system

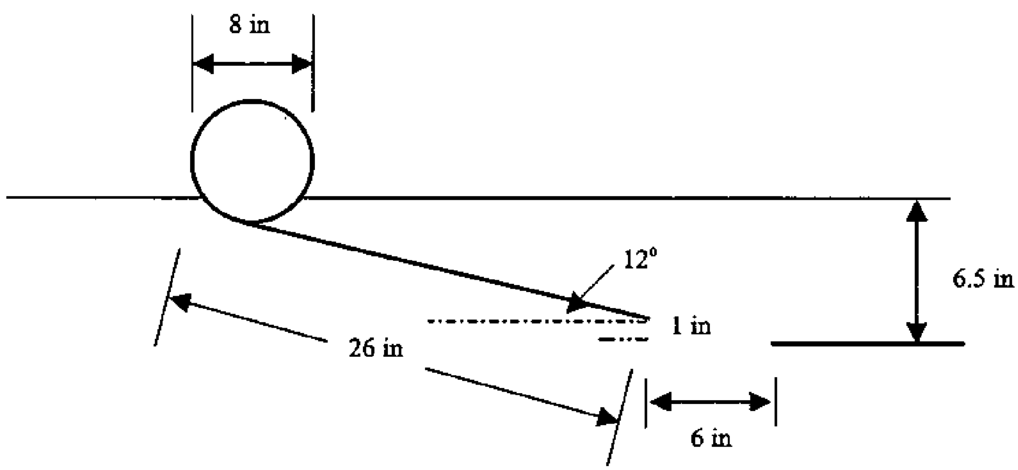


Figure 21: Original model

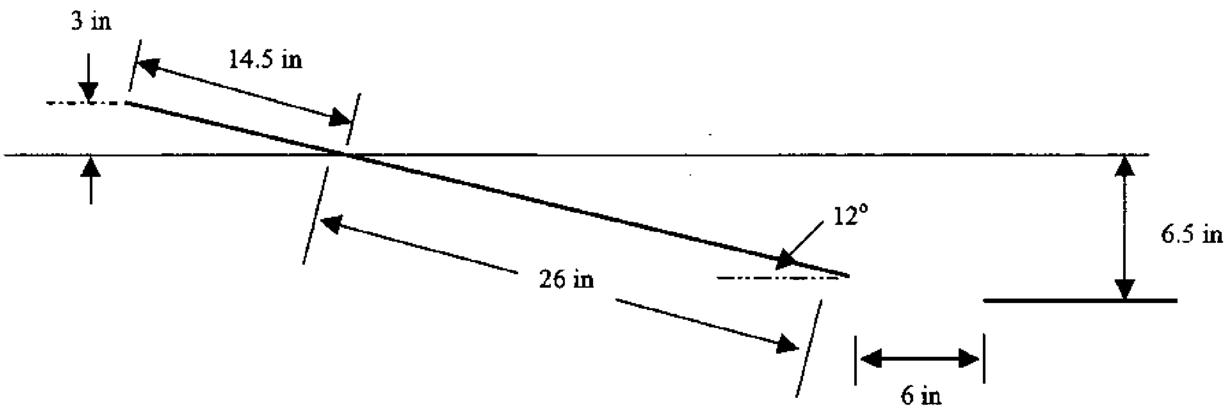


Figure 22: Extended plane

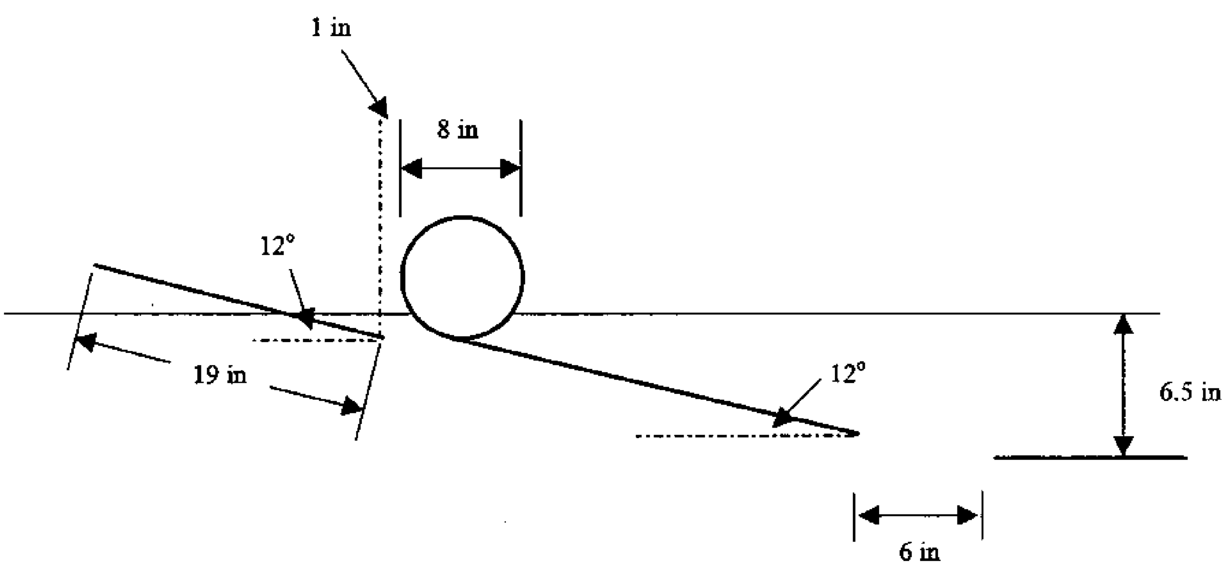


Figure 23: Preceding plane

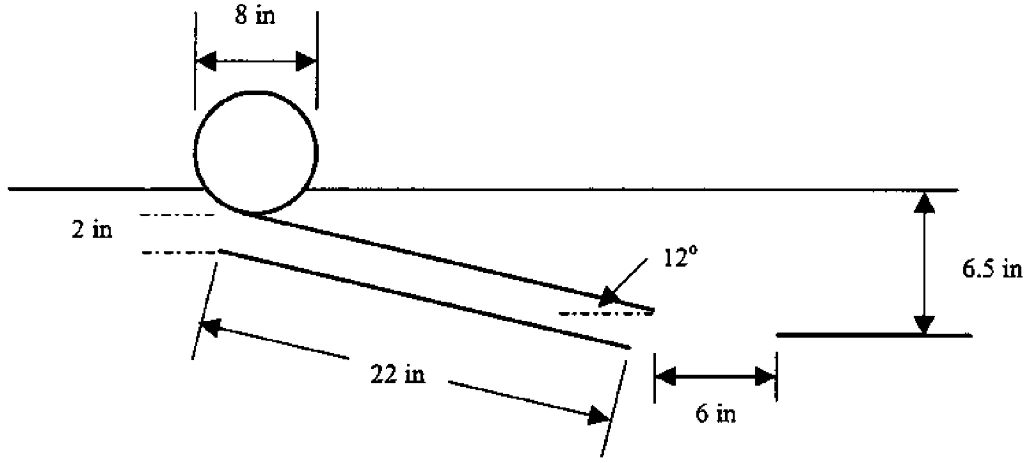


Figure 24: Parallel shroud

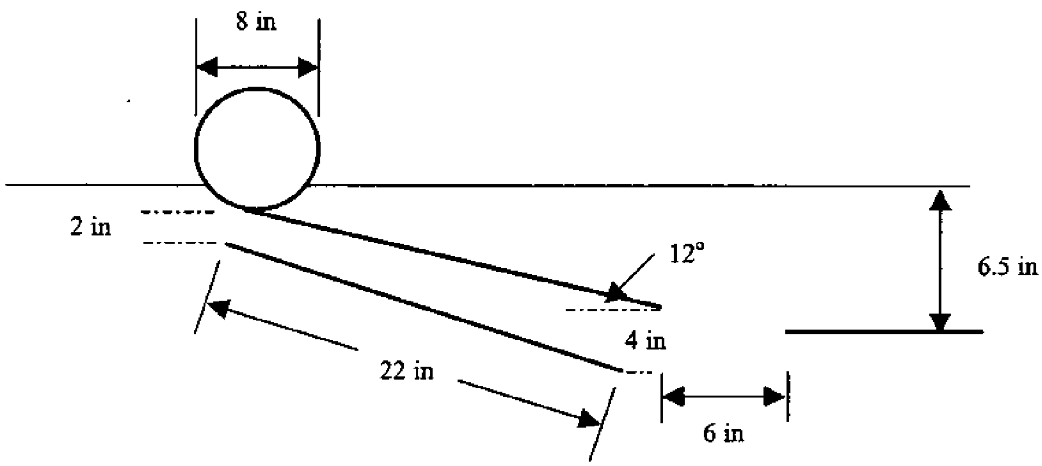
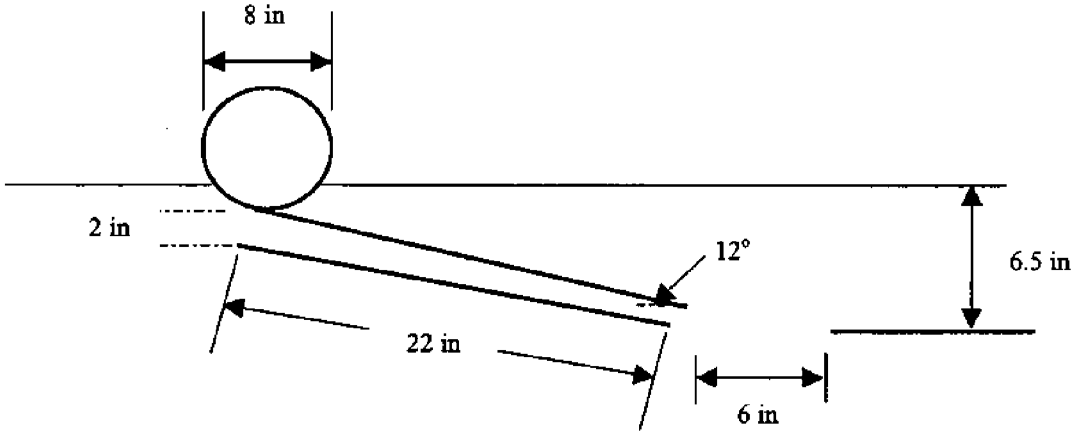


Figure 25: Enlarged exit shroud



Exit gap between submergence planes is 1 in

Figure 26: Decreased exit shroud

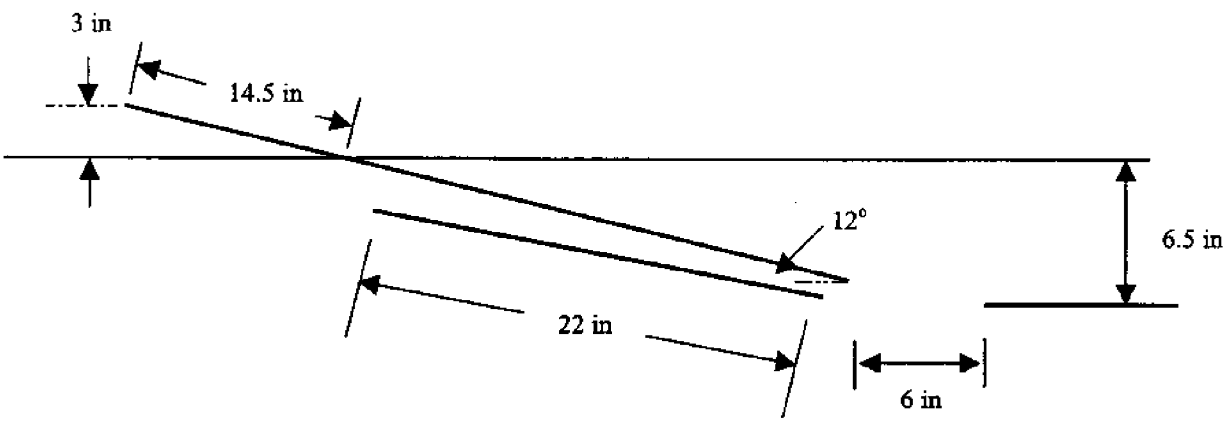


Figure 27: Extended plane with decreased exit shroud

An fluid container, valve and thin flexible tube was hung next to the flume and filled with rotamine dye. This dye was chosen because it will not dilute as readily as other dyes and is not as expensive as other means to visually compare the generated turbulence such as an air bubbler or hydrogen emitter. The nozzle for the dye input was set at the water surface in the center of the flume, twenty-three inches from the sides, and eight inches from the waterline of the model. The nozzle was pointed horizontally towards the model. It was hung from the cross sections to rest upon the surface. It was free to move side to side with the current.

A ten-inch plastic board was attached at the upstream end of the flume just below the surface about 190 inches from the model (see Figure 28). This was the bead deployment platform. The beads were poured in the center of the platform and carried off by the current. The platform was an attempt to insure that the beads had negligible vertical acceleration and remained at the surface to simulate the oil slick.

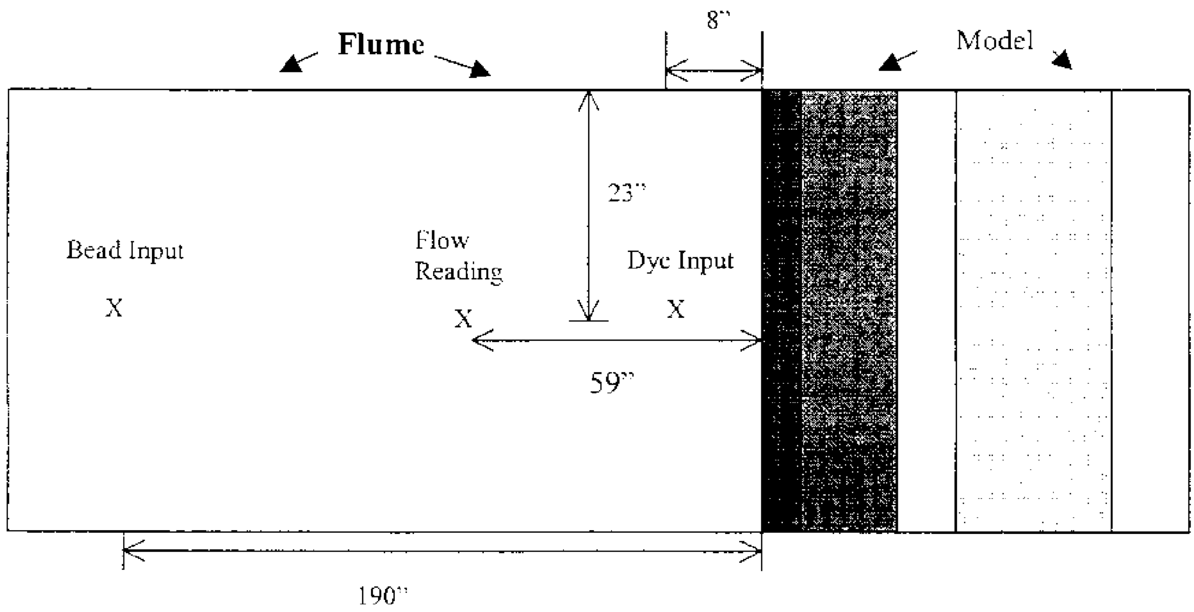


Figure 28: Diagram of test setup

To fix the flow speed, the input to the motors was set at 47 Hz. This input value was the same for each test performed to generate an expected current. Once the water current reached steady state a Marsh-McBirney Flo-Mate 2000 was used to measure the current. For a detailed description of the flow meter see the appendix. The flow meter was placed at a depth of 2 inches and used to measures the average velocity over ten seconds. This was one measurement. Seven more reading were taken at this location. The sensor was then lowered to a depth of 13.5 inches, and eight more readings were taken at that location. At this point all test preparation was complete.

Dye Test:

The dye test was a qualitative test among all models. It allowed visual comparison of the amount the dye breaks up as it encountered the bow for each model. The dye input was switched on to allow and the dye to flow out of the nozzle towards the model. The video camera recorded each dye test so that they could be compared. Once the observation was complete the dye was shut off and removed from the flume completing the dye test.

Bead Test:

The bead test was a quantitative test among all models, in which the amount of captured beads was measured. Though more difficult than real oil, beads provide a good basis of comparison for each test. 2000 milliliters (ml) of beads with a specific gravity of 0.96 were measured in a graduated cylinder. Once the Video camera was ready, the beads were poured in the center of the platform. The beads were carried off with the current and encountered the model. Once the last bead hit the model, the motors were turned off and a screen was placed in front of the model to prevent the re-circulation of beads. This insured that only one pass by the beads was made, as they collected against the screen as they re-circulate through the flume until the current completely stoped. All beads located in the containment region were considered captured beads and were removed by use of a fish net and placed in a pile to dry. All other beads were considered lost and un-captured. These beads were collected and placed in a pile to dry. Once the beads had dried, the captured beads were volumetrically measured in the graduated cylinder. Once this value was recorded the lost beads were added to verify that all beads were accounted for. With all the beads cleaned out the model and baffle were removed from the flume until the next test.

V. Results

The raw data from the testing of the 7 models can be seen in Table 1 below.

Table 1: Bead test results

Test #	Model Type	Initial Bead Volume	Captured Volume	Percentage Captured	Flume Speed (ft/s)	Flume Speed (m/s)	Flume Speed (knots)
1	Original	2000	500	25	2.09	0.64	1.24
2	Original	2000	600	30	2.10	0.64	1.24
3	Extended	2000	1050	52.5	2.13	0.65	1.26
4	Extended	2000	1000	50	2.21	0.67	1.31
5	Preceding	2000	550	27.5	2.25	0.69	1.33
6	Preceding	2000	500	25	2.28	0.69	1.35
7	Parallel	2000	900	45	2.27	0.69	1.34
8	Parallel	2000	925	46.25	2.26	0.69	1.34
9	Enlarged Exit	2000	625	31.25	2.30	0.70	1.36
10	Enlarged Exit	2000	800	40	2.21	0.67	1.31
11	Decreased Exit	2000	1000	50	2.26	0.69	1.34
12	Decreased Exit	2000	1050	52.5	2.20	0.67	1.30
13	Extended Plane w/Decreased Exit	2000	1500	75	2.17	0.66	1.29
14	Extended Plane w/Decreased Exit	2000	1400	70	2.25	0.69	1.33

Averaging the percentages captured and flume speeds for each model provides a more clear and concise table. Since knots are generally used as the speed scale for the Hydrofoil/Fast-Sweep, speeds in Table 2, on the following page, will be in knots.

Table 2: Model performance

Model Type	Average Bead % Captured	Average water speed (knots)
Original	27.50%	1.24
Extended Plane	51.25%	1.285
Preceding Plane	26.25%	1.34
Parallel Plane Shrouded	45.63%	1.34
Enlarged Exit Shrouded	35.63%	1.335
Decreased Exit Shrouded	51.25%	1.32
Extended Plane w/Decreased Exit Shroud	72.50%	1.31

From the above table, it's clear that some models performed much more efficiently than others. With the exception of the preceding plane design, all of the 2-dimensional models outperformed the original bow in the bead test. The extended plane design showed a clear improvement over the original bow. The parallel plane and the decreased exit shroud designs both performed well, while the enlarged exit shroud design allowed for too much spreading of the contained oil, and didn't perform well. Cavitation was also prevalent between the submergence plane and shroud in the enlarged exit design, creating further turbulence and mixing. Since the decreased exit shroud proved the most effective of the three shroud designs, it was added to the extended plane model. Testing of this model clearly showed that it was the most effective design alternative tested. Although almost all models collected more beads than the original model, the extended plane design with the decreased exit shroud was clearly the most effective.

The speed of the incoming oil was measured for each test to make sure that it was around 1.3 knots. Exposing the 1/5 scale model to this speed is equivalent to a full-scale model speed of about 3 knots. The water speeds, which were measured at a depth of 2 in. below the surface, varied only slightly. Because the variation was small, their effects on bead collection percentages were not taken into account in this study.

Along with the bead tests, dye tests were also performed on each of the scaled models. The purpose of the dye test was to gain a visual understanding of the water flow as it passed by the bow. No quantitative results can be listed from the dye test, but certain visual observations can. The following is a list of observations made while watching the dye flow past the bow:

1) The dye underwent severe mixing as it encountered the bluff cylindrical bow in the original model.
2) The mixing of the dye at the front edge of the bow was much more mild for the extended plane model.
3) The dye mixed vertically as it traveled down the submergence plane of the models due to the growth of the boundary layer.
4) The vertical mixing was limited to the size of the gap between submergence planes in the shroud models.
5) In the preceding plane design, the area between the preceding plane and the original bluff cylinder seemed to force the dye upwards.
6) The dye generally missed the gap, due to its lack of buoyancy.

One important thing to realize about the results obtained during testing is that they cannot be compared with the performance of an equivalent full-scale system. Because of the limited size of the facilities used for testing, the water didn't flow naturally as it would under standard operating conditions. A percentage of beads were dispersed vertically before they even reached the model, and wall effects were always present due to the short width of the tank. It's for these reasons that this study was strictly comparative.

VI. Discussion

As Tables 1 and 2 in the Results section show, the original model collected the second lowest percentage of incoming beads. Knowing that the original bow doesn't perform well at speeds above 3 knots, poor bead retention was expected at a speed equivalent to 3 knots full scale. The bow turbulence was clearly mixing up the incoming beads, sending many of them vertically downward. The tests conducted simply reiterated the fact that bow turbulence is a major problem with the Hydrofoil/Fast-Sweep.

The extended plane design was significantly more effective than the original bow design. No severe bow wave was present to mix up the incoming oil, and the majority of the beads were able to travel smoothly down the submergence plane. The fact that the extended plane model nearly doubled the quantity of beads collected by the original model shows that the elimination of the incoming oil's exposure to a bluff, rigid body greatly improves oil collection.

The preceding plane model did not perform as well as expected. The preceding plane was intended to divert the incoming oil away from the bluff, cylindrical float, allowing it to travel smoothly down the submergence plane. However, as the beads passed the back edge of the preceding plane, they were sucked up into the gap between the preceding plane and the front float. Once in the gap, the beads were exposed to severe turbulence, and they were shot back out of the gap vertically. As it turned out, the bow turbulence from the front float still had an effect on the incoming beads. The dye test done on this model revealed a tendency for the dye to mix in the small gap, and the bead test confirmed that oil collection felt the negative effects from this mixing.

As seen in the Results section, all of the shroud models were improvements over the original bow design. Each model was effective at containing the oil after it had been broken up by the bow wave. The enlarged exit shroud design proved the least effective because it allowed for too much vertical spreading of the oil. This was a concern when this model was conceived, and both modes of testing (dye and bead) proved that the vertical spreading was detrimental. The decreased exit shrouded design proved to be the most effective shroud design. The concern with this model was the possible creation of too much energy in the containment region of the system. Although no quantitative values were measured to describe this energy, it was noted that the containment region remained a quiescent zone when the system was exposed to a current. The limited motion of the collected beads showed the calm nature of the region.

Adding the most effective shroud configuration to the extended plane model further enhanced oil collection percentages. This design includes the positive features of both the extended plane design and the decreased exit shrouded design. The incoming oil doesn't undergo severe mixing due to a rotational bow wave, and the added shroud contains the oil to limit vertical mixing. This model possesses both attributes that were shown to be most important in bead collection.

VII. Conclusion

From the results of the testing, two of the three design criterion listed in the Design Considerations section proved to be very beneficial to the performance of the bow. Recall that the first criterion involved eliminating the incoming oil's exposure to the bow wave created by the bluff front float. The second criterion involved diverting the incoming oil away from the bluff front float. Finally, the third criterion attempted to contain the oil after being broken up by the bow wave. The shrouded designs, 2 of which proved effective, incorporate the third design criterion, while the extended plane model incorporates the first.

Results from the preceding plane design tests showed the difficulty in designing a bow that diverts the incoming oil from the negative effects of the rigid float. For this reason, we feel that the extended plane design, which eliminates the bluff body from the waterline, is far superior to the original design. The extended plane decreased exit shroud model, which is the most promising model tested, shows the added benefit of containing the oil that's mixed at the front edge of the bow.

The testing performed in this project showed that the bow of the existing Hydrofoil/Fast-Sweep model could be improved to allow for more productive oil collection. Of all the alternative designs considered, the extended plane decreased exit shrouded model is the design that would be considered to replace the current bow. Although it would be more difficult to fabricate, the new bow configuration would increase oil collection, ultimately providing more efficient oil clean up. The extended plane model would be the model that is easiest to fabricate and still substantially more effective than the original model. Field tests performed with a larger model would help confirm the conclusions made from the flume tests.

VIII. References

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IX. Appendix

Froude Scaling Procedures and Model Speeds:

Froude Scaling Laws:

When physical modeling of systems where gravity and inertial forces take precedence over other forces, such as viscous and elastic, Froude scaling is used. Another rule of thumb is that if the object breaks the free surface boundary, Froude scaling should be used over Reynolds number scaling. The definition of the Froude number is the ratio of the inertial forces to the gravity force. The mathematical equation for a Freud number is as follows:

$$Fr := \frac{V}{\sqrt{g \cdot L}}$$

Where

V is the fluid velocity
g is the acceleration due to gravity
L is the comparative length parameter

In order for a model to be Froude-scaled, the model and system must be geometrically similar and have identical Froude numbers.

Flow Meter Operation:

Before use the Marsh-McBirney Flo-Mate 2000 must first be calibrated by placing in still water and waiting for the settings to read zero. The operation of the Flow meter is explained in the following, which was taken from the owner's manual:

> "The Flo-Mate measures flow using the Faraday law of electromagnetic induction. This law states that as a conductor moves through a magnetic field, a voltage is produced. The magnitude of this voltage is directly proportional to the velocity at which the conductor moves through the magnetic field.
>
> When the flow approaches the sensor from directly in front, then the direction of the flow, the magnetic field, and the sensed voltage are mutually perpendicular to each other. Hence, the voltage output will represent the velocity of the flow at the electrodes.
>
> The sensor is equipped with a electromagnetic coil that produces the magnetic field. A pair of carbon electrodes measures the voltage produced by the velocity of the conductor, which in this case is the flowing liquid. The measured voltage is processed by the electronics and output as a linear measurement of velocity."

Test Procedure:

1) Baffle placed at desired depth in water
2) Model placed with correct gap geometry
3) Flume Input set at 47 Hz
4) Marsh-McBirney Flo-Mate 2000 inserted in water to measure flow speed
5) Dye input placed 8 inches from front of bow and activated
6) Dye input shut off and removed from flume
7) 2000 ml of beads are poured into flume at specified location
8) Once all beads have been deployed a mesh barrier is placed in flume to prevent the re-circulation of beads.
9) As last bead encounters bow the motors are shut off
10) Beads enclosed in the baffle region are retrieved and placed in captured pile
11) All remaining beads are in flume are un-captured
12) Beads left to be completely dried to insure continuity of measurement
13) Volumetric measurement of captured beads. Uncaptured beads are then measured and the results are quantified

Test Data:

Notes: 1) Station 1 is 2" below water surface
2) Station 2 is 13.5" below water surface
3) 8 measurements taken at each station
4) Motor speed is 47 Hz for all tests
5) Gap bite is assumed to be 1", unless otherwise stated
6) Gap length is assumed to be 6"
7) ϕ is assumed to be ~ 12°, unless otherwise stated

Test # 1: Original Model

	Speeds (ft/s) ------------------>								Average speed
Station 1	2.03	2.08	2.03	2.15	2.14	2.21	2.04	2.05	2.09125
Station 2	1.79	1.75	1.81	1.77	1.77	1.75	1.53	1.69	1.7325

Initial Bead Volume: 2000mL
Bead Volume Captured: 500 mL
Percentage of beads captured: 25 %
Date Performed: 1/23/01
Date of captured volume measurement:1/25/01

Test # 2: Original Model

	Speeds (ft/s) ------------------>								Average speed
Station 1	2.16	2.13	2.27	2.04	2.05	2.12	1.93	2.1	2.1
Station 2	1.87	1.98	1.91	1.78	1.71	1.79	1.88	1.94	1.8575

Initial Bead Volume: 2000mL
Bead Volume Captured: 600 mL
Percentage of beads captured: 30 %
Date Performed: 1/25/01
Date of captured volume measurement:1/30/01

Test # 3: Extended Plane Model (gap ~ 2", ϕ ~10°)

	Speeds (ft/s) ------------------>								Average speed
Station 1	2.13	2.15	2.09	2.26	2.11	2.25	2.28	2.17	2.18
Station 2	1.91	1.77	1.97	1.92	1.85	1.86	1.77	1.83	1.86

Initial Bead Volume: 2000mL
Bead Volume Captured: 1600 mL
Percentage of beads captured: 80 %
Date Performed: 1/30/01
Date of captured volume measurement: 2/06/01

Test # 4: Extended Plane Model

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.23	2.12	2.09	2.16	2.15	2.06	2.13	2.09	2.12875
Station 2	1.65	1.78	1.64	1.89	1.77	2.03	1.76	1.96	1.81

Initial Bead Volume: 2000mL
Bead Volume Captured: 1050 mL
Percentage of beads captured: 52.5 %
Date Performed: 2/06/01
Date of captured volume measurement: 2/08/01

Test # 5: Extended Plane Model

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.22	2.13	2.24	2.3	2.1	2.18	2.27	2.21	2.20625
Station 2	1.79	1.79	1.73	1.97	1.99	1.89	1.73	1.98	1.85875

Initial Bead Volume: 2000mL
Bead Volume Captured: 1000 mL
Percentage of beads captured: 50 %
Date Performed: 2/06/01
Date of captured volume measurement: 2/08/01

Test # 6: Extended Plane Model (gap ~ 2", ϕ ~10°)

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.03	2.16	2.33	2.17	2.33	2.25	2.27	2.19	2.21625
Station 2	1.89	1.99	1.93	1.84	1.84	1.89	1.89	1.58	1.85625

Initial Bead Volume: 2000mL
Bead Volume Captured: 1600 mL
Percentage of beads captured: 80 %
Date Performed: 2/08/01
Date of captured volume measurement: 2/13/01

Test # 7: Parallel Plane Shrouded Design

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.22	2.34	2.16	2.34	2.16	2.36	2.26	2.34	2.2725
Station 2	1.87	1.94	1.85	1.96	1.79	1.89	1.85	1.83	1.8725

Initial Bead Volume: 2000mL
Bead Volume Captured: 900 mL
Percentage of beads captured: 45 %
Date Performed: 2/13/01
Date of captured volume measurement: 2/15/01

Test # 8: Parallel Plane Shrouded Design

	Speeds (ft/s) ------------------->								Average speed
Station 1	2.33	2.42	2.17	2.26	2.29	2.22	2.24	2.13	2.2575
Station 2	1.91	1.74	1.83	1.91	1.73	1.79	1.9	1.87	1.835

Initial Bead Volume: 2000mL
Bead Volume Captured: 925 mL
Percentage of beads captured: 46.25%
Date Performed: 2/13/01
Date of captured volume measurement: 2/15/01

Test # 9: Preceeding Plane Model

	Speeds (ft/s) ------------------->								Average speed
Station 1	2.24	2.4	2.25	2.28	2.33	2.15	2.17	2.15	2.24625
Station 2	2.11	1.93	1.78	1.8	1.72	1.85	1.9	1.74	1.85375

Initial Bead Volume: 2000mL
Bead Volume Captured in front: 200 mL (10%)
Bead Volume Captured in back: 500 mL (25%)
Total percentage of beads captured: 35%
Date Performed: 2/20/01
Date of captured volume measurement: 2/27/01

Test # 10: Preceeding Plane Model

	Speeds (ft/s) ------------------->								Average speed
Station 1	2.32	2.41	2.18	2.35	2.23	2.38	2.24	2.15	2.2825
Station 2	1.76	1.8	1.86	1.94	1.64	1.77	1.97	1.86	1.825

Initial Bead Volume: 2000mL
Bead Volume Captured in front: 250 mL (12.5%)
Bead Volume Captured in back: 450 mL (22.5%)
Total percentage of beads captured: 35%
Date Performed: 2/20/01
Date of captured volume measurement: 2/27/01

Test # 11: Shrouded Design (2" enterance gap, 4" exit gap)

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.27	2.43	2.33	2.24	2.21	2.39	2.24	2.31	2.3025
Station 2	1.66	1.74	1.86	1.88	1.81	1.85	1.84	1.92	1.82

Initial Bead Volume: 2000mL
Bead Volume Captured: 625 mL
Percentage of beads captured: 31.25%
Date Performed: 2/28/01
Date of captured volume measurement: 3/18/01

Test # 12: Shrouded Design (2" enterance gap, 4" exit gap)

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.32	2.08	2.16	2.22	2.07	2.29	2.31	2.24	2.21125
Station 2	2.06	1.84	1.96	1.97	1.91	1.84	1.85	1.96	1.92375

Initial Bead Volume: 2000mL
Bead Volume Captured: 800 mL
Percentage of beads captured: 40%
Date Performed: 2/28/01
Date of captured volume measurement: 3/18/01

Test # 13: Shrouded Design (2" enterance gap, 1" exit gap)

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.51	2.36	2.23	2.27	2.22	2.11	2.18	2.18	2.2575
Station 2	1.78	1.89	1.92	1.84	1.72	1.79	1.9	1.75	1.82375

Initial Bead Volume: 2000mL
Bead Volume Captured: 1000 mL
Percentage of beads captured: 50%
Date Performed: 3/22/01
Date of captured volume measurement: 3/26/01

Test # 14: Shrouded Design (2" enterance gap, 1" exit gap)

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.2	2.25	2.22	2.17	2.01	2.29	2	2.46	2.2
Station 2	1.89	1.73	1.88	1.85	1.91	1.91	1.84	1.82	1.85375

Initial Bead Volume: 2000mL
Bead Volume Captured: 1050 mL
Percentage of beads captured: 53%
Date Performed: 3/22/01
Date of captured volume measurement: 3/26/01

Test # 15: Shrouded Design (2" enterance gap, 1" exit gap) on Extended Plane

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.18	2.3	2.12	2.03	2.08	2.23	2.18	2.21	2.16625
Station 2	1.73	1.83	1.83	1.82	1.81	1.87	1.73	1.8	1.8025

Initial Bead Volume: 2000mL
Bead Volume Captured: 1500 mL
Percentage of beads captured: 75%
Date Performed: 3/29/01
Date of captured volume measurement: 4/03/01

Test # 16: Shrouded Design (2" enterance gap, 1" exit gap) on Extended Plane

	Speeds (ft/s) --------------------->								Average speed
Station 1	2.16	2.19	2.18	2.15	2.44	2.28	2.35	2.26	2.25125
Station 2	1.84	1.87	1.84	1.91	1.94	1.95	1.91	1.89	1.89375

Initial Bead Volume: 2000mL
Bead Volume Captured: 1400 mL
Percentage of beads captured: 70%
Date Performed: 3/29/01
Date of captured volume measurement: 4/03/01

Average Collection Percentages:

	Average Collection Percentage
Original Model:	27.5%
Extended Plane Model:	51.3%
Extended Plane Model (gap ~ 2", ϕ ~10°):	80.0%
Parallel Plane Shrouded Design:	45.6%
Preceeding Plane Model:	35.0%
Shrouded Design (2" enterance gap, 4" exit gap):	35.6%
Shrouded Design (2" enterance gap, 1" exit gap):	51.5%
Extended Plane Shrouded Design (2" enterance gap, 1" exit gap):	72.5%