DEVELOPMENT OF A RAPID CURRENT CONTAINMENT BOOM:

PHASE III, YEAR 2

TECHNICAL REPORT

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1. INTRODUCTION

1.1 Purpose and Scope

Historically, conventional oil booms have been essential tools in oil spill cleanup efforts. In environments where currents are present, however, booms have often had difficulties containing oil. If the perpendicular component of the relative current speed exceeds a critical value, the oil boom fails. This critical value has been found to be between 0.6 and 1.0 knots depending on the oil's properties. This poses a serious problem since tidal and river currents exceed this critical value in many harbors and ports where bulk oil is handled.

The main purpose of the work described here is to develop a new type of flexible oil barrier which can restrain oil in current speeds 2 - 3 times that of conventional oil booms. This rapid current barrier makes use of a submergence plane concept in which oil is deflected downwards and then is trapped in a large, surface containment region as shown on Figure 1. This report covers the fourth year of a four-year program

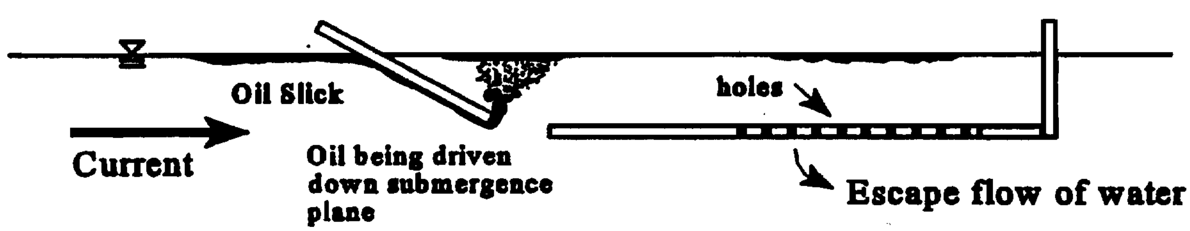

Figure 1. Cross-section schematic of the submergence plane barrier.

(see Table 1) supported by the United States Coast Guard (USCG) and the Minerals Management Service (MMS).

Table 1. Summary of Four-Year Program

PHASE I - USCG funded Year 1
- "Best cross-section shape"
  - Two-dimensional models
  - Recirculating flume
  - Full scale
  - Hard, fixed components

PHASE II - USCG funded Year 2
- "Duplicate best shape in free-floating, flexible system"
  - Three-dimensional representative segments
  - Duplicate two-dimensional cross-section
  - Buoyancy & ballasting, strength
  - Flexible surfaces
  - Flume, tank & estuarine deployment

PHASE III - MMS funded Year 1
- "Design for performance, full width catenary barrier"
  - Parameter optimization
  - Representative segment testing
  - Concept selection
  - Full-width scale modeling
  - Full-width prototype design & construction
  - Tank & Ohmsett testing
- "Plane, vertical barrier failure observations"
  - UNH flume
  - Slick shape recording

PHASE III Year 2 - MMS funded Year 2 (Work described in this report)
- "Commercial Containment Boom"
  - Estuarine and harbor testing
  - Ohmsett evaluation
  - Strength analysis and materials selection
  - New barrier design and construction
- "Plane, vertical barrier failure observations"
  - UNH flume
  - Slick shape recording
  - Draft changes and waves

In the effort covered by this document, the design is carried from the first prototype stage to an upgraded, tested product suitable for commercial production and usage. The design and fabrication work was done in cooperation with JPS/OILTROL - a New Hampshire manufacturer of oil spill response equipment. Field tests included harbor deployment exercises using boats, personnel and a staging area under the management of the Piscataqua River Cooperative which is the consortium of four petroleum product terminals on the fast moving, tidal Piscataqua River, New Hampshire. Oil retention capabilities were evaluated at the Ohmsett facility operated in New Jersey by MMS. Lessons learned in the development and test program were incorporated into the final commercial design. Activities pertaining to the flexible barrier portion of this study have also been described by DiProfio (1998).

A second purpose in the previous year's work was to continue an experimental program to observe and record oil containment failure of standard, vertical skirt oil booms. Tests were conducted using heavy oil in a recirculating flume. Slick profile data sets were acquired in a form suitable for comparison with numerical models, particularly those being developed concurrently at the University of Rhode Island (URI).

1.2 Previous Work

As outlined in Table 1, the first year work (Phase I) resulted in the two-dimensional submergence plane concept shown in Figure 1. This concept has been tested in laboratory flume studies using oils with a wide range of physical properties as described by Swift et al. (1995, 1996) and Coyne (1995). Results showed retention rates above 80% in all cases and greater than 90% under several important high viscosity conditions. The flow speed of these tests was 1 1/2 knots which is at least three times the failure speed of a standard, single, vertical plane skirt of the same draft under similar flume test conditions.

The second year (Phase II) work involved design, construction and testing of flexible, three-dimensional submergence plane representative segments having the proven two-dimensional cross-section (see Swift et al., 1996). The results of the Phase II effort included semi-rigid modules that could be linked and a full-length longitudinal, flexible representative segment. These systems were field tested in estuarine tidal currents using an oil substitute.

Phase III, Year 1 accomplishments began with a study of the effects of draft. University of New Hampshire (UNH) tow tank experiments indicated that an increase in draft led to better containment. A short longitudinal version of the flexible barrier was then developed thereby providing a second flexible system design alternative. Upgraded representative segments (6 - 12 feet wide) of the two alternative concepts were tested at Ohmsett during June, 1997. Though both performed well, the edge was given to the short longitudinal concept for further development.

After preliminary testing using a 1/5 scale model in the UNH tank (to verify shape retention and stability behavior), a full-width (40 feet) flexible barrier prototype was designed and constructed with the assistance of JPS/OILTROL. The 40 foot width (in the cross-current direction) was selected as the largest practical size for Ohmsett testing leaving room for mooring points and not having side effects. In principle, the design could be lengthened (or shortened) in the cross-current direction depending on end use.

Experiments carried out at Ohmsett in August 1997 were very encouraging (see Steen, 1997 and Swift et al., 1998). Tests were conducted using Hydrocal and Sundex oils, used various speeds without waves (mostly) and with a regular wave train having a wavelength selected to provoke maximum water motion and system response. In all tests up to 2 knots, the wake was very clean with respect to oil residue. The best numerical results were 98% retention at 2 knots using the high viscosity Sundex. Speeds were limited by spillover at the aft barrier. Oil loss in waves was also due to slop over the aft barrier as well as forward at the bow freeboard buoyancy position.

Overall, results indicated that the next step, the focus of the work described here, should be to use the full-width prototype as the basis for a commercial design. This version would incorporate increased freeboard as well as upgraded strength features to withstand field deployment.

Also during Phase III, Year 1, UNH conducted experiments in a recirculating flume (see Swift et al., 1998) to observe oil containment failure processes of plane, vertical barriers. Three experiments were carried out in which the shape of the slick profile was recorded using a computerized optical system consisting of a high resolution video camera, a frame grabber and a personal computer with expanded memory. Tests were also recorded using two standard video cameras and 35 mm still photography. The desired "failure by critical accumulation" mode, described by Delvigne (1989), was observed, and computer images were provided to URI for comparison with their numerical models. Remaining questions regarding standard boom failure mechanisms pertained to the effects of draft and waves.

1.3 Objectives

Activities during the Phase III, Year 2 project covered in this report may be grouped into two areas - commercial development of submergence plane technology and the experimental investigation of standard boom failure modes. The major objectives, organized in this manner, are provided below:

High speed current boom development

1. Rebuild first prototype version incorporating design changes to improve performance,
2. Conduct estuarine/harbor trials to investigate handling and deployment procedures (redesign/rebuild prototype as necessary),
3. Conduct oil retention evaluation of the revised prototype at Ohmsett,
4. Design new version incorporating successful changes as well as modifications to improve manufacturing and design life,
5. Construct the commercial, full-width, flexible, high speed current barrier.

Standard oil boom testing

1. Conduct flume tests corresponding to two-dimensional, plane, vertical skirt barriers,
2. Investigate performance variations with draft,
3. Record dynamical effects due to waves.

1.4 Approach

The overall plan for developing the submergence plane, flexible barrier was to use the existing prototype (henceforth referred to as Bay Defender) as the basis for design modifications, test the modified Bay Defender and rebuild depending on the results. Lessons learned, as well as a general upgrading of strength of materials and robustness aspects, would be incorporated into the final design and commercial version (termed Bay Defender II) construction.

The process began with adding freeboard and buoyancy to the aft barrier and to the submergence plane bow. Next, field deployment procedures were investigated in four field exercises completed on the Piscataqua with the help of Piscataqua River Cooperative personnel and facilities. The goal here was to deploy Bay Defender with angled standard boom as lead-ins on each side increasing its effective width. In essence, the hybrid configuration resembled a standard containment configuration with the flexible barrier occupying the critical apex position. Towing dynamic loads, mooring line angles and loads, and buoyancy additions were pre-tested using a 1/5 scale model in the UNH tow tank.

The oil retention capabilities of the modified Bay Defender were then tested at the Ohmsett facility in New Jersey. The device was subjected to various current speed and wave conditions while collecting oil. The percent oil retained was calculated and recorded after each test run.

The design and fabrication of the commercial version began after deployment and oil testing experiments were completed. This allowed for the most complete information to be used in the design. Several 1/5 scale physical model tests were conducted to measure towing and mooring loads which must be reliably sustained by the device. Each major component of the device was redesigned, and new materials for the rigid members were chosen. Commercial vendors contributed high quality fabricated parts to the final version - Bay Defender II.

Standard oil boom experiments were conducted using single vertical barriers and real oil in the UNH recirculating flume. The specialized optical measurement system, standard video and 35 mm photography were used to record two-dimensional test results. Dampening materials, such as that used by Milgram and Van Houten (1978), were used to eliminate losses due to sidewall effects/corner vortices.

Two issues, which came to light in the Phase III, Year 1 work, were the effects of plane barrier draft and the response of the slick to waves. The rigid "skirt" was adjusted vertically between tests to evaluate draft variability. To accommodate wave testing, a wavemaking system was designed and constructed for the recirculating flume. Resolution, field of view and rate of image acquisition issues were addressed by employing three cameras (instead of one as used previously) recording into a central computer.

2. GENERAL CHARACTERISTICS OF BAY DEFENDER

2.1 Key Components

At this point it would be beneficial to have a general description of the key components that make up Bay Defender and their purpose. There are six primary components:

- End longitudinals
- Intermediate longitudinals
- Submergence plane
- Horizontal baffle
- Front reserve flotation
- Containment boom.

Components are identified on Figure 2.

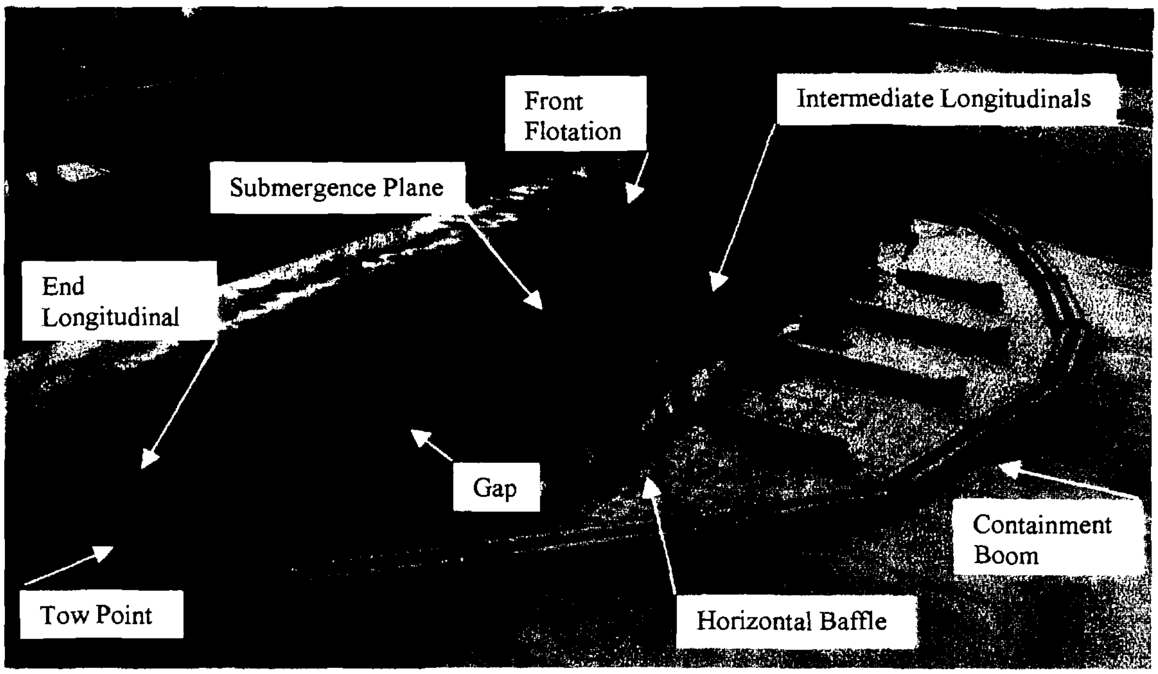

Figure 2. Labeled picture of the 1997 prototype.

2.2 End Longitudinal/Intermediate Longitudinal

The end longitudinals are two of the major components in the strength and shape retention of the device. Each end longitudinal has attachment points for the submergence plane, the horizontal baffle and the rear boom. The primary tow points for the device are located near the middle base of each end longitudinal. These points also serve as mooring points when the device is anchored in the deployed position.

The intermediate longitudinals serve one primary function - maintaining the shape of the submergence plane with respect to the horizontal baffle. They help to ensure that the proper submergence plane angle and gap opening are maintained at all times during deployment. The intermediate longitudinals do not function as strength members.

2.3 Submergence Plane and Horizontal Baffle

The submergence plane and horizontal baffle provide the functionality of the device. As shown in Figure 3 (and previously diagramed in Figure 1). The submergence plane forces the oil to submerge to the gap. Here, the oil enters through the gap and rises into the containment region. The horizontal baffle contains another strength member. Along the leading edge there is a chain that is connected at each end to an end longitudinal. This chain acts as a tension member and bears a large portion of the load when the device is deployed. Holes in the horizontal baffle also provide the exit area for the water flowing through the device.

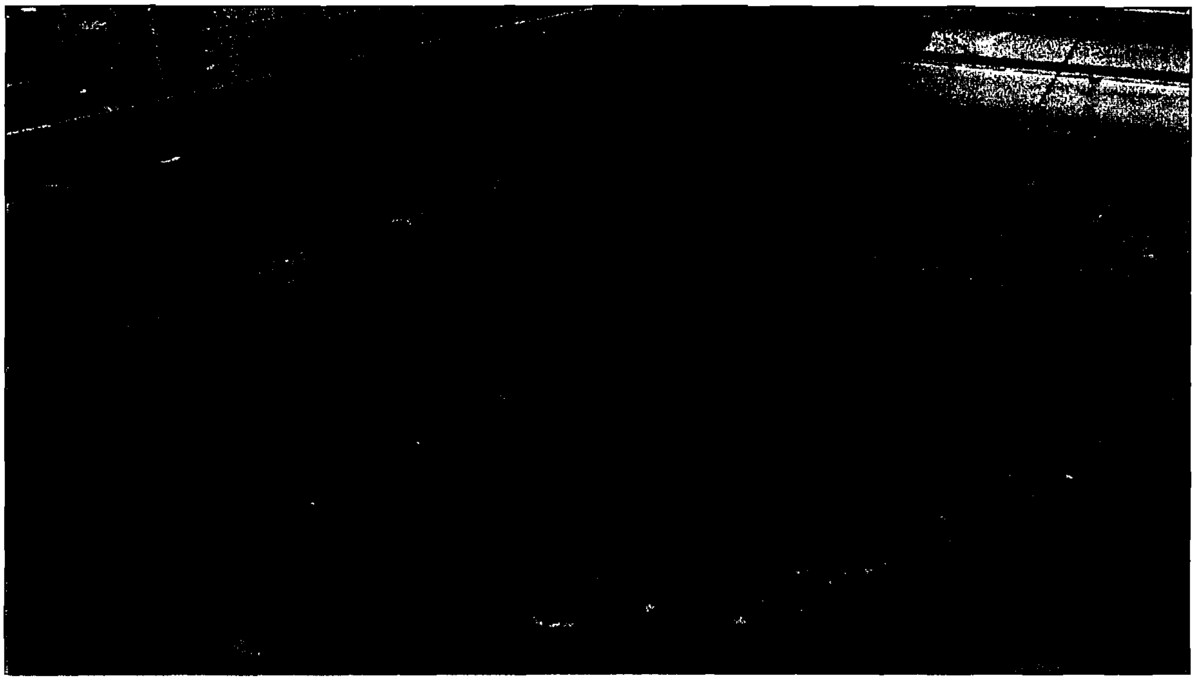

Figure 3. 1997 prototype in action at the Ohmsett testing facility.

2.4 Front Flotation and Rear Boom

The front reserve flotation serves two purposes. The first is as reserve buoyancy in the event that the front end should try to submerge. The second is as a front containment barrier should oil being contained encounter it. The rear boom provides a rear containment barrier and is simply a section of conventional oil boom.

3. PISCATAQUA RIVER DEPLOYMENT STUDY

3.1 Pre-Deployment Design Issues

Prior to the first deployment exercise there were numerous issues that needed to be addressed. Several of these issues were brought to light during the testing of the 1997 prototype. Issues that were addressed were as follows:

- Mooring angle effects
- Significance of the attachment point location
- Proposal for dynamic tensioning
- Front end reserve flotation upgrade
- Rear boom upgrade
- Squaring off of the end longitudinals.

3.1.1 Mooring Angle Effects

When the device is anchored in the deployed position, the mooring line forms an angle with a line parallel to the average axis of the system (see Figure 4). This angle is referred to as the mooring angle and occurs on each side of the device. It was not known what effect, if any, an adjustment of the mooring angle would have on the desired shape of the device in the deployed position. If the mooring line continued the catenary shape formed by the leading edge of the horizontal baffle, the device would naturally assume the correct position. This ideal mooring angle was found to be 18.6 degrees, based on the catenary equations used to determine the shape of the leading edge of the horizontal baffle. If the mooring angles were to become too large, the device would no longer be able to maintain the tensioning required to hold shape, and the front would begin to collapse in upon itself.

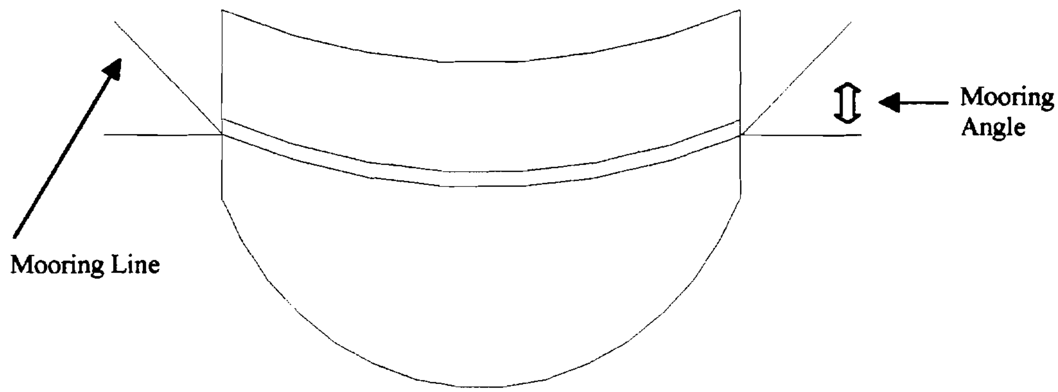

Figure 4. Mooring angle used in model tow tests.

Using a one fifth scale model of the device in the UNH tow tank, Froude scaled tests were conducted to determine the effects of mooring angle on system shape retention. The mooring angles were set to values ranging from 18 degrees to 57 degrees. The device was towed at a constant speed of two knots (full-scale) for each of the angle settings. The tests showed that as the mooring angle became larger, the device began to lose the smooth catenary shape. The leading edge of the submergence plane began to crumple, and the device no longer held the ideal shape. The device did not, however, deform to the extent that there was catastrophic failure. The device retained acceptable shape between the angles of 18 and 50 degrees. The tests showed that mooring angles, while they affected the shape of the device, did not lead to catastrophic failure and that a large region of acceptable angles existed.

3.1.2 Attachment Point Location Tests

The significance of the location of the mooring attachment points was also questioned. Another series of controlled tests were performed to determine the effect the location of the attachment point in conjunction with the changing mooring angle had on the shape retention of the device.

The attachment point of the model (tow points in the tank tests) was moved forward 2.75 inches, which corresponded to a 13.75 inch adjustment on the full-scale prototype. The same testing procedure used in the mooring angle tests was used. The device was towed at two knots (full-scale) for mooring angles ranging from 18 to 57 degrees.

The results of these tests showed an improvement in shape retention throughout the full range of mooring angles. The distortion of the catenary shape at the higher angles with the shifted tow points was noticeably less. By moving the tow point forward, approximately 10 degrees could be gained. Ten degrees was not a significant enough gain to warrant moving the tow point on the full-scale prototype, given the effort that would be involved in such an adjustment.

3.1.3 Suggestion for Dynamic Tensioning

Since the device was to be deployed in a dynamic environment, the question was raised as to whether the environmental conditions could be used to help maintain the proper shape and tension on the device. The idea proposed was to use a vertical wing extending from each end longitudinal, as shown in Figure 5, to catch the oncoming water and force the device to open into the proper shape.

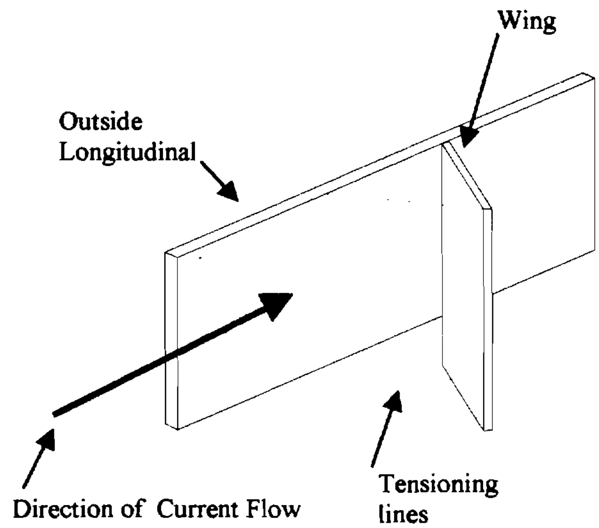

Figure 5 Drawing of wing attached to an end longitudinal to provide dynamic tensioning.

The proposed wings were attached to the end longitudinals of the model, and several tests were conducted. The model was towed at speeds ranging from 1 to 2.5 knots (full-scale). In addition to tests with ideal mooring angles several tests were run with different mooring angles to see if the wings would improve the shape retention at higher angles. The tests showed that the wings tested lacked the ability to create enough fluid dynamic force to make any significant difference in the shape of the device.

3.1.4 Front End Reserve Flotation Upgrade

The front-end flotation on the 1997 prototype consisted of small blocks of rigid, blue housing insulation foam positioned between each of the intermediate longitudinals. It was shown that this amount of flotation was not sufficient to prevent the front end from submerging when subjected to waves. In addition, if oil or contained fuel should reach the front flotation, there were openings between the blocks allowing a breach. Additional blocks of blue foam were added between the existing blocks using small flaps of fabric and zip ties to secure them. This nearly doubled the available reserve buoyancy and provided a much better barrier to front-end breach.

3.1.5 Rear Boom Upgrade

The rear boom used in the 1997 prototype consisted of two 50 foot sections of conventional oil boom having six inch diameter foam flotation. The problem with this arrangement became evident during tests performed in 1997, which resulted in spill over the rear barrier. The solution was to double the volume of flotation and double the existing freeboard. A new rear boom was purchased which had a 12 inch diameter flotation member and did not cause any effect on the deployed shape of the device. Through both the front flotation and rear boom upgrades, the significant limitations recognized in 1997 were addressed.

3.1.6 Front End Re-Design

One possible deployment configuration involved attaching conventional boom directly to the device making a continuous hybrid system. The front edges of the end longitudinals were identified as the obvious choice of attachment points. The 1997 prototype end longitudinals did not support this type of attachment since the front was angled as shown in Figure 6. The new design would square off the front end providing a vertical member that was suited for attachment to conventional boom. The 1997 prototype was modified, and an attachment points provided.

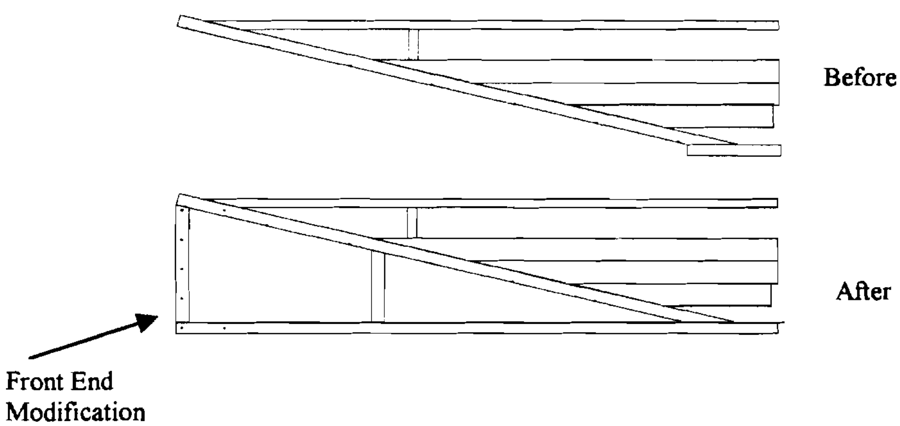

Figure 6 Front of outside longitudinal with and without the attachment.

3.2 First Deployment Exercise

3.2.1 Site and Personnel

The first river deployment exercise was held on April 27,1998 at the Sprague-Newington shipping terminal located on the tidal Piscataqua River. In this area of the river, currents have been measured ranging from 1 to 3 knots during the tidal cycle. The deployment team consisted of an assembly group and boat crews. The boats and pilots were associated with the Piscataqua River Cooperative. The two boats used in the exercise were the Great Bay Responder and the Portsmouth Towing Whaler.

3.2.2. Purpose

The purpose of the first exercise was to answer the most immediate questions involving practical deployment of the device. These were:

- How difficult is the device to assemble?
- Is the device easily maneuvered off the beach?
- Once off the beach is the device easily moved into position?
- How difficult is the mooring process?

3.2.3 Procedure

The exercise was accomplished in 3 phases: assembly, movement into position and anchoring. The assembly was to take place on the bank of the river during low water, which would provide the most beachfront to lay out and assemble the device. One of the boats would be piloted close to shore where a line would be attached to one of the eyebolt tow points on an end longitudinal. The device would then be walked off the beach as it was being towed into the river until it was floating on its own. The device would be towed to the anchoring position where the second boat would attach a line to the opposite tow point and pull the device perpendicular to the oncoming current. Anchors would be attached and the device would be anchored one side at a time, the second side being used to make minor tension and position adjustment.

3.2.4 Results

The complete assembly took one hour and thirty minutes. This was longer than expected and would be unacceptable in an emergency situation. The attachment of the submergence plane and horizontal baffle were particularly difficult. Attachment of the horizontal baffle required two people, one to lift the end longitudinal and another to attach the fabric to the base. The most time consuming procedure was the attachment of the front reserve buoyancy. Each block of foam had to be positioned individually and zip tied securely. There were 26 blocks of foam each requiring 4 zip ties to attach them. The mud from the beach also presented problems, making it difficult to attach nuts without first rinsing the bolts with water.

Movement off of the beach went smoothly with the Great Bay Responder coming close to shore where both the tow line and mooring line were attached. The attachment eye was through bolted to the steel bracket termination for the chain tension member. This was by far the strongest point in the end longitudinal and allowed the system to be towed endwise as shown in Figure 7.

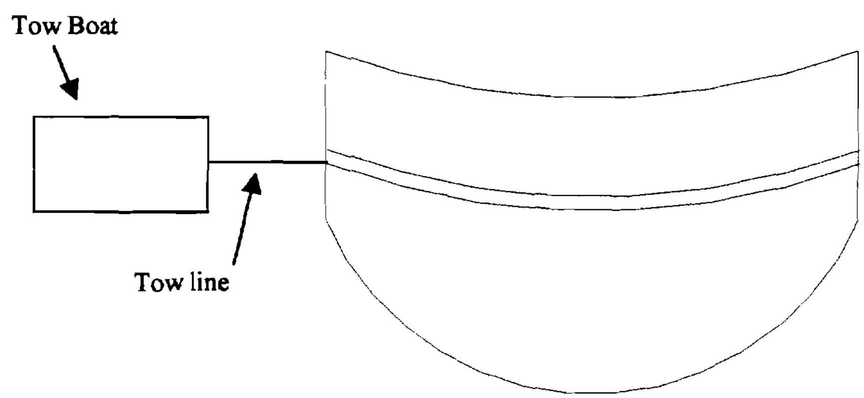

Figure 7 End tow configuration

Problems with towing the device became immediately evident when the lead end longitudinal submerged as the towboat began to accelerate. The device was towed to the deployment position with nearly 1/3 of its full length submerged. The second boat then attached the opposite mooring line and brought the device perpendicular to the oncoming current. The first anchor was released, and after the device was put in tension by the opposite mooring line, the second anchor was released. After the second anchor settled the device was fully deployed. It held shape well and appeared to be adequately tensioned. While in this position, it collected seaweed and other debris that strayed into it's path. This was very encouraging and indicated that functionality in the deployed state had not been sacrificed. Though there were several evident design changes needed, the first deployment exercise was viewed as a success by both the UNH team and the Piscataqua River Cooperative participants.

3.3 Modifications for Second Deployment Exercise

The most critical issue noticed in the first deployment exercise was the submergence of the first 1/3 of the device during tow. A meeting was held between the UNH team and Steve Root, the lead pilot for the Cooperative. Several potential solutions were discussed, and two promising ideas were chosen for further investigation. The first proposal was to attach a bridle to the lead end longitudinal which would angle it much like the bow of a boat in hopes that this would force it to stay on the surface. The second proposal was to add large amounts of reserve buoyancy to counteract the force driving the device under.

The one-fifth scale model was again tested in the UNH tow tank. Before testing could begin, it was necessary to ensure that the model emulated the device when subjected to similar conditions. To this end the model was connected to a vertical tow post extending below the carriage. The towline was secured to the post near the waterline thereby simulating the towboat. The model was towed at speeds ranging from 0.5 knots to 2 knots (full-scale). As expected the model's performance mirrored that of the full-scale prototype with one third of it's length submerging at higher speeds.

The testing of the bridle proposal was conducted first. Two separate bridle configurations were used as shown in Figure 8. The model was towed at speeds ranging from one to three knots (full-scale). It was connected to the tow carriage in the same manner as in the previous emulation tests.

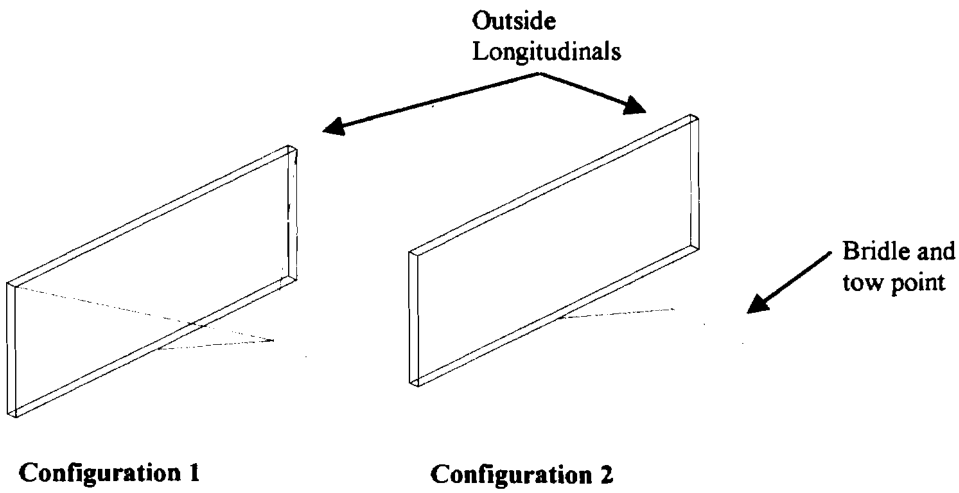

Figure 8 The two different bridle configurations used during the model tests.

The results of these tests showed that the device could be forced to stay on the surface by means of a bridle attachment. Both configurations showed very similar results. When the model was towed at two knots (full-scale), there was significant water flow over the longitudinal. At three knots there was more overflow of the longitudinal, and there was significant bending in upper support. The upper support was not designed as a load bearing member, and bending was undesirable.

The next series of tests involved attaching a proportionally large flotation member to the upper part of the end longitudinal. The first test was performed with a flotation member having a triangular cross section. This was used to reduce drag and help the model cut through the water. The single tow point was used and the model was attached to the carriage in the same manner as the previous two tests. It was towed again at speeds ranging from one to three knots (full-scale).

The results of these tests were very promising. The flotation member proved to be more than adequate in keeping the model on the surface. There was no submergence, and there was no overflow of the longitudinal. With no bridle attached to the upper support there were apparently no undesirable loads being placed on the model.

Because the triangular cross-section might prove to be difficult to manufacture, a simpler square cross-sectional member was used in its place in the next series of tests. While also being simple to manufacture, the square cross-sectional member provided more volume and, therefore, more reserve buoyancy. The same test parameters were used. The results were identical to the previous test.

The reserve flotation member solution was implemented using closed cell industrial insulation. Large blue foam members were purchased from Northeast Building Supplies located in South Berwick, Maine. Typically these members were used as flotation for lake side docks and rafts. An individual member measured 22 inches wide, 10.5 inches thick and 8 feet long. By splitting a member longitudinally the desired cross-section was achieved. Finally the reserve flotation was attached to the prototype end longitudinals using long threaded rods. After these modifications and a day of minor repairs the device was ready for the second Piscataqua River field exercise.

3.4 Second Deployment Exercise

3.4.1 Purpose

One purpose of the second deployment exercise was to validate the end longitudinal flotation modification; secondly, incorporation of conventional oil boom into the system was also desired. The desired effect was an integrated oil containment system to replace the standard, U-shaped containment configuration. Conventional oil boom would serve as lead-ins to the device in the apex position.

3.4.2 Procedure

Prior to the exercise a meeting to formulate a plan was held between the UNH team and Steve Root. The plan of attack was to deploy a pair of 100 foot, six inch draft conventional boom segments in a catenary shape with the apex of the catenary left open as shown in Figure 9. The Bay Defender would then be positioned at the apex perpendicular to the on-coming current.

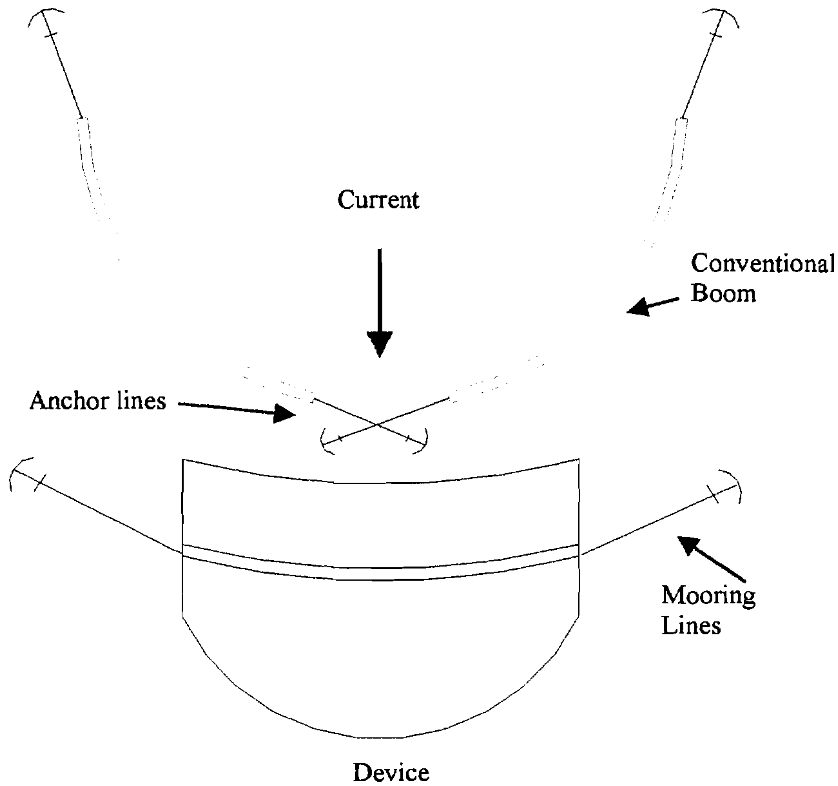

Figure 9 The proposed deployment configuration for the 2nd exercise

3.4.3 Results

The assembly again took approximately one hour and thirty minutes. During the assembly, the Great Bay Responder and the Portsmouth Towing Whaler positioned the conventional boom. Positioning of each 100-ft. section proved to be a more cumbersome task than first anticipated. There was significant difficulty in positioning the apex in the correct location. It was only through superior piloting skill that the boom was finally positioned.

The GB Responder then pulled the device, with assistance from the team members on shore, off the beach and into the river. The device was towed to the deployment position at the apex of the conventional boom with no difficulty. The modified flotation on the end longitudinals prevented the device from submerging while towing, which in turn allowed for greater tow speeds. Once in position the Whaler picked up the tow line on the opposite side and brought the device perpendicular to the current and down-current of the apex. The GB Responder released anchor first. The device drifted a small amount and then stabilized. The Whaler then released anchor, and it's side of the device drifted significantly. Bay Defender came to rest canted at approximately a 45 degree angle to the current and no longer covered the apex of the conventional boom.

The problem was that the anchor was sailing considerably with the current before it would grab the bottom of the river. The Whaler made a second attempt, this time moving past the perpendicular position in hopes of compensating for the drift. To move past the perpendicular the tow line and the device had to be brought almost over one leg of the apex. At one point the end longitudinal tow point and the connector on the conventional boom became entangled, and it took nearly thirty minutes to release the device. Finally on the third attempt the device was positioned in a less then perfect, but adequate position.

There were two obvious problems that needed to be addressed prior to the third deployment exercise. The first was the problem of positioning the conventional boom. The second was the sailing anchor issue which caused the device to stray from the correct position.

3.5 Third Deployment Exercise

3.5.1 Purpose

The purpose of the third deployment exercise was to achieve an easily executed deployment that did not depend on pilot skill. The course of action should also be insensitive to current variability.

3.5.2 Procedure

Another meeting was held, and deployment strategies were again discussed. Two modifications were suggested. The first was to deploy the conventional boom as a single unit by connecting the apex with a line and a single anchor. The second was to run lines from the lead edge of the conventional boom to the tow points on the device to hold it in position. The theory was that the new stabilizer lines would prevent the device from drifting and the side mooring lines could be used primarily for tensioning as shown in Figure 10.

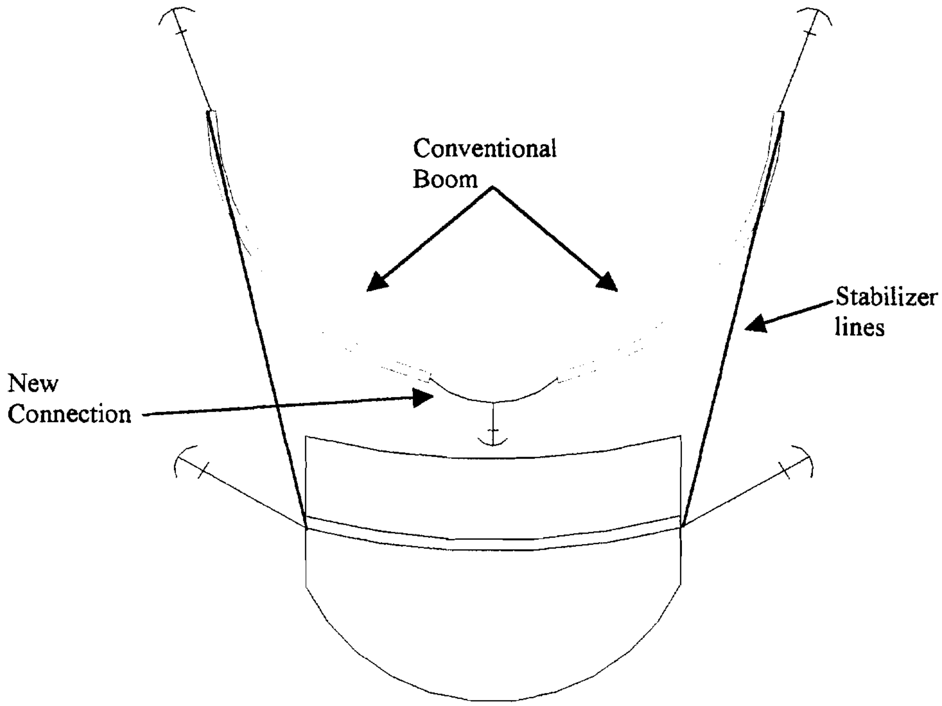

Figure 10 Improved deployment configuration for the 3rd exercise.

Each of these modifications was made. The deployment procedure was the same as the previous second exercise. The conventional boom would be set first, and the device would be moved into position and attached to the conventional system then tensioned with the mooring lines.

3.5.3 Results

In this exercise the assembly took only one hour. This improvement was attributed to practice. The conventional boom was attached as proposed and brought out for deployment. Each boat took one leg of the attached boom and set the lead ends. The apex anchor was then attached at the center of the apex line and released. Once the boom settled there was significant J'ing at the apex. J'ing refers to boom planform shape forming the letter "J" rather than a gradual curve. It was apparent that the tension on the apex anchor was not sufficient, and several attempts were made to improve the shape. The shape finally obtained did not remove the J'ing completely but was adequate.

The device was towed to position without event. With each boat holding a tag line from each end longitudinal, the stability lines from the conventional boom were attached to the device simultaneously. The device collapsed inward when it was released to the stability lines. There was not adequate tension to straighten out the submergence plane. The side anchors were attached, and the first anchor set attempted. The anchors continued to sail with the current similar to the last exercise. The pilots were unable to deploy the device in the correct position. There were several setbacks during the exercise including one anchor line being cut because of entanglement and one crown line caught in the prop of the Responder. A heavier anchor was attached to one side of the device in an attempt to reduce drift. This attempt was also an improvement, but since the tidal current was diminishing to slack water the exercise was concluded without a successful deployment. The closest attempt had the device deployed canted and off center of the apex.

It was apparent that a new approach was needed. By deploying the conventional boom and the device separately, there were too many variables, and the skill required by the boat pilots was too great. A new method had to be found that incorporated the conventional boom into the device so that they could both be deployed simultaneously.

3.6 Fourth Deployment Exercise

3.6.1 Purpose

In the fourth deployment exercise the primary objective was to execute a new deployment plan that allowed for simultaneous deployment of both the conventional boom and the device. The plan needed to be simple in execution and not rely on skilled boat pilots for implementation.

3.6.2 Procedure

The course of action chosen was one that had been anticipated from the beginning of the project. The conventional boom would be attached to the front of each end longitudinal as shown on Figure 11. This measure had not been taken before because it was feared that there might be some catastrophic failure of the end longitudinals or the submergence plane due to the forces applied when the 100-ft sections were attached.

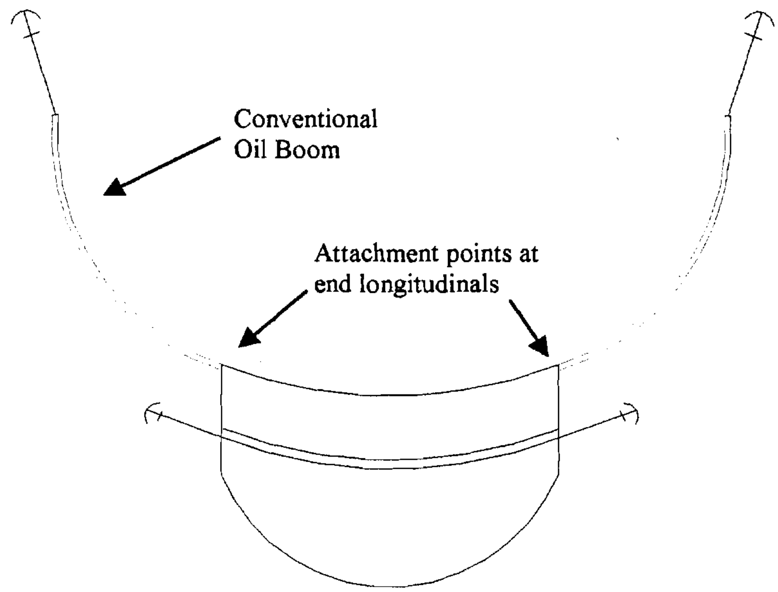

Figure 11 Physical attachment of conventional boom with the device.

To guard against the submergence plane failing in tension, webbing was added to the sides and corners to strengthen the material. The attachment mechanism would be a piece of fabric approximately one and a half feet in length bolted to the end longitudinal at one end and connected to the conventional boom with an ASTM Z-connector at the other (see Figure 12).

The conventional boom was to be attached while the device was just off the beach and from there be towed to the deployment position. At that point the second boat would retrieve the end of one of the boom sections and anchor it. While the first boat still held the device with the tow line the second boat would take the second leg of boom and bring the device perpendicular to the current and set the anchor. At this point the device would be held by the lead-in boom, and the device could be tensioned with the side mooring lines.

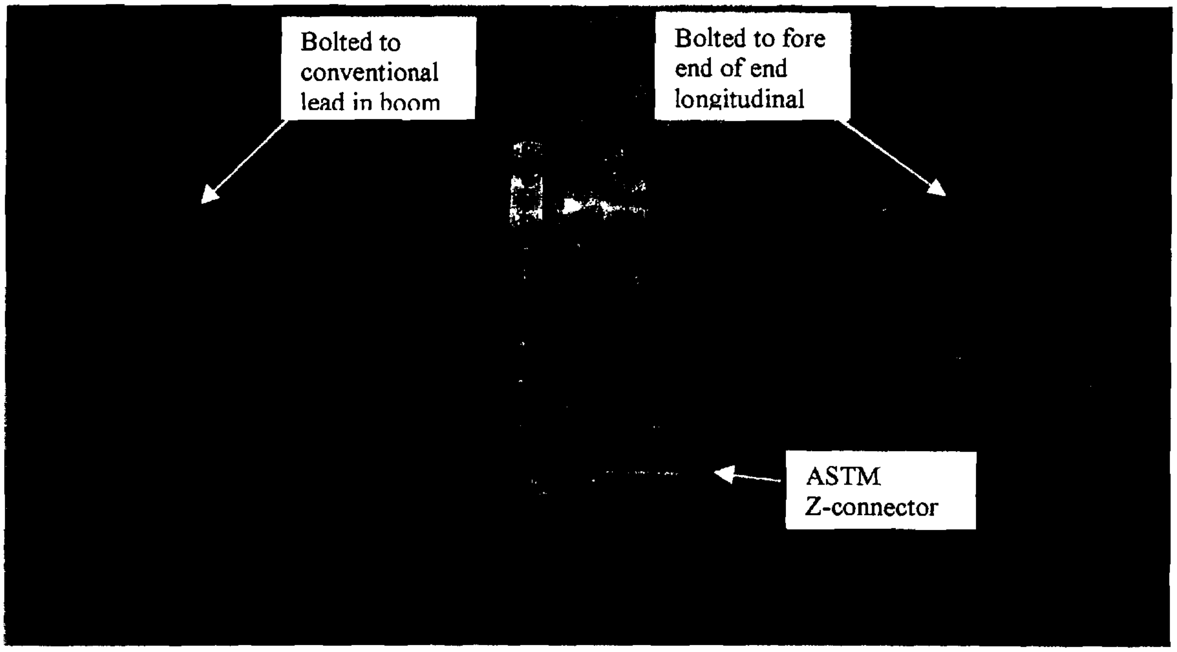

Figure 12 Front-end connector for joining conventional boom to the device.

The major concern with this plan was the tensioning. It was unclear whether the device would collapse in on itself. Preparations were made to provide additional tensioning to the mooring lines using a 2 ton come-along and a specially modified mooring line with loops to hook onto. In case the device required greater tension a come-along on each side could be used to bring the device to the proper shape.

3.6.3 Results

Assembly of the device (during rain) was not timed in this exercise. Once the device was assembled and floating, the Great Bay Responder brought over the two 100 ft. sections of conventional boom. They were attached to the device with the Z-connectors, and the device was towed off shore by the Whaler. The device was towed to the deployment position, where the Responder retrieved and set one of the 100ft sections of boom. With the Whaler still holding the device with the towline, the Responder retrieved the second length of boom and brought the device perpendicular to the current and set the anchor. As the device was being brought around the Whaler slacked off the towline until the full drag force on the device was being held by the conventional boom lengths. The tension that the J'ing of the booms applied to the device proved sufficient enough to open it to the deployed position. The device was essentially deployed without the use of the side mooring lines. The side mooring lines were then set to provide more tensioning bringing the device to a near perfect position for oil containment. Figure 13 shows the device in its fully deployed position with the conventional boom incorporated.

Figure 13 Fully deployed Bay Defender with conventional boom integrated.

3.7 Deployment Conclusions

It was the overall objective of the deployment study to find a simple, rapid means to deploy the Bay Defender prototype. With the fourth exercise that means was found. When the boom is attached to the front of the device the handling and positioning become very simple. Maneuvering in this configuration does not require expert pilots, unlike the skill level needed to maneuver in the first three exercises.

There was one other key issue that arose during the exercises. The assembly of the device needed to be significantly simplified if the device was ever going to realistically be used in an emergency. Several key areas that needed improvement were: the attachment of the front flotation, attachment of the submergence plane and horizontal baffle and the use of zip-ties for securing the rear boom and front flotation. The time and manpower required to attach these components was unacceptable. The front flotation was composed of 26 different fabric and foam pieces. The attachment of this component alone took over 25 minutes. Simplicity should be the key to any future assembly and is essential if time is to be kept to a minimum.

The deployment study was looked on as a success by both the UNH team and the Piscataqua River Cooperative participants. The desired incorporation of the prototype with conventional boom into one system was achieved. The study demonstrated the Bay Defender's practical merit as an emergency response system in a rapid current tidal area.

4. OHMSETT OIL RETENTION TESTS

4.1 Purpose

The third objective of this study was to test the oil containment capability of the newly modified device. To do this the device must be subjected to conditions that would best represent actual oil collection conditions. It was important to find out if the modifications made to the 1997 prototype during the deployment exercises decreased or enhanced the performance characteristics of the device. The UNH tow tank could not support the Bay Defender prototype and is not equipped to utilize real oil. For this reason the outdoor tow tank located at Ohmsett in New Jersey was used. The Ohmsett tank has both the capacity and oil use capability to accommodate the Bay Defender.

4.2 Ohmsett Organization

The Ohmsett tow tank is operated by the Minerals Management Service (MMS) through a contract with MAR Inc.. The tank is located on the northern coast of New Jersey and is an outdoor facility. Figure 14 shows a planform diagram of the Ohmsett facility (Steen, 1997). The tank is 666 feet long, 65 feet wide, 11 feet deep and holds 9.84 million gallons of brackish water. The facility is equipped to handle actual oil studies and is utilized by many commercial oil barrier manufacturers for prototype testing. There are three narrow tow carriages, referred to as bridges, positioned along the

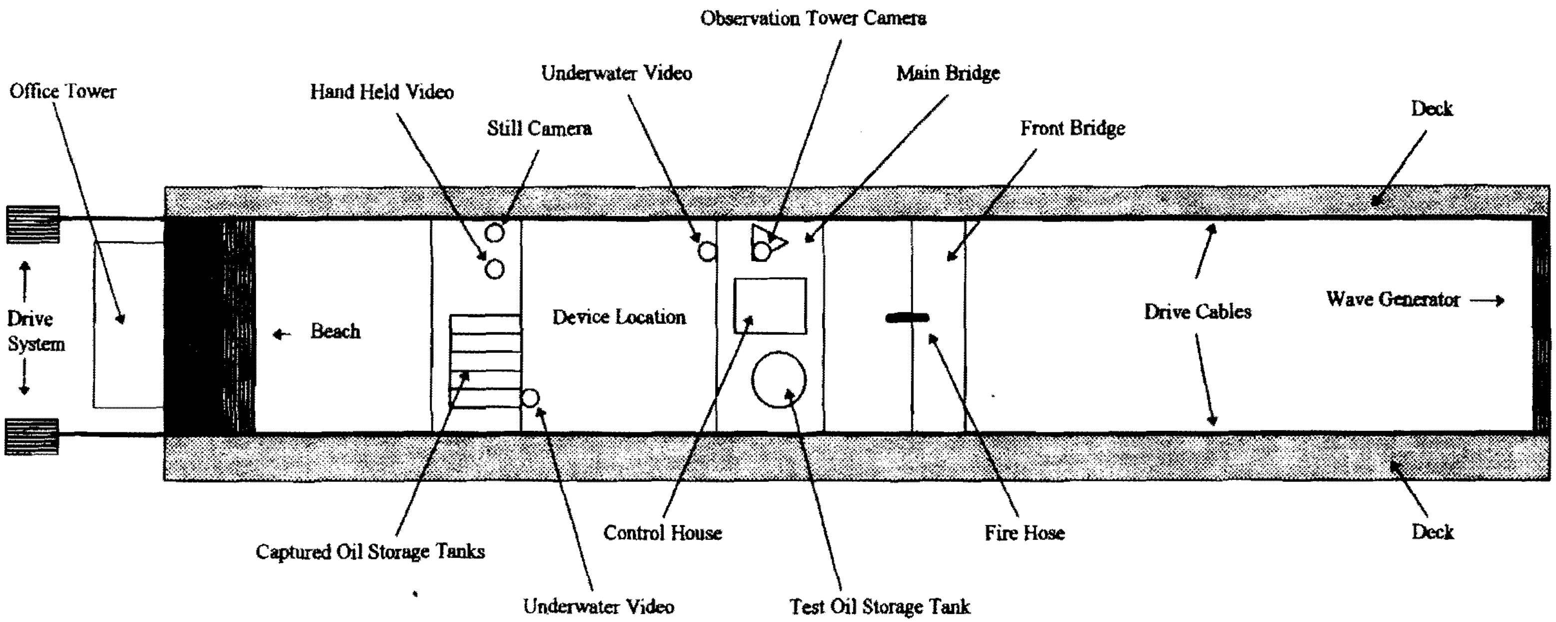

Figure 14 Ohmsett configuration, not to scale (Steen, 1997).

length of the tank. They are connected to a cable drive system that runs along both sides of the tank. Each bridge can be independently positioned. The cable drive system is capable of tow speeds ranging between zero and six and a half knots. The tank is also equipped with wave making capabilities. Measurement of oil recovered is conducted using recovery tanks and chemical analysis. The oil contained within the device at the conclusion of a run is pumped into a recovery tank where it is allowed to sit. Once the majority of water has separated from the oil, it is decanted off the bottom of the tank. A sample of the oil is taken for chemical analysis to determine the percentage of water and other material still present in the recovered oil. Using this analysis, the amount of oil recovered is determined. Once the amount of oil recovered is known, it is recorded as a retention percentage by dividing by the amount of oil introduced during the run and multiplying by 100 (Steen, 1997; Swift et al., 1998). Properties of the two oils commonly used in testing at Ohmsett, are given in Table 2.

Table 2 Characteristics of common oils used at the Ohmsett testing facility.

Oils	Kinematic Viscosity (centistokes)@ 20 C	Specific Gravity	Interfacial Tension (dyne/cm)	Surface Tension (dyne/cm)
Sundex	20,000	0.955	34.4	35.5
Hydrocal	190	0.897	25.9	33.6

Tests are administered by the test director and a team of Ohmsett employees. Each run is video taped and logged. At the conclusion of testing Ohmsett assembles a packet and sends video and oil recovery data to the client organization.

4.3 1998 Ohmsett Tests

The issues that were brought to light in the 1997 Ohmsett tests were the catalysts for the first work done during the preparations for the deployment study. The front reserve flotation and rear boom upgrades were direct results of the observations made. As was stated before, the gaps that existed in the front flotation were filled with additional foam members, and the rear boom buoyancy and freeboard were doubled. These were the two major design differences that were seen as having a direct effect on the outcome of the tests. The addition of the side flotation members and the squaring of the end longitudinals were also in place for the Ohmsett tests, but were not expected to impact the results in any way.

There were three specific objectives that were sought after during this series of tests. The first was to ensure that the modifications made during the deployment study did not detract from the performance of the device. The second was to show that the front and rear flotation upgrades limited washout during wave testing. The third was to shift the maximum oil retention speed up to between 2.5 and 3 knots with the new rear boom upgrade.

The 1998 prototype was brought to Ohmsett July 13, 1998 for experiments conducted over a five-day period from Monday through Friday. Weather conditions were not a factor in the test schedule. The system was first assembled on the side of the tank and slowly lowered in with the help of the Ohmsett team. Ohmsett had replaced the tow posts used in 1997 with newer posts. This caused some initial concern since it was unsure if the same test condition could be obtained. The device was tensioned between the new posts in the same manner as the 1997 tests (see Figure 15). The same test protocol was observed, and the same oil retention measurement procedures were used.

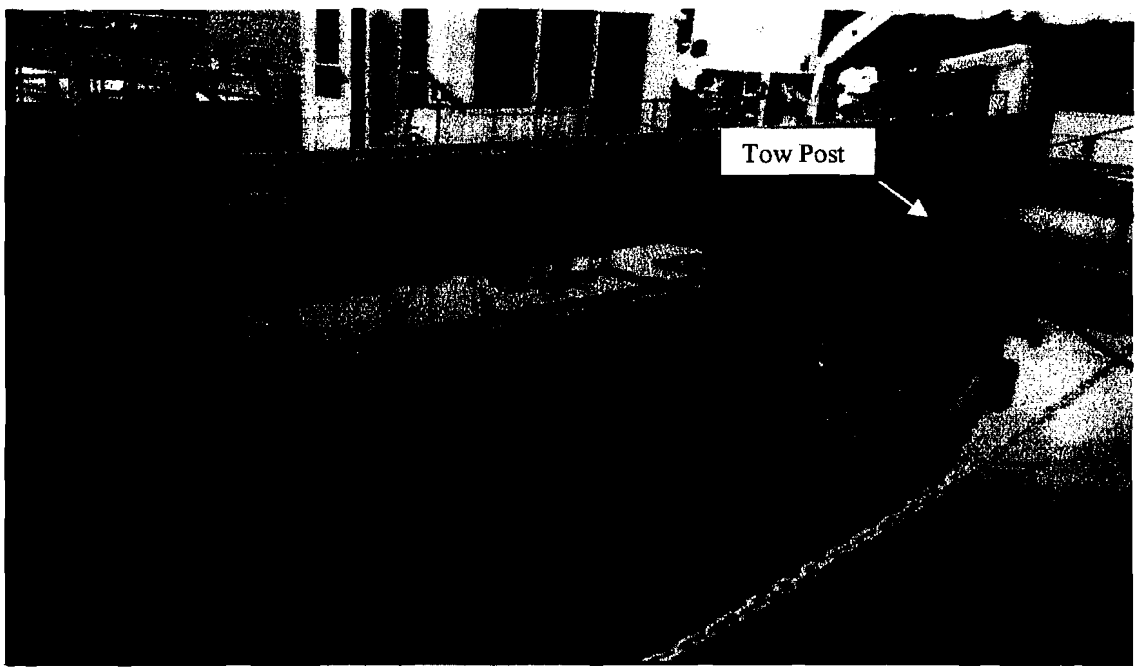

Figure 15 1998 Bay Defender prototype with upgrades positioned for testing at Ohmsett.

There were 23 runs made with tow speeds ranging from 1 to 2.5 knots. Wave tests were conducted with a wave height of 0.5 feet and a period of 2.61 seconds. The first three test runs and the very last run were hydrodynamic observation runs and were not oil retention tests. Each oil containment test was repeated at least once to provide some form of test redundancy. Each oil retention test consisted of a run at constant speed with oil deployment to the water surface in front of the device. Once the device was brought to a halt at the end of a run, the recovered oil was removed to the bridge recovery tanks where the samples were taken and volumes measured.

4.4 1998 Test Results

The 1998 test results were also very encouraging with some oil retention percentages just slightly higher than 1997 and some slightly lower. The maximum tow velocity with little or no flow over the rear boom was found to be 2.25 knots with complete failure between 2.4 and 2.5 knots. See Table 3 for tabulated average oil retention percentages.

Table 3 Oil retention results for 1998 Ohmsett tests.

Test Number	Oil Type	Tow Speed (knots)	Waves	Ave. Retention Percentages
4,5	Sundex	1	No	82.40
6,7	Sundex	1.5	No	87.15
8,9	Sundex	2	No	87.79
10,11	Sundex	1.5	Yes	90.61
12,13	Hydrocal	1	No	90.735
14,15,22	Hydrocal	1.5	No	81.23
16,17,20,21	Hydrocal	2	No	46.95
18,19	Hydrocal	1.5	Yes	77.30

There was significant improvement in the wave handling characteristics. There was no noticeable "wave slop" over either the fore or aft barriers during any of the wave runs. While retention of heavy oil (Sundex) remained excellent, containment of light oil (Hydrocal) at two knots was disappointing.

4.5 Ohmsett Test Conclusions

The test results, while encouraging, were not as exceptional as were hoped for. One interesting result in the oil retention data was the low values obtained for Hydrocal at two knots. In the previous year a retention of 77% at two knots was obtained. The better retention obtained in the 1997 tests may be due in part to cooler temperatures. The higher temperatures during these tests reduced the oil viscosity, which is known to inhibit submergence plane performance (Swift et al., 1996).

Because of the poor results in the initial two Hydrocal runs at two knots, there were two additional runs made. During the initial tests, it became apparent that the device might not have been sitting as low in the water as the 1997 prototype. After reviewing the video of the 1997 tests, this concern was validated. Extensions were manufactured and attached to the posts to lower the device to the level of the previous year. The second two runs of Hydrocal were at this lower level. The results were still lower than expected. The submergence plane appeared to be planing up causing water to rush into the device at higher speeds than were expected. These higher speeds then affected the horizontal baffle area where the contained oil was caught in vortices that formed at the rear boom and exited out the back of the device. One possibility was that there was not adequate exit area which caused the vortices to form and the oil to escape. Another explanation might have been in the condition of the slick itself. When the oil was introduced to the water it did not remain as a contiguous slick, but instead it broke into clouds of droplets which reduced its ability to rise in the containment area. Releasing the oil above the water level higher than in 1997 may have contributed to slick dispersal.

The second interesting result was the maximum effective tow speed of only 2.25 knots. The rear boom upgrade doubled the reserve buoyancy, so greater top end speed had been anticipated. After discussion amongst the UNH team, the problem appeared to be one of continuity. The flow into the system did not seem to match the flow out of the system. This was causing the water to gather at the rear boom and eventually overwhelm it. The exit holes in the horizontal baffle, however, provide more than two times the area of the entrance gap. This meant that the holes near the front of the baffle were not being utilized by the exit flow. One solution would then be to increase the exit area at the extreme rear of the containment area.

The increase of both the fore and aft flotation did effectively eliminate the problem of "wave slop". These were features that would definitely be incorporated into the new commercial prototype.

5. COMMERCIAL PROTOTYPE DESIGN AND MANUFACTURE

5.1 Design Rationale

The next logical step in the evolution of the Bay Defender study was to design the first commercially viable system using the results of both the deployment study and the tests at Ohmsett to define the design criteria. The key criteria which were decided on were:

- Deeper draft from 12 inches to 15 inches
- Adjustability of gap opening and aft exit area
- Continuous front flotation
- Improvement of side flotation members
- Use of more durable materials.

The maximum oil retention speed of 2.25 knots from the Ohmsett tests was disappointing. The previous modification had been to increase the rear boom buoyancy and freeboard in an attempt to discourage rear wash out. With only the small gain in speed, it was shown that merely increasing freeboard and buoyancy could not solve the problem. As mentioned before the problem then became one of continuity. The exit holes in the horizontal baffle were not providing enough exit area, and the water was seeking alternate routes of exit, primarily over the rear boom. The proposed solution for the commercial device was to have an adjustable exit area at the barrier's apex. If the device was going to be subjected to speeds of greater than 2.25 knots, then the rear apex could be opened to provide a larger exit area.

Another proposed adjustable feature for the commercial device would be the gap opening. In the previous year's tests, video taken of the gap opening during test runs showed significant amount of oil missing the gap altogether and eventually rising at the front exit holes in the horizontal baffle. By adjusting the gap, specifically the vertical distance from the base of the submergence plane to the leading edge of the baffle (or the bite), the opening can be set to maximize capture of oil which was previously bypassing the gap entirely.

The time needed to assemble the front flotation during the deployment exercises was unacceptable. The proposed solution for the commercial device was the design of a continuous front flotation member. Thus reducing the need to assemble 26 individual flotation components. By making the front barrier continuous, there would also be minimal oil escaping during extreme wave conditions.

The side flotation for the 1998 prototype was effective, but was not very durable. The foam used was standard blue insulation foam and had a tendency to soak up limited amounts of oil. This was undesirable, and more appropriate foam, as well as a more aesthetic appearance, was requested.

Over the two years of testing, the prototype took a tremendous amount of abuse. The effects were readily apparent in the dilapidated appearance of the end longitudinals and intermediates. The commercial device would need to be constructed from much more durable, as well as stronger materials, primarily the end longitudinals and intermediates. The submergence plane and horizontal baffle would need to be reinforced to prevent tearing at tension points.

5.2 Design and Construction

Design of the commercial system primarily involved improving on the existing system using new, stronger materials and using components that were not expendable after a single use. Each major component was either replaced entirely or modified to fit the new design.

The two end longitudinals are major structural components of the Bay Defender system. For this reason strength and durability were a primary concern in their design. The material chosen for the new end longitudinals was 6061-T6 aluminum. Aluminum was chosen specifically for its strength and ability to be used in the marine and river environments. It was also chosen over other materials, such as wood or fiberglass, based on cost, strength and manufacturing issues. The primary structural members were box beams 2 inches by 3 inches with 1/8 inch thick walls. The new longitudinals are slightly longer than the previous design to incorporate the new 15 inch draft. Each end longitudinal uses aluminum chambers built in for it's flotation. The longitudinals were made independently stable with the use of these chambers and lead ballast. The tow point is a steel eyebolt bolted at the point adjacent to the leading edge of the horizontal baffle.

The primary difference between the new and old end longitudinals (besides the material) is the attachment points for the submergence plane and the horizontal baffle. Aluminum angle stock welded to the side of the longitudinal serve as the attachment point base. This removes the need for the longitudinal to be picked up for attachment of the fabric. The bolts used to attach the components are left in place and do not have to be removed during attachment. This saves time and prevents the bolts from being dropped in the mud and becoming difficult to handle. Figure 16 shows the end longitudinal. See the Appendix for technical drawings.

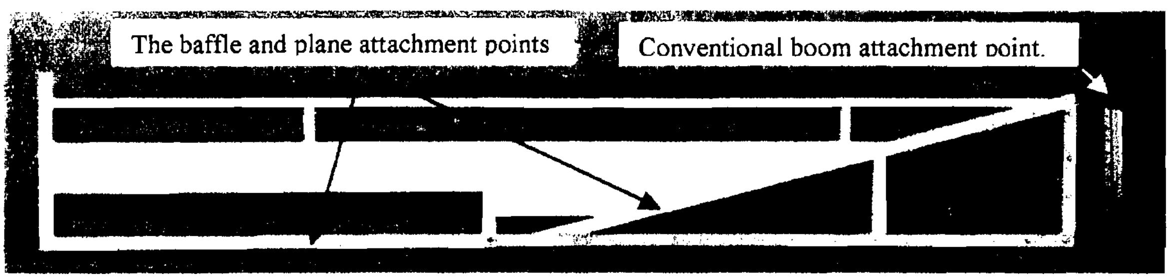

Figure 16 A completed end longitudinal. The longitudinal's frames were built by Custom Welding and Fabrication located in Northwood, NH.

The intermediate longitudinals also went through a complete redesign. Again aluminum was used for durability and corrosion resistance. The desire was to remove all exposed foam flotation from the longitudinals to increase the durability and lower maintenance. Unfortunately in the case of the intermediates, it was not cost effective to design and build aluminum flotation chambers for each one. Instead new foam was chosen to replace the existing foam. The previous foam was blue house insulation foam, and was attached using standard wood glue. The wood glue did not hold the foam in place very well when the foam was subjected to any outside force (i.e., fire hoses used in the Ohmsett tests). In addition, this foam was quite brittle and would break when force was applied. The new foam is not rigid and is held on both with an epoxy compound and long thin rods bolted at each end to prevent the foam from breaking away should the epoxy fail.

The adjustability of the bite (vertical distance from the rear edge of the submergence plane to the leading edge of the baffle) was incorporated into the intermediates. A telescoping tube/pin arrangement, as shown in Figure 17, allows for the leading edge of the horizontal baffle to be lowered increasing the bite.

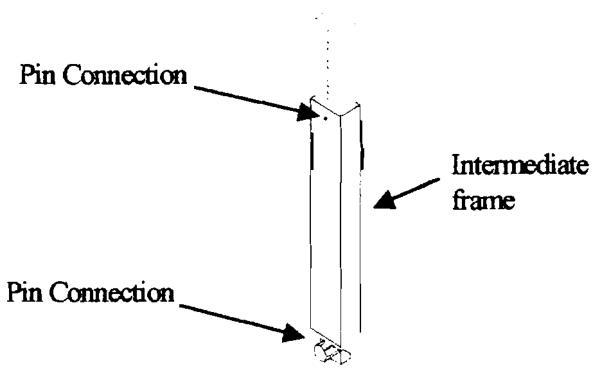

Figure 17 AutoCAD rendition of the telescoping tube/pin arrangement.

Attachment of the intermediate to the rest of the device is accomplished with two standard bolts and pin at the leading edge of the horizontal baffle (see Figure 18).

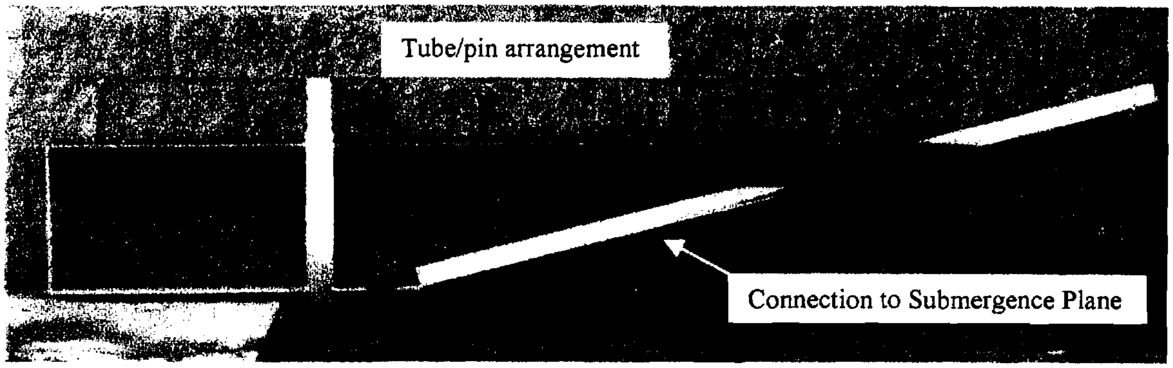

Figure 18 A completed intermediate longitudinal. The intermediates were built by Custom Welding and Fabrication.

The front flotation was the most drastically changed of all the components. The foam members and fabric flaps were completely omitted. A four-inch diameter inflatable tube providing 234 lbs. of reserve buoyancy replaced the foam. The flotation is encased in a pocket that is a continuation of the submergence plane. The pocket is secured using stainless steel snaps. This new flotation is continuous and should eliminate any leakage from the front of the barrier. The omission of the individual fabric flaps, the 26 foam pieces and the need to use zip ties will drastically improve the assembly time of the device.

The side flotation was merely bolted to the side of the earlier prototype, and the foam was subjected to significant wear during the deployment exercises. A comprehensive search did not yield a more acceptable substitute. Since the existing foam would have to be used, it would need to be protected. The new side panels for the longitudinals would be designed to incorporate the foam into them. The foam would be encased in the fabric protecting the foam from both wear and oil.

A new submergence plane and new horizontal baffle were cut from large pieces of fabric provide by JPS/OILTROL, Inc. Webbing was also used to strengthen the submergence plane at its critical points. Steel grommets were used as connection points to the end longitudinals. The fixed exit area in the horizontal baffle remained twice that of the inlet area at the gap.

The existing rear boom was modified to accommodate the deeper draft by adding three inches to the skirt length. The adjustability of the apex exit area was designed into the rear boom. An adjustable rope-lacing configuration was used as shown in Figure 19. The rope can be loosened at the top of the boom and the apex will open according to how much slack is permitted in the line. The boom can also be fixed in place using standard steel quicklinks, which are used in the non-adjustable portion of the boom. The quicklinks were used to replace the zip ties in the previous design.

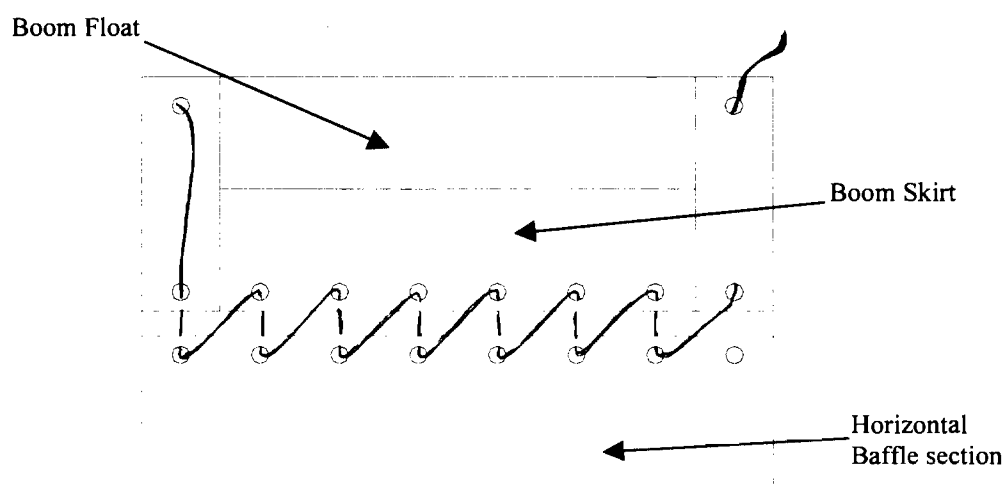

Figure 19 Section of boom showing the rope lacing used to adjust the apex.

One other modification was made to the old design. The end longitudinals and the intermediates in the previous design were angled inward and stayed perpendicular to the catenary curve of the submergence plane and horizontal baffle. In the commercial prototype they were positioned parallel to the current. This was done to make design, construction and assembly easier.

5.3 Dynamic loading tests

The materials chosen and the design used for the commercial prototype were seen as more than adequate to handle expected loads. However, for completeness some simplified strength calculations were performed. To perform these calculations it was important to understand what loads the new device would be subjected to. This question prompted several dynamic loading tests. The tests (Froude scaled) were performed using the 1/5 scale model in the UNH tow tank.

There were two configurations of the device identified during the deployment study that would subject the device to its greatest loads. The first is when the device is being towed from the tow point (approximately midway) on the end longitudinal. The second is when the device is towed by one of the lengths of boom attached to the fore end of one of the end longitudinals.

During the tow tests, it became apparent that the physical model would not withstand the full range of speeds that were required to determine the loads wanted. In addition the loadcell available had a maximum load of 10 lbs. To determine the loads desired several runs were made with speeds ranging from 0.5 to 2 knots (full-scale), and loads were measured using the loadcell. Theory was then used to extrapolate within the range of interest.

From dimensional analysis, the drag force on an object is given by

$$D_f = \tfrac{1}{2}\,\rho\; C_D\, A\, U^2 \quad . \tag{1}$$

In this equation, D_f is the drag force, C_D is the coefficient of drag, U is the speed of the tow, A is the area seen by the fluid, and ρ is the density of the fluid medium.

If the area is considered to be constant throughout the tests, then the drag coefficient and the area can be combined into one term S. Using the drag forces obtained from the loadcell during the test it is possible to obtain a value for S. Then using the average value of S, it is possible now to determine the drag force produced by any speed desired. A maximum speed of 6 knots was chosen for the strength calculations. This value represents the device being towed, for example, at three knots against a three-knot current.

Maximum loads on the end longitudinals could then be calculated. At a speed of 6 knots the tow point on the longitudinal was found to be subject to a load of approximately 3,000 lbs. If towed from the corner of the end longitudinal by a length of boom, the applied load was determined to be approximately 10,000 lbs.

The areas of concern for the tow load of 3,000 lbs. are the eyebolt, which will be in direct tension, and the end longitudinal structure which will be put in bending as the tow load is applied. The eyebolt selected is rated for a working load of 5,200 lbs. which provides a factor of safety of about 1.7 (in addition to the manufacturer's factor of safety).

To simplify calculation of the bending stress produced in the end longitudinal, it was necessary to make several assumptions. The first assumption was that the submergence plane and horizontal baffle act as a distributed load along the longitudinal putting it in static equilibrium with the tow load. A shear force and bending moment analysis was then done, and the maximum bending moment was found. From this maximum bending moment it was possible to calculate the resultant bending stress and compare that to the yield stress of the material. A cross-section of the entire structural longitudinal at the location of the highest moment was used in the calculation of the resultant bending stress. The bending stress was found to be 13,700 psi. The yield stress of aluminum is between 38 and 40 ksi. A detailed derivation of this analysis can be found in DiProfio (1998).

Two factors should be taken into account when considering the last analysis. First the chosen tow speed of 6 knots is fairly large in relation to the expected tow speed of between 2 and 3 knots. The second is that while it shows that the longitudinal as a whole will withstand the load, there may be some localized stress issues. If the base beam itself is assumed to withstand the entire load, the resultant bending stress nears the yield stress of the material. For this reason it is recommended that a small reinforcing bar of approximately 1/4-inch aluminum be welded beneath the tow point.

The critical components of the corner configuration, subject to the 10,000 lb. tow load, are the fabric of the submergence plane, the conventional oil boom and the ASTM Z-connector used to attach the boom to the device. The submergence plane fabric is reinforced by 2 inch nylon webbing, which is rated to 12,000 lbs. in tension. The oil boom fabric is rated to 500 lbs/in. The webbing reinforces over 20 inches of oil boom fabric, which alone can withstand the corner load. Failure of the submergence plane or oil boom fabric are, therefore, not of critical concern.

The Z-connector would be subjected to two possible modes of failure, failure in tension and failure in shear. When subjected to the 10,000 lbs. load, the normal stress produced in the connector is approximately 2.5 ksi. When the shear component is calculated, the shear stress is found to be approximately 1.3 ksi. There is, consequently, no concern of the Z-connector failing.

The results of this analysis show that the commercial prototype was designed to handle the expected loads. The 1997, 1998 prototype underwent the deployment exercises with no failures due to excessive loading, and the new commercial prototype is built with stronger, more durable materials. Failure of the device due to excessive loading is not expected.

5.4 Costs

While it is difficult to project manufacturing costs because of the differences in possible manufacturing procedures, it is possible to give the cost of materials and fabrication of major components of the prototype. Steps taken to reduce the cost of the prototype included avoiding the use of custom-made material components, (instead, using standard dimensions of aluminum tubing) and the use of commonly found fasteners. Another step was to avoid using external paid labor in fabric work and final assembly; what could be done in-house was. Once the components were received from the vendors it took approximately 54 man-hours to complete construction. Table 3 shows the breakdown of components, their cost and their supplier, as well as the total cost of the prototype.

Table 3 Breakdown of cost and suppliers of individual components.

Item	**Supplier**	**Cost**
End Longitudinal	Custom Fabrication and Welding	$1500
Intermediate Longitudinal	Custom Fabrication and Welding	$2110
Horizontal Baffle and Submergence Plane (Fabric and Webbing)	JPS/OILTROL Inc.	$1000
Rear Boom	American Boom and Barrier Corp.	$600
Front Flotation	Slickbar Inc.	$230
Side Flotation	Northeast Building Supplies	$162
Intermediate Flotation	UFP Technologies	$248
Miscellaneous (fasteners etc.)	--------	$300
Total		**$6150**

6. STANDARD OIL BOOM FAILURE EXPERIMENTS

6.1 Purpose and Approach

The purpose of this part of the research program was to generate data detailing how standard oil booms ultimately fail to hold oil slicks as current speed is increased. The data was to be processed to a form useful to URI for comparison with their numerical models for the interaction of oil slicks with standard booms. Though there have been many experimental studies of these processes done in the past, none provide the detailed documentation needed for a rigorous comparison with the more recent Grilli et al. (1996, 1997) two-dimensional computer simulations. High resolution slick thickness measurements, as a function of position and time for a complete set of recorded fluid properties, environmental parameters and boundary conditions, were needed.

The focus of this work was on high viscosity oils since disasters often involve unrefined product or oils that have been subject to weathering. Experiments by Delvigne (1989), using a wide variety of commercially important oils, show that oil booms fail to contain high viscosity oils by a process of "failure by critical accumulation". This failure mode, therefore, was of principal concern. In this study, any additional failure mechanisms brought to light in wave action experiments were also of interest.

The approach was to conduct experiments in the UNH recirculating flume, which has clear plastic sides at the test section for observing slick profiles. The intent was to achieve two-dimensional slick geometry with no variation across the flume. The UNH recirculating flume, shown schematically in Fig. 20, is 12.2 m (40 feet) long, 1.22 m (4 feet) wide and 1.22 m (4 feet) in overall height. The flow is driven by two counter-rotating propellers, which are powered by two variable speed electric motors. The flume has recently been upgraded in an extensive effort conducted by Rule (1999). Sources of ambient turbulence have been reduced considerably, and the motor power was increased allowing a higher maximum flow speed. The system was calibrated so that flow speed was known as a function of motor frequency which was precisely controlled electronically. This facility is dedicated to oil spill research, and is routinely used with petroleum products.

Three experiments using real, high viscosity oils were carried out on May 20 and 21, 1999. A plane, constant draft panel positioned vertically across the tank, represented the standard oil boom/skirt configuration. In the first two experiments, the height of this panel was changed between tests to assess the effects of draft. In the third experiment, waves were introduced to observe the dynamical effects of monochromatic (regular) wave motion. Slick profile shapes were recorded using a computerized optical system consisting of three high-resolution video cameras, a frame grabber and a personal computer with expanded memory. Experiments were also logged using a standard video camera placed to view the slick continuously. Still pictures were taken of major activities, observations and events using a 35 mm camera.

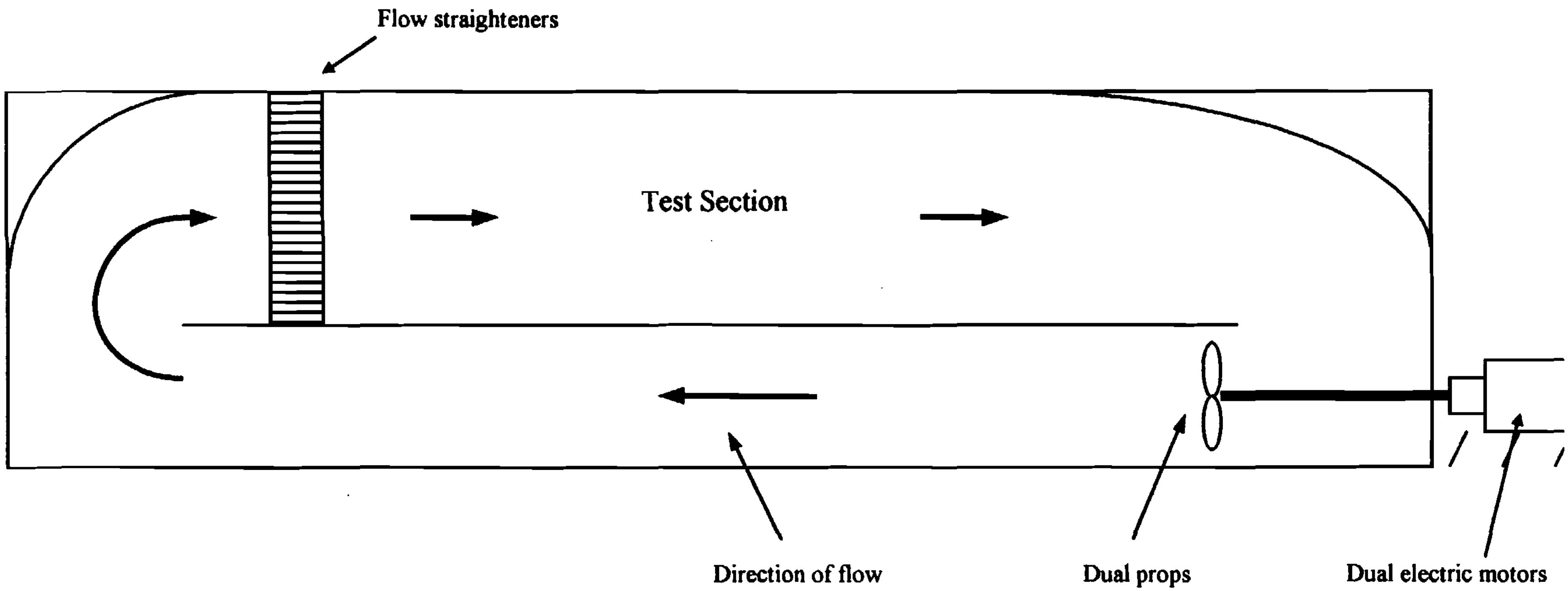

Figure 20 Schematic of the UNH recirculating flume.

Recorded profile images were then examined and processed. Software was written and used to compute thickness as a function of position. Descriptions of the experiments and final image processing products were communicated to the URI team.

6.2 Oil Experiment Methodology

Oil experiments were completed in the UNH recirculating flume using the set-up shown in the Figure 21 photo. The plane barrier across the flume was 3.8 cm deep

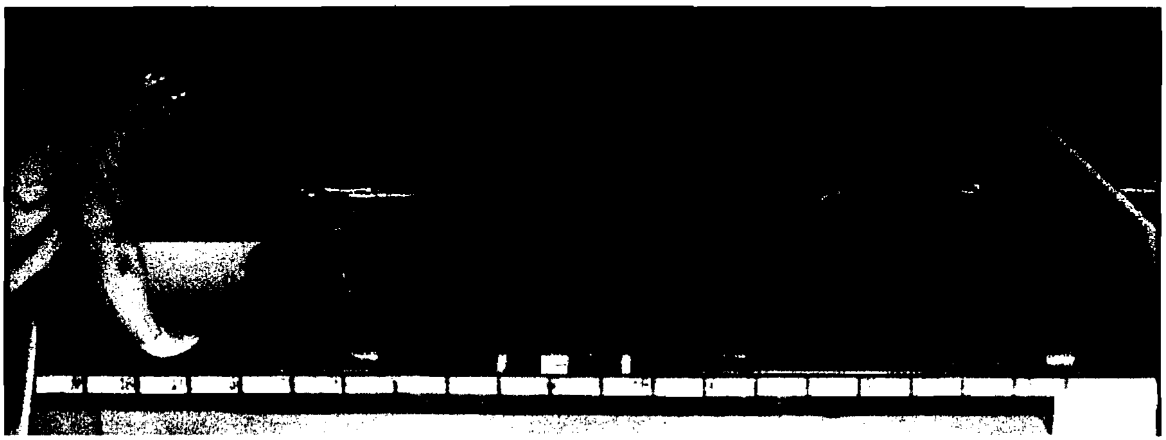

Figure 21 Graduate student J. Belanger setting up the oil slick in the flume. The Horsehair panel barrier can be seen to the right.

in Experiment 1 and 6.4 cm deep in Experiments 2 and 3. Initial slick length (in the direction of current) was much larger than the barrier draft in order to avoid the effects of a stagnation region just up-current from the barrier. The problem of corner vortex generation was dealt with by placing synthetic horsehair in front of the barrier as suggested by Milgram and Van Houghton (1978). A uniform layer of horsehair extended the full width of the flume and at the full draft of the barrier. The horsehair was 20 cm long in the direction of the current and was hung from horizontal rods inserted into the vertical panel. In these tests, the horsehair layer itself was regarded as the leading edge of the barrier.

Experiment activities were logged by a standard video camera placed on the near side beneath where the Figure 21 photo was taken. The camera was mounted on a tripod and was run continuously during the experiments. Color still photographs were taken of significant events and processes using a 35 mm camera. The slick profile against the near side clear plastic tank wall was recorded by three high resolution video cameras with output directly to a computer. Heavy, high viscosity Sundex oil was used in all three experiments. This oil's properties (specific gravity of 0.96 and kinematic viscosity of 18,000 centistokes) are within the range of oils for which oil loss would be due to "failure by critical accumulation". A volume of 21.8 l was used in each test providing an initial slick length of approximately 2 m. Parameters for the three experiments are summarized on Table 4.

Prior to the oil experiments, the flume was recalibrated using a laser doppler velocimeter and (as a check) by timing neutrally buoyant particles. Calibration was achieved by relating measured steady state flow velocity to the frequency set on the AC electric motor speed control. A common time was established by placing a clock within view of the side cameras. Water/oil temperature was recorded for each experiment.

Table 4 Parameters for the oil experiments in the UNH flume.

Parameter	Experiment 1	Experiment 2	Experiment 3
Channel Width (m)	1.22	1.22	1.22
Water Depth (cm)	75	75	75
Barrier Draft (cm)	3.8	6.4	6.4
Oil Volume (liters)	21.8	21.8	21.8
Temperature (deg C)	21	21	21
Water Density (g/cm^3)	1	1	1
Oil Density (g/cm^3)	0.96	0.96	0.96
Oil Kinematic Viscosity (centistokes)	18,000	18,000	18,000
Oil-Water Surface Tension (dynes/cm)	34	34	34
Wave Height (cm)	None	None	7.5
Camera Speed (frames/sec)	1/12	1/12	30.0

Markers were placed every 10 cm along the flume rail for reference, and the position of the horsehair/barrier was clearly distinguished from the black oil by placing a contrasting white sheet of paper over the horsehair end area.

The use of three cameras solved the field of view/resolution trade-off problem that compromised previous measurements made using a single camera. The cameras were positioned in a row to view the slick profile from the side. Each camera's field of view was set to cover an overlapping section of the initial slick length. The black and white signals entered the frame grabber via lines normally used for red, blue and green during color photography. Thus simultaneous data acquisition of the three input signals was accomplished using a single computer system.

Images were continuously recorded during Experiments 1 and 2 using a relatively slow sampling rate (yet much faster than the time scale of slick evolution). In Experiment 3, because of the wave dynamics, the frame speed needed to be much faster. In order to not overload the computer's RAM, burst sampling was employed. In all experiments, distance calibration information was obtained by recording a solid black 5 cm diameter circle placed on the tank wall near the slick profile.

A specially designed and fabricated wavemaker was used to generate single frequency (regular), propagating surface waves. The wavemaker was of the hinged flap type and was mounted at the upstream end of the test section to produce wave trains propagating in the direction of the current. Because the current flow also needed to pass through the wavemaker position, the paddle was ventilated as described by Turmelle et al. (1999). Essentially, the paddle surface consisted of horizontal slats hinged to the paddle frame. The slats opened on the back stroke while closing to push water ahead on the forward stroke. In practice, the system produced reasonable quality propagating waves over a limited range of frequencies and wave heights. In Experiment 3, wave height was 7.5 cm, while wavemaker frequencies were 1.3 Hz and 1.5 Hz for, respectively, current speeds of 9 - 13 cm/s and 15 - 17 cm/s.

The experiments started by deploying the oil while flow speed was 7 cm/s - a gentle drift with just enough movement to form the slick as it came against the barrier. Flow speed was then increased to 9 cm/s and slick image data recording began. Subsequently, flow speed was increased in 2 cm/s steps. In Experiments 1 and 2, optical data was taken continuously, while in Experiment 3, a burst of data was acquired at each step in speed. When the oil moved beneath the horsehair/panel, the barrier was considered to have failed, and the experiment was terminated.

6.3 Observations

In all experiments, Sundex oil was introduced to form the slick while the flume ran at 7 cm/s (just fast enough for the oil to collect in front of the barrier). Initially, the slick was approximately 2 m long and 1 cm thick. Some secondary flows persisted preventing a completely ideal two-dimensional situation. The speed was then increased in increments of 2 cm/s to a maximum speed of 17 cm/s (which was observed to be the critical velocity). After each speed increase, observations were made as the slick deformed. Because of the viscosity (18,000 centistokes), deformation processes were very slow with time scales on the order of minutes.

Slick behavior patterns in Experiments 1 and 2 (without waves) were nearly identical despite the draft difference, and both were very similar to previous Sundex experiments described by Swift et al. (1998). As the current speed was increased above 12 cm/s, the slick was compressed and the characteristic thickening of the leading edge or "head wave" was formed. Early in the experiment, there were also occasional downward protrusions. These never grew to the point of breaking off, and eventually the slick underside stabilized.

In general for speeds below 16 cm/s, the speed step increase would introduce slick compression and a change in profile shape (including headwave growth). The profile would then eventually come to equilibrium. Above 16 cm/s, dynamics, though very slow, were continuous. Waves would form at the oil-water interface, evolve and move oil volume towards the barrier.

At the highest speed, 17 cm/s, well-defined, scalloped waves formed, grew and transported oil mass towards the horsehair/panel barrier as shown in Figure 22.

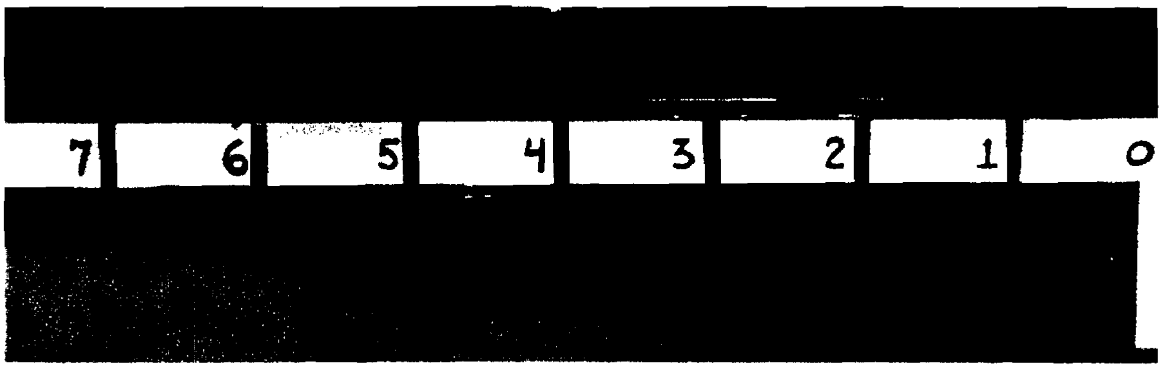

Figure 22 Scalloped wave growth at the oil-water interface.

When wave crests (downward) moved under the horsehair portion of the barrier, the barrier was considered to have failed and the experiment was concluded.

In general, Experiments 1 and 2 showed slick lengths, profile shapes and velocities at failure that were well within the range of "critical accumulation" results presented by Delvigne (1989). Though critical velocities were the same in Experiments 1 and 2, failure actually occurred in less time in Experiment 1 compared to Experiment 2. Since draft was less in Experiment 1, the time needed for oil thickness growth to reach barrier depth was reduced. Both Experiments 1 and 2 served to confirm results seen in previous UNH plane barrier tests using Sundex (Experiments 1 and 3 of the Swift et al., 1998, study). In the previous work, however, flume speed had been further increased to 20 cm/s, though scalloped wave growth had been evident by 17 cm/s. The additional velocity resulted in steeper, more pronounced, scalloped waves and generally accelerated the "failure by critical accumulation" process.

The presence of incident, water surface waves in Experiment 3 added a new failure mechanism in addition to the basic processes described for Experiments 1 and 2 with currents only. Waves did not seem to substantially alter the underlying slick form (shaped by the current) but added a small-scale dynamical structure superimposed on the basic shape.

Essentially, the leading edge of the slick could not follow the surface wave motion of the water, so water began to slop on top of the slick. Water collected in small, randomly distributed pockets. The water pockets, being heavier than the oil, sank through the slick creating large downwards protruding bubbles as illustrated in Figure 23.

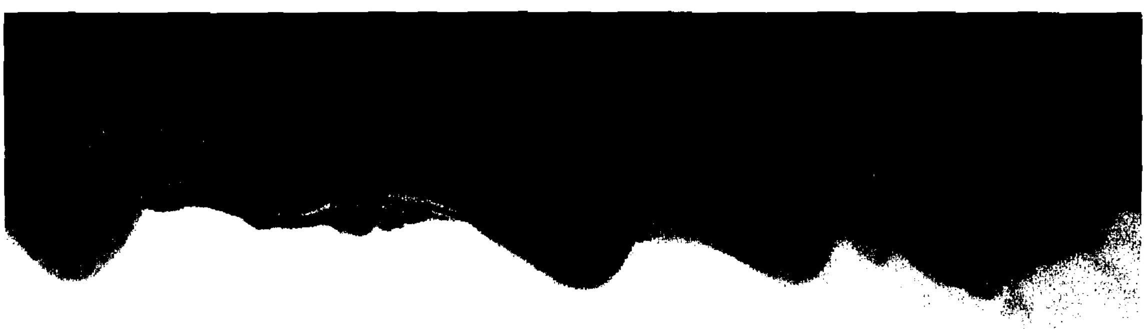

Figure 23 Downward protruding "bubbles" containing pockets of water. View looking up towards bottom of slick.

The bubbles were randomly distributed in position and time as well as in size. Eventually each water-filled bubble burst downwards leaving a hole as seen in the Figure 24 photo.

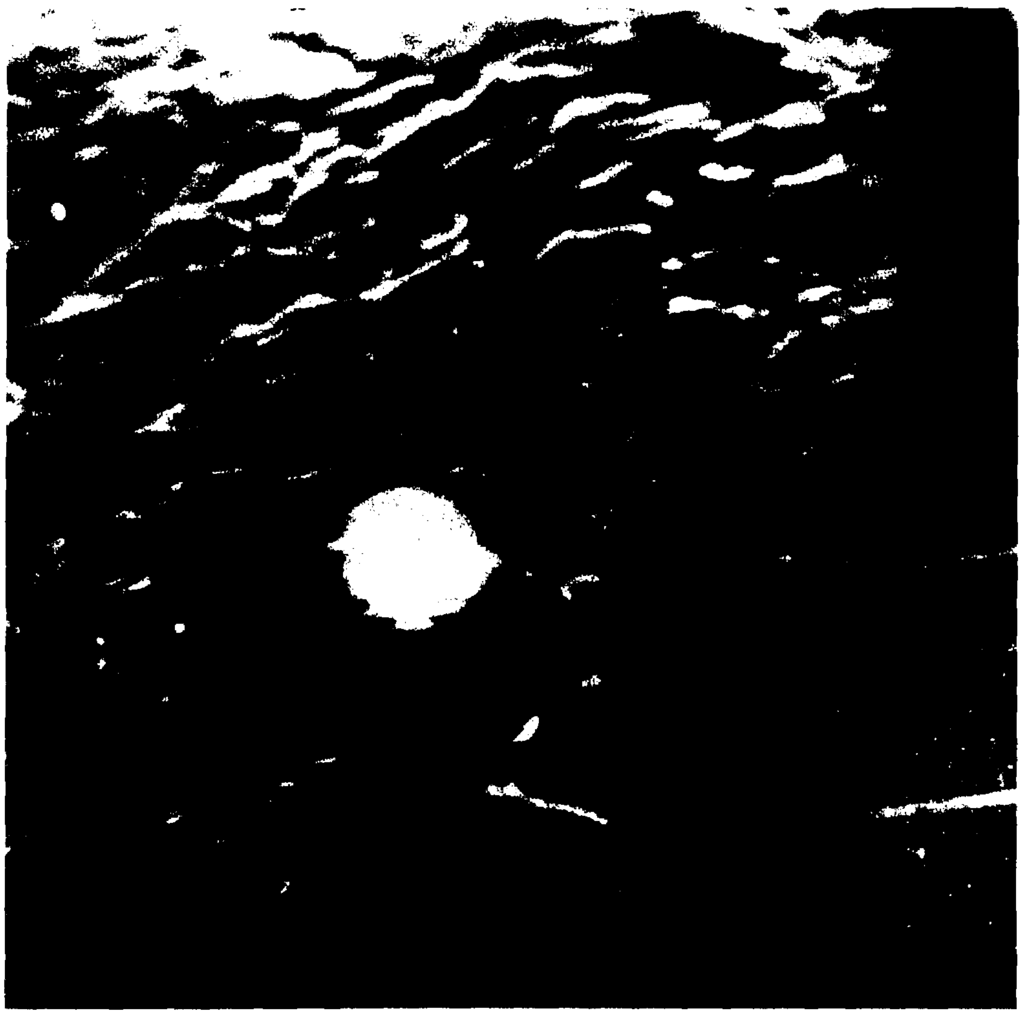

Figure 24 Hole left when bubble bursts downward. View is down towards top of slick. Horsehair barrier is to the right.

The burst bubble's oil remnants were carried by the full force of the current towards the barrier. This was significant as a transport mechanism contributing to oil thickness build-up at the barrier which eventually resulted in oil leaking under the bottom.

6.4 Image Data Processing

The optical measurement system acquired a sequence of images from each camera with each image stored as a separate file. The time assigned to each image was the start time of the sequence (logged separately) plus the image file count number multiplied by the sampling interval. Each image file consists essentially of a 484 pixels by 768 pixels array with each position assigned a gray scale number from 0 to 256. Image data sets were analyzed using MATLAB written programs. The images may also be displayed, printed and edited using other commercial digital image software (such as Microsoft Paintbrush).

Each digital image of slick profile shape (corresponding to the time the frame was taken) was processed to yield thickness as a function of horizontal position. The first step was to define the gray scale criterion for what is dark enough to be considered part of the slick and what is light background. Analysis then proceeded column by column identifying the cumulative vertical length (in pixels) occupied by the oil. Horizontal position-thickness values within overlapping field of views of adjacent cameras were then discarded. Non-overlapping results from the three cameras were merged. In addition, a calibration process was carried out to convert lengths in pixels to lengths in cm. Black 5 cm circles, mounted on the tank sides, were included in each camera's field of view for this purpose. The final products were slick profile shapes, one for each time step, in the form of thickness (in cm) as a function of horizontal position (in cm).

Analysis was accomplished using computer programs written at UNH in MATLAB, and final products were archived in the form of MATLAB data files. Thus the extensive capabilities of the MATLAB commercial package are easily applied for viewing and any further analysis desired. Final slick profile products were provided to the URI modelers for comparison with their simulations.

7. CONCLUSIONS

7.1 Flexible Barrier/Bay Defender

The work presented here has shown that a full-width, flexible, oil barrier, based on the submergence plane concept, can replace conventional oil boom in areas where currents are present. Field experiments on the Piscataqua River, NH demonstrated that practical deployment of the device can easily be accomplished by oil spill response personnel. The new barrier, retested at Ohmsett, is capable of retaining heavy oil at speeds 2 to 3 times the failure velocity of conventional oil boom. The most recent, "commercial version" is robust, easily stored, transported and assembled. The system is not expensive to manufacture and makes use of common materials - most of which are fabric and foam similar to those used in conventional oil boom.

Extensive future use in field exercises and incorporation into spill contingency planning are anticipated. The next step may be to extend the length of the system beyond 40 feet, possibly to span over 100 feet, thus having the capability to secure a larger rapid current area during an emergency.

7.2 Plane Barrier Experiments with Oil

Observations of standard oil boom "failure by critical accumulation" in steady currents yielded results consistent with previous laboratory work by Delvigne (1989) and

Swift et al. (1998) but provided much more detail regarding actual slick profile shape. The processed data was put in a convenient form for comparison with corresponding numerical models.

The two different draft settings generated nearly identical observations and critical failure velocities. It is expected that this is generally true unless draft is so small that drainage failure occurs first or slick length is too short relative to draft (thus putting the oil in a stagnation region). It should be noted that for heavy, high viscosity oils, processes are very slow, taking several minutes. As pointed out by Milgram and Van Houghton (1978), tow tanks may have insufficient length to provide the necessary run time.

In the wave experiments, a new mechanism transporting oil mass towards and eventually under the boom has been identified. The contribution of this failure mode in rough seas may be considerable.

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APPENDIX

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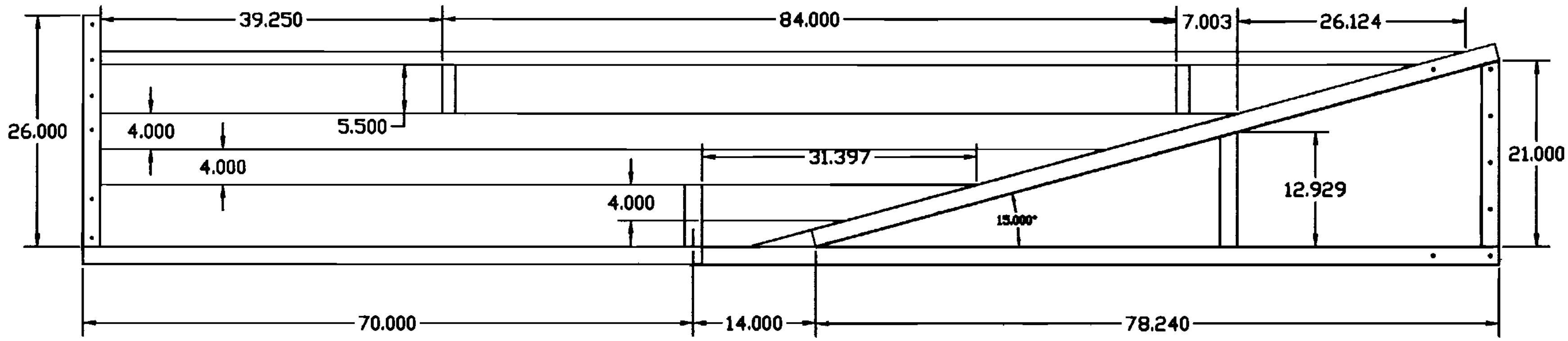

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TITLE

End Longitudinal

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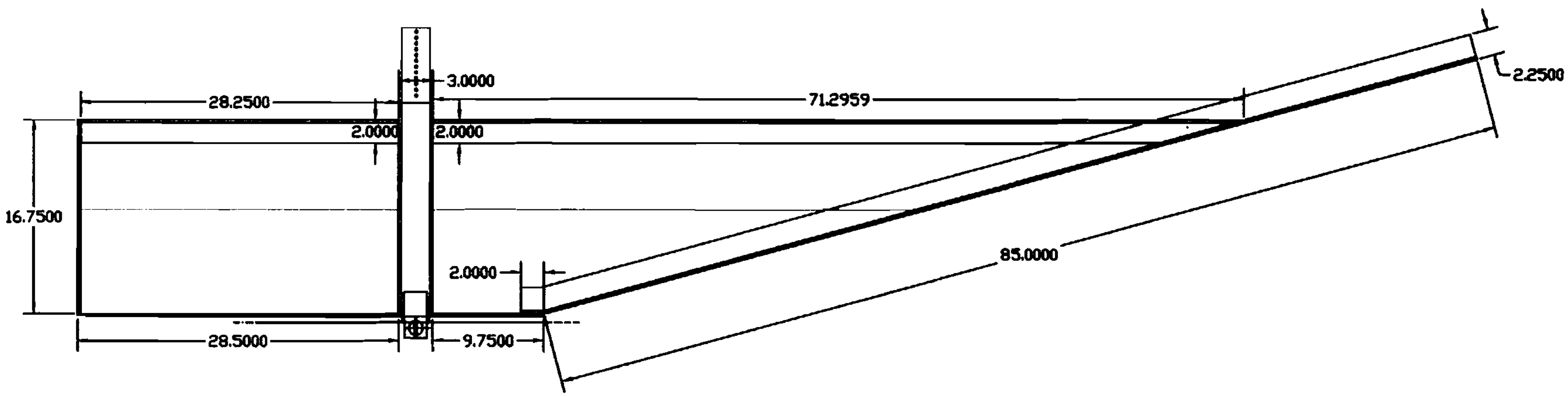

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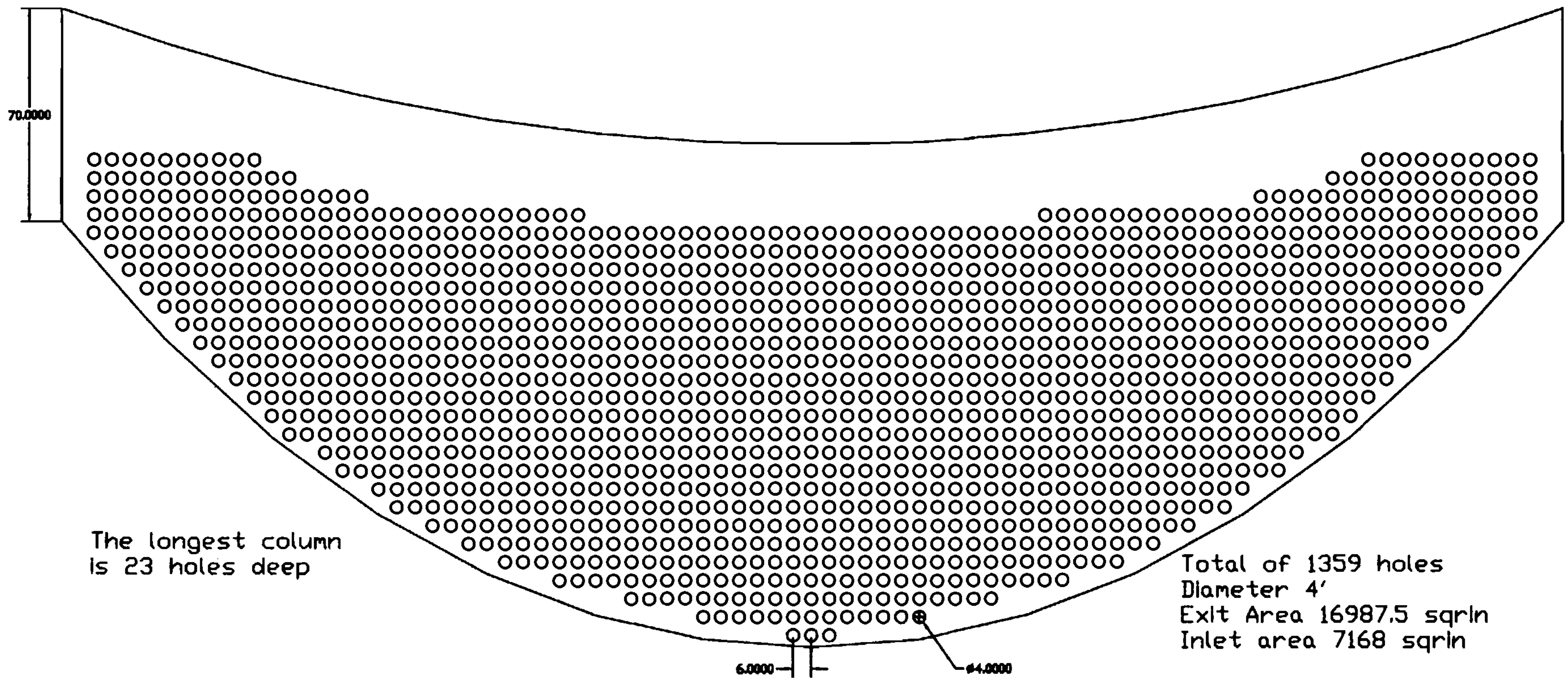

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TITLE

Rear Baffle Holes

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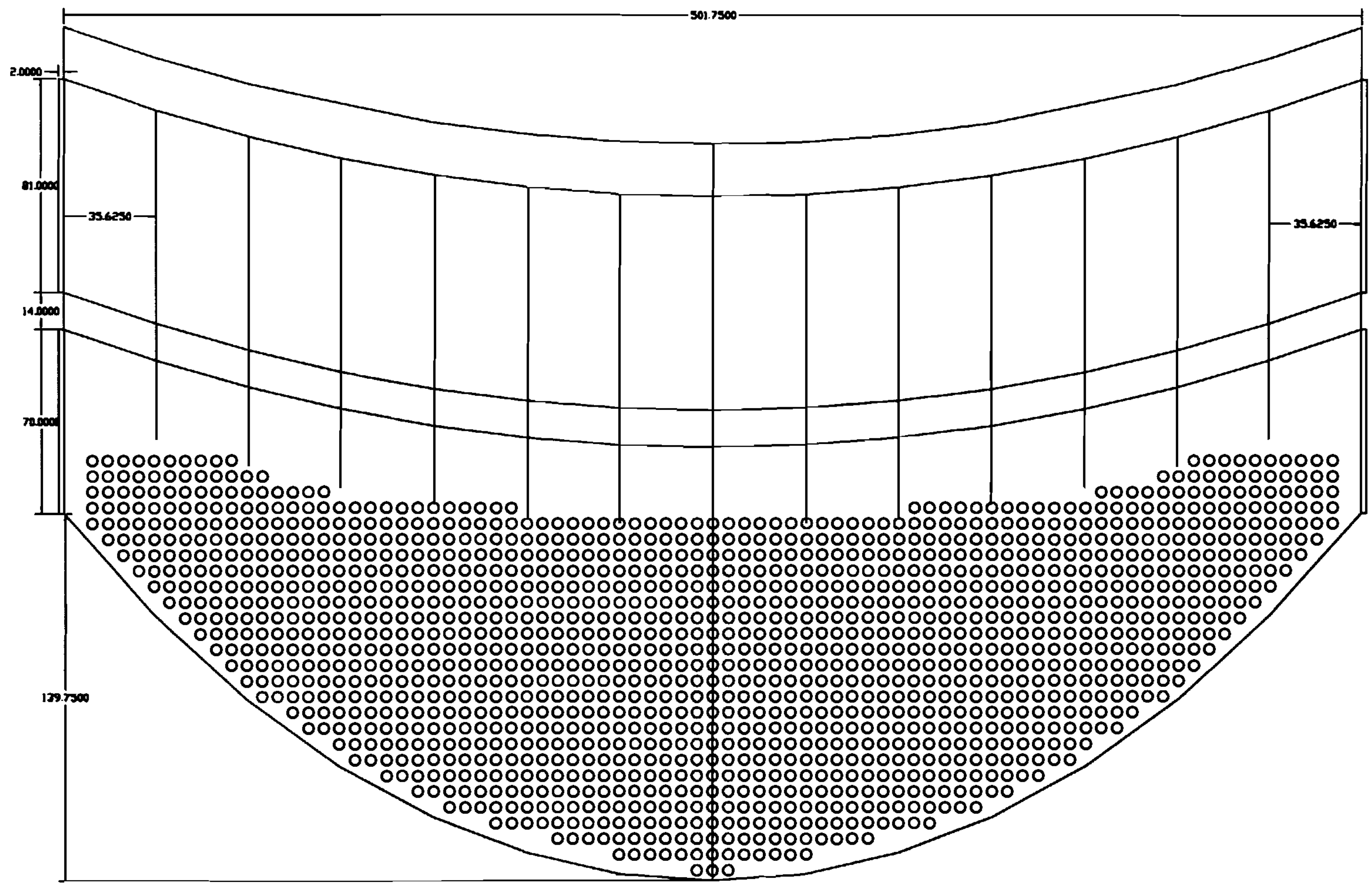

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TITLE

Submergence Plane and Rear Baffle

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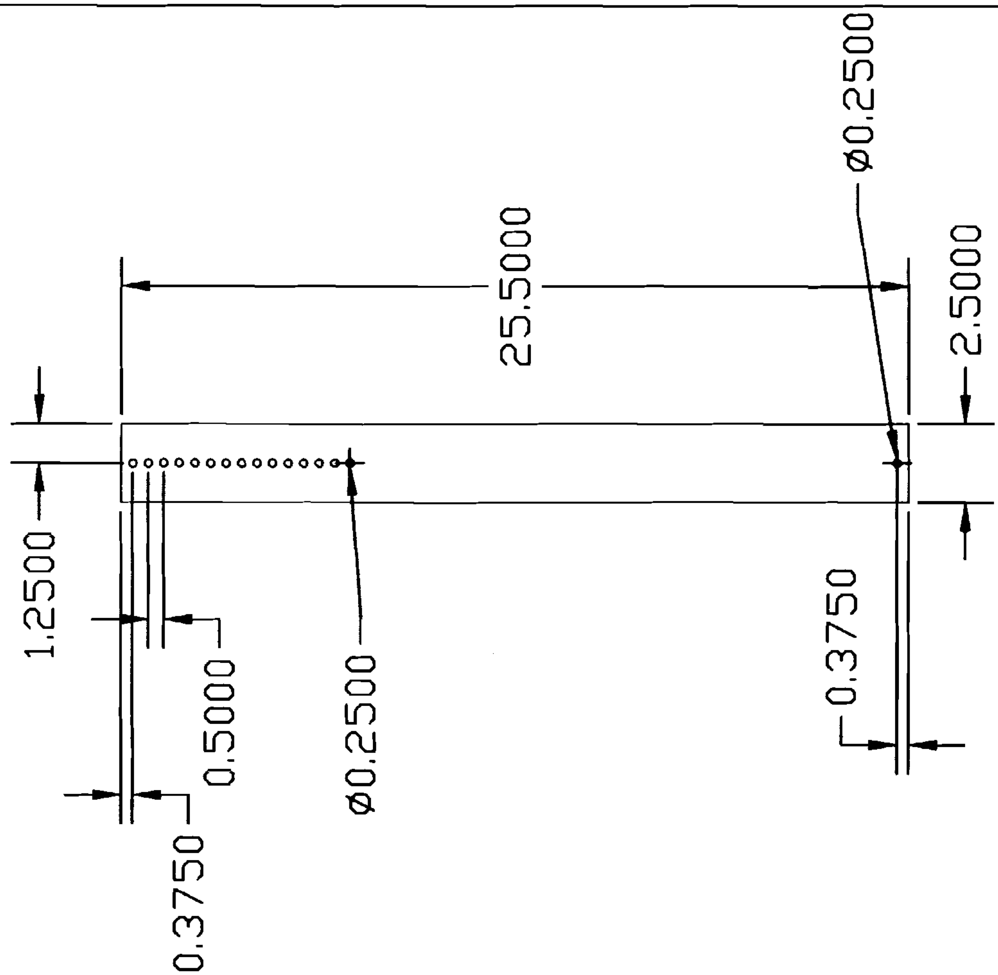

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Adjuster

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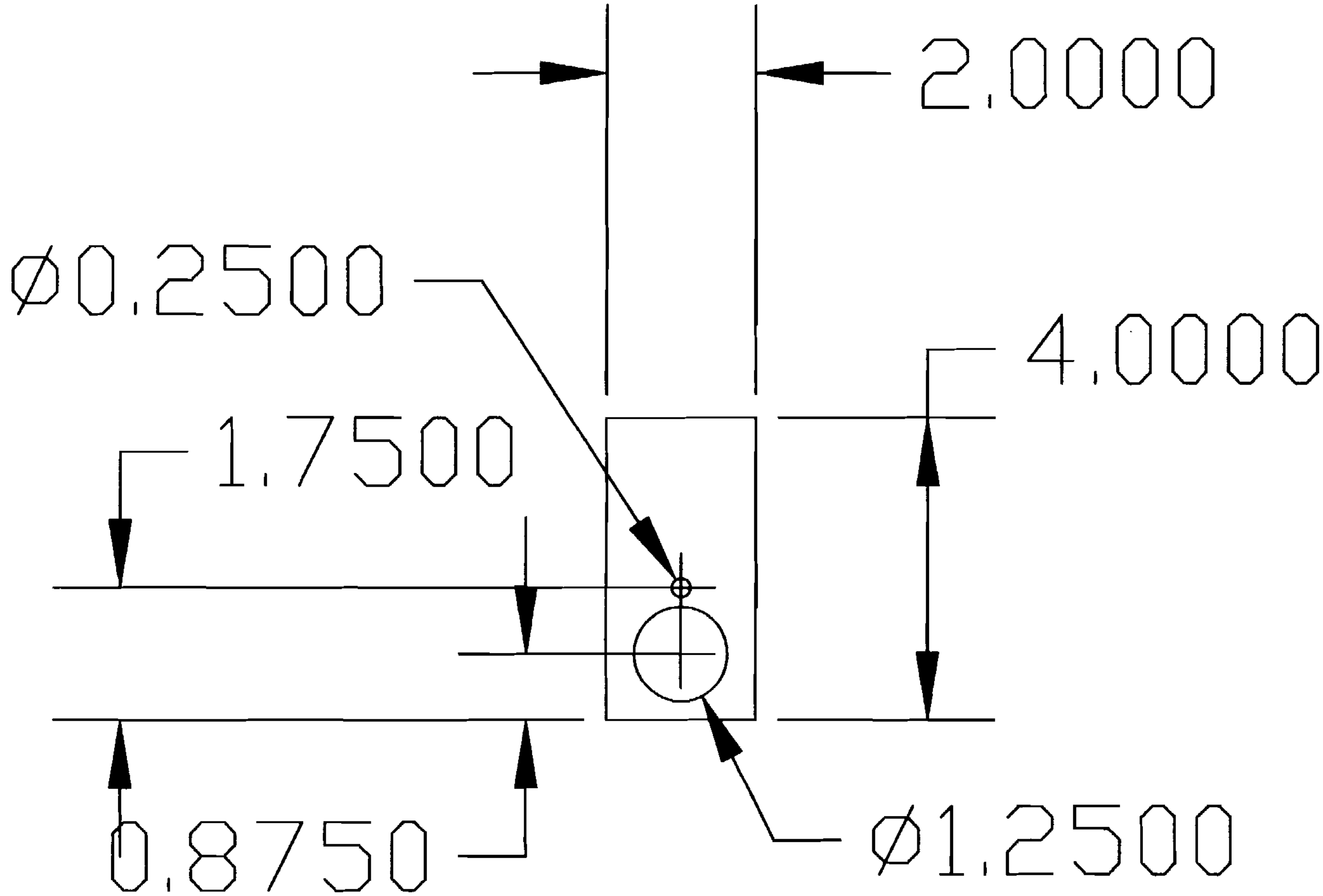

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Connector

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