DESIGNING OFFSHORE INTAKES FOR FISH PROTECTION

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INTRODUCTION

Cooling water intake structures are often located offshore to avoid problems with shoreline pack ice, severe wave action, heavy debris accumulations, siltation, and fouling organisms. In addition, offshore locations are sometimes selected due to the availability of deeper, cooler water or the low level of biological activity. Numerous offshore intakes exist on the Atlantic and Pacific coasts and on the Great Lakes which are utilized for both once-through and closed-loop cooling purposes.

Since 1972, the impingement and entrainment of fishes at cooling water intakes has become a major concern due to the potential impacts which fish losses may have on the fisheries resources of an area. As a result, extensive research has been directed toward developing methods for diverting or collecting fish within intakes or preventing their passage into structures altogether. This research has led to the development of several intake design concepts which have shown varying degrees of success in achieving the goal of fish protection. This paper addresses five concepts which have been, or are being, pursued actively: velocity caps, wide-spaced louvers, behavioral barriers, wedge-wire screens, and infiltration intakes. Several of these designs have not been shown to yield a high degree of biological effectiveness or have limited applicability due to design, operational and maintenance problems. However, they are presented below to afford the designer with the information necessary to select an intake which best suits the site-specific requirements of the power plant under consideration.

VELOCITY CAP INTAKES

The velocity cap was evolved from preliminary research carried out in 1956 by F. R. H. Jones. It was found that fish cannot sense a vertical displacement of flow to any substantial degree. Up to this time, water intakes were open pipes usually built up from the ocean or lake bottom with possibly a large-spaced trashrack placed over the opening.

When it was found that fish do not respond to vertical flow components, the velocity cap was designed (15) and was applied to the El Segundo Steam Electric Station. In essence, the cap changes vertical flow components to horizontal components which allow fish to sense their movement toward the structure and escape the intake system. Preliminary

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decreases in fish entrapment averaging 80 to 90 percent were recorded at El Segundo and later at Huntington Beach using intakes which incorporated velocity caps. Further research by Schuler and Larson (8) has theoretically lowered the entrapment factor even more. By extending the top of the cap and the sill of the intake, eddies which concentrated the flow, and thus created higher velocities in lower parts of the intake opening, were eliminated and a more uniform approach velocity was maintained. Lower average velocities and a longer approach to the vertical intake shaft allowed fish to sense the drawing influence of the intake and avoid entrapment. Velocity caps have since become standard features on many power plant offshore intake structures.

Although the velocity cap apparently acts to reduce fish entrapment, it has two inherent biological drawbacks. First, experience on the Great Lakes has shown that some operating plants utilizing a cap still entrap large quantities of fish each year, sometimes numbering in the millions (9). Without an additional system onshore to safely collect or divert those fish which are not excluded, all entrapped fish will ultimately die within the inake system. Second, since the cap acts on a behavioral basis requiring an active avoidance response, this system is ineffective in preventing the passage of nonmotile organisms, such as fish eggs and larvae. Therefore, unless the intake is located in an area of low fish abundance at a distance from spawning areas, this design will afford little protection for the early life stages of fish.

In conclusion, while the velocity cap intake acts to reduce fish impingement, the level of reduction at a specific site may require implementation of additional fish protection measures. Further, it is difficult to quantify, a priori, the reductions which might be achieved, since similar designs at different sites often yield conflicting results. Finally, a velocity cap design will not protect the early life stages of fish, except by virtue of the fact that it may be located in a nonproductive area.

WIDE-SPACED LOUVERED INTAKES

One possible solution to fish entrapment could be to prevent the presence of fish in the screenwell area by diverting them to a bypass within the offshore intake. Such an intake design, as shown in Figure 1, was tested hydraulically and with live fish in a full-scale model (11).

This intake design, representing a self-contained module, could be used for closed-loop cooling system or incorporated into a once-through cooling system by connecting several segment modules to an intake shaft. Conceptually, the intake module would incorporate a wide-spaced louver array through which the cooling water would pass while directing fish to a bypass. The louvers would be spaced 10 in. (0.25 m) apart to minimize clogging, angled at 11.5 deg to the flow in the horizontal, and leading to a bypass 2 ft (0.61 m) wide by 2.5 ft (0.76 mg) high. A center wall would be incorporated between the louver arrays to enhance fish guidance. The bypass flow would be induced by an offshore submerged jet pump. The driving flow for this jet pump would be supplied from the blowdown or discharge system onshore.

Prior to biological testing of this concept in a full-scale (1:1) model, hydrodynamic studies were conducted in a 1:9 scale model. The objectives were to study the flow distribution along the louvers for various louver geometries, louver array angles, and locations of the backwall of the structure. The 1:9 scale model is shown in Figure 2. Nine different louver configurations were tested. A louver configuration which has progressively longer louvers toward the downstream end (as shown in Figure 3) was selected for testing with live fish in the full-scale model. The selection of this configuration was based on the resultant velocity gradient along the face of the louver (Figure 3), which was judged desirable for fish diversion, and on the small region of high velocity that was located at a greater distance from the leading edge of the louver than the other louver configurations. Moving the backwall further away from the louvers resulted in a slightly improved velocity distribution along the louver face, as shown in Figure 3 (Configuration B). This additional feature was not, however, tested in the full-scale model with fish.

The objectives of the full-scale model testing were to evaluate the effectiveness of the wide-spaced louvers in guiding fish to a bypass and to verify the 1:9 scale hydraulic model results on a larger scale. The full-scale (1:1) model was constructed in a large basin, as shown on Figure 4. Since the intake was symmetric around the center wall, only half of the structure was modeled. The velocity distribution achieved along the face of the louver is shown in Figure 5. Unfortunately, it was found that the velocities increased gradually and then suddenly decreased in the vicinity of the bypass. This could have resulted in the poor fish guidance which was observed.

The biological testing strategy was straightforward and involved placing fish in the upstream end of the model basin and allowing them to react naturally to the established hydraulic conditions. Test species included rainbow smelt and alewife. Louver section entrance velocities of 2, 3, and 4 fps (0.5, 0.9, and 1.2 m/sec) and bypass velocities ranging from 2.25 to 4.8 fps (0.69 to 1.5 m/sec) were tested. Water temperatures ranged from 39 to 85^{o}F (3.9 to 29.4^{o}C). Tests were conducted in three distinct periods between the fall of 1974 and the fall of 1975: fall of 1974 (eight alewife tests); spring and summer 1975 (23 alewife tests, 4 smelt tests); and fall 1975 (10 alewife tests).

The results of the wide-spaced louver studies were statistically analyzed. The number of smelt tests was too small to include in the analysis; however, the mean diversion efficiency for 4 tests was 22 percent, with a 95 percent confidence interval of ±7.9 percent. The mean diversion efficiency for alewives under all conditions tested was 48 percent with a 95 percent confidence interval of ±14.5 percent. A predictive least-squares model was developed from the data and was applied to actual conditions at a power plant located on Lake Ontario. Because of the large variability in the laboratory test results, it was predicted that a wide-spaced louver system installed in the offshore intake at this plant could be from 27.8 to 86.3 percent effective in diverting fish to a bypass.

On the basis of results obtained during the offshore intake diversion system study, it did not appear that such a concept, as presently designed, offered a practical solution to the problem of fish entrapment at offshore intakes due to the wide variability in the data and lack of confidence in the predicted efficiencies which might result. The installation of wide-spaced louvers at the offshore intake would result in a large and costly structure. Further, the operation of such a system would necessitate the withdrawal of approximately 20 percent additional flow, as required for the bypass and jet pump. Assuming that flow is positively related to entrapment, this could result in additional entrapment, thus reducing the effectiveness of the system relative to the total number of fish saved. For the specific power plant under consideration during these studies, this concept was eliminated from consideration. Instead, a highly effective screenwell fish diversion and transportation system will be used to minimize impingement at the plant (12).

WEDGE-WIRE SCREEN INTAKES

Wedge-wire screens are in use today in many applications. The recent concern for the protection of small organisms at power plant intakes has resulted in biological and engineering evaluations of these screens for such a purpose (1, 2, 14). Biological research on cyclindrical wedge-wire screens indicates that they could be relatively effective in preventing the entrainment of fish eggs and most larvae at power plants provided that the screen slot size is small (approximately 0.5 to 1 mm), that the through-slot velocity is low (approximately 0.5 fps; 0.15 m/sec), and that a relatively high velocity cross flow exists to carry organisms around and away from the screen (1).

In laboratory studies, Hanson et al (4) found that entrainment of fish eggs (striped bass), ranging in diameter from 1.8 to 3.2 mm, could be eliminated with a wedge-wire screen incorporating 0.5 mm slot openings. However, striped bass larvae, measuring 5.2 to 9.2 mm (4 to 20 days old), were generally entrained through a 1 mm slot at a level exceeding 75 percent within one minute of release in the test flume. Larval tests were conducted in a static mode with no cross flow passing the screen. It was concluded that, since positive rheotaxis was observed among these early larvae, a cross flow would act to reduce entrainment to some extent. However, where current velocities are very low (less than 0.5 fps; 0.15 m/sec), it could be expected that the early larvae of many species would be susceptible to entrainment. Further, with 0.5 to 1.0 mm slot openings, eggs of some species would also be subject to entrainment depending on egg diameters.

Despite encouraging biological results with wedge-wire screens under experimental conditions, certain design, operational and maintenance problems exists which may limit the applicability of this screening concept at some power plant sites. General engineering criteria that should be considered in evaluating wedge-wire screens for possible power plant application are given below:

1. Clogging - To minimize clogging, the screen should be located in an ambient current of at least 1 fps (30 cm/sec) to establish suitable hydraulic conditions for self-cleaning and the dispersal of backflushed debris. An adequate backwash system is also required for periodic cleaning of the screen. Compressed air or water can be utilized.

2. Velocity distribution - A uniform velocity distribution along the screen face is required to minimize the probability of entrapment of motile organisms and to minimize the need for debris backflushing (2).

3. Navigation - The screens must be located such that they do not interfere with navigation.

4. Large debris - In many areas, large debris (trees, etc) and pack ice could damage or block the screens.

5. Frazil ice - In northern latitudes, provisions for the prevention of frazil ice formation on the screens must be considered.

6. Siltation - Allowance should be provided below the screens for silt accumulation to avoid blockage of the water flow.

7. Biofouling - Screen materials should be used which will minimize the degree of biofouling and its resulting effect on hydraulic efficiency.

8. Access - The screens should be readily accessible for maintenance and performance monitoring.

To date, proven methods for preventing frazil ice formation have not been developed. Limited field testing has been conducted to develop methods for backflushing the screens with water or compressed air. Testing of various materials is also ongoing to determine their biofouling characteristics (7).

Since the above-mentioned clogging and icing problems have not been resolved, wedge-wire screens are presently more suitable for closed-loop makeup flow intakes than for once-through systems. Wedge-wire screen and perforated-pipe submerged intakes (which are similar in concept to the wedge-wire screens) are operating satisfactorily on a number of make-up systems on the Ohio, Mississippi, Susquehanna, and Big Sandy Rivers.

A conceptual wedge-wire screen intake arrangement for a once-through cooling system on the Great Lakes (800 cfs; 22.7 m^3/sec) that incorporates many back-up systems for backwashing and deicing is shown on Figure 6.

The screens would be placed parallel to the predominant current direction and would be sized for a through-slot velocity of 0.5 fps (0.15 m/sec). The system would incorporate a warm water backflushing capability to melt ice which could accumulate around the screens and a warm water diffuser to minimize frazil ice formation on the screen. Compressed air would also be provided within the screens to air-burst debris away from the screens. An emergency onshore intake would also be provided to supply water in case of severe clogging of the wedge-wire screens. Hydraulic model studies would be required to optimize the header pipe design to achieve equal flow withdrawal from the screens. Also, in situ long-term (more than 1 yr) pumping tests would be required to determine the effect of frazil ice formation, clogging characteristics, potential damage by pack ice, and biofouling effects on the hydraulic efficiency of the screen.

BEHAVIORAL BARRIERS

Extensive research has been conducted to determine the effectiveness of behavioral barriers in guiding fish or preventing their upstream or downstream passage. Behavioral devices which have been evaluated for possible power plant application include air bubble curtains, electrical barriers, lights, sound, hanging chains, visual keys, water jet curtains, and velocity barriers. In general, behavioral barriers have not proven effective in deterring the passage of fish, either in laboratory studies and in actual applcation. To date, sound, lights, and air bubble curtains are the only devices which have been evaluated at actual power plant intakes.

The U.S. Environmental Protection Agency (13) states that, "as far as could be determined, there are no existing intakes where a light barrier is functioning successfully. Light also has the adverse effect of attracting fish under certain circumstances and has resulted in a complete shutdown of plants." Studies with sound-generating devices have yielded similar results. The feasibility of using sound to guide or deter fish passage is complicated by species-specificity. For example, not all fish possess the ability to perceive sound or localize acoustical sources. Many fish species possess a limited ability to perceive or distinguish sounds (poor auditory capacity). These fishes rely primarily on their lateral line system to distinguish near-field disturbances (5). Thus, sound may attract some species, repel some, or have no effect at all. In addition, some fish have demonstrated rapid habituation to sound, negating the effectiveness of continuously operated underwater sound generation. For these reasons, sound has not been shown to be an effective means of preventing fish entrapment at power plant intakes.

Air bubble curtains have been used at many locations in an attempt to divert fish. The success of this device has been variable and appears to be affected by such factors as species, temperature, light intensity, water velocity, and orientation within a water body. Power plant air bubble curtain applications have not been highly successful. For example, an air curtain was not effective at the Indian Point Generating Station on the Hudson River (13). After several years of operation, the air curtain was removed. Similarly, at the Commonwealth Edison Company Quad-Cities Generating Station, located on the Mississippi River, an air bubble curtain was not found to be effective in reducing the entry of fish into the intake canal (6). At the Prairie Island Nuclear Generating Plant on the Mississippi River, small decreases in impingement were achieved for several species when an air curtain was placed across the intake canal. However, the number of individuals of other species entering the canal actually increased (3). The air curtain was therefore removed. At Detroit Edison's Monroe Power Plant, an air bubble curtain was installed across the main intake canal in 1972. On the bais of daily fish counts made with the system either on or off, it was concluded that the curtain was ineffective in preventing fish from entering the canal.

Considering these failures, it is not believed that an air bubble curtain represents a highly effective means for reducing fish losses at intakes. This conclusion is further substantiated by laboratory studies that were conducted with behavioral barriers specifically for application to offshore, submerged intake structures. In 1976, a model facility was constructed to test the effectiveness of three behavioral barriers (air bubbles, hanging chain, and water jets) in deterring the passage of alewives and smelt into an offshore, velocity cap intake (10). Tests were conducted over a range of water temperatures from 44 to 79°F (7 to 26°C). The model (Figure 7) consisted of two identical intake segments located in a large test basin. The segments were separated by a screen thus allowing two tests to be run simultaneously. The air bubble test device was constructed of 2 in. (5 cm) ID pipe with 1/32 in. (0.8 mm) holes spaced on 2 in. (5 cm) centers over a distance of about 5 ft (1.5 m). The diffuser was located 3.5 ft (1.0 m) in front of the 2 ft (0.6 m) high, 5 ft (1.5 m) wide intake opening to avoid air entrainment.

The hanging chain test device consisted of an array of 3/16 in. (4.8 mm) chain lengths each 3 ft (1.5 m) long and spaced on 2 in. (5 cm) centers. The actual clear opening between chain lengths was 1.25 in. (3.2 cm).

The water jet curtain test device consisted of 3/4 in. (1.9 cm) diameter vertical tubes spaced 1 ft (0.3 m) apart. Each tube had a line of 1/32 in. (0.8 mm) diameter nozzles spaced on 1/2 in. (1.25 cm) centers. Each barrier was tested in each segment at intake entrance velocities of 0.5, 1.2, and 2.0 fps (0.15, 0.37, and 0.6 m/sec). Control tests were also conducted in which no device was installed. Smelt tests were conducted with 200 fish per test, with a total of 40 tests. Alewives were tested in individual groups of 400, 600, 800, or 1,000 fish (48 tests).

Test results showed that the three behavioral barriers significantly reduced the number of fish entrained into the intakes relative to the control; however, the barriers were not in themselves significantly different in efficiency. The predicted mean number of fish entrained per test was 151 for controls, 66 for the air bubble curtain, 77 for the hanging chains, and 41 for the water jet curtain. Thus, although the devices reduced entrainment, they would not be expected to eliminate fish losses completely.

When considering the use of behavioral barriers at an intake structure, the effect of such devices on intake operation should be carefully evaluated. For example, an air bubble curtain at an offshore intake should be placed away from the face of the intake to avoid air entrapment into the tunnels which would result in air blow-backs. Similarly, in designing a water jet curtain, as shown in Figure 8, the vertical bars should be placed about 1 ft (30 cm) apart in order to prevent potential blocking of the intake due to debris accumulation. Warm water could be used to operate the water jet curtain to reduce the potential of frazil ice formation. Filtration of the supply water would also be required to minimize clogging of the small jet nozzle openings. Operational problems of hanging chains due to wave action, debris, and icing should be considered. The chains should be placed far enough from the intake face (as shown in Figure 9) to eliminate the potential for entanglement and to allow cooling water to flow through the open area between the chains and the intake should the chains clog with debris or ice.

In conclusion, the decision to install a behavioral barrier at a power plant intake should be made on the basis of cost-effectiveness. Further, in selecting a specific barrier for application, consideration must be given to the installation, maintenance and operational criteria that exist at a specific site. In general, it does not appear that behavioral barriers alone offer a high potential for reducing fish entrapment at power plant intakes.

INFILTRATION INTAKES

There are presently two types of infiltration intakes: the radial well and the artificial filter bed. Since these intakes function essentially in the same fashion as a natural aquifer, resulting in very low velocities, little or no biological impact is expected to occur as a result of operation. However, experience indicates that the maximum capacity of a single radial well is limited to about 10,000 to 20,000 gpm (0.6 to 1.25 m^3/sec). For a once-through application, given a suitable aquifer, about 20 to 30 miles (30 to 45 km) of shoreline could be required to supply 500,000 to 1,000,000 gpm (30 to 60 m^3/sec) of cooling water. This consideration and the associated costs of pumps and a large piping network would rule out this principal as a practical solution for once-through application.

CONCLUSION

Infiltration and wedge-wire screen intakes offer an effective and practical solution for fish and larval protection for closed-loop cooling systems when adequate hydraulic conditions exist. However, for once-through cooling systems, further developmental work is required for wedge-wire screen intakes. Over the range of hydraulic and environmental parameters evaluated to date, behavioral barriers appear to offer only limited efficiency in deterring fish from entering an intake structure. The wide-spaced louver concept will require further development if it is to become a practical and effective method of bypassing fish within offshore, velocity cap intakes.

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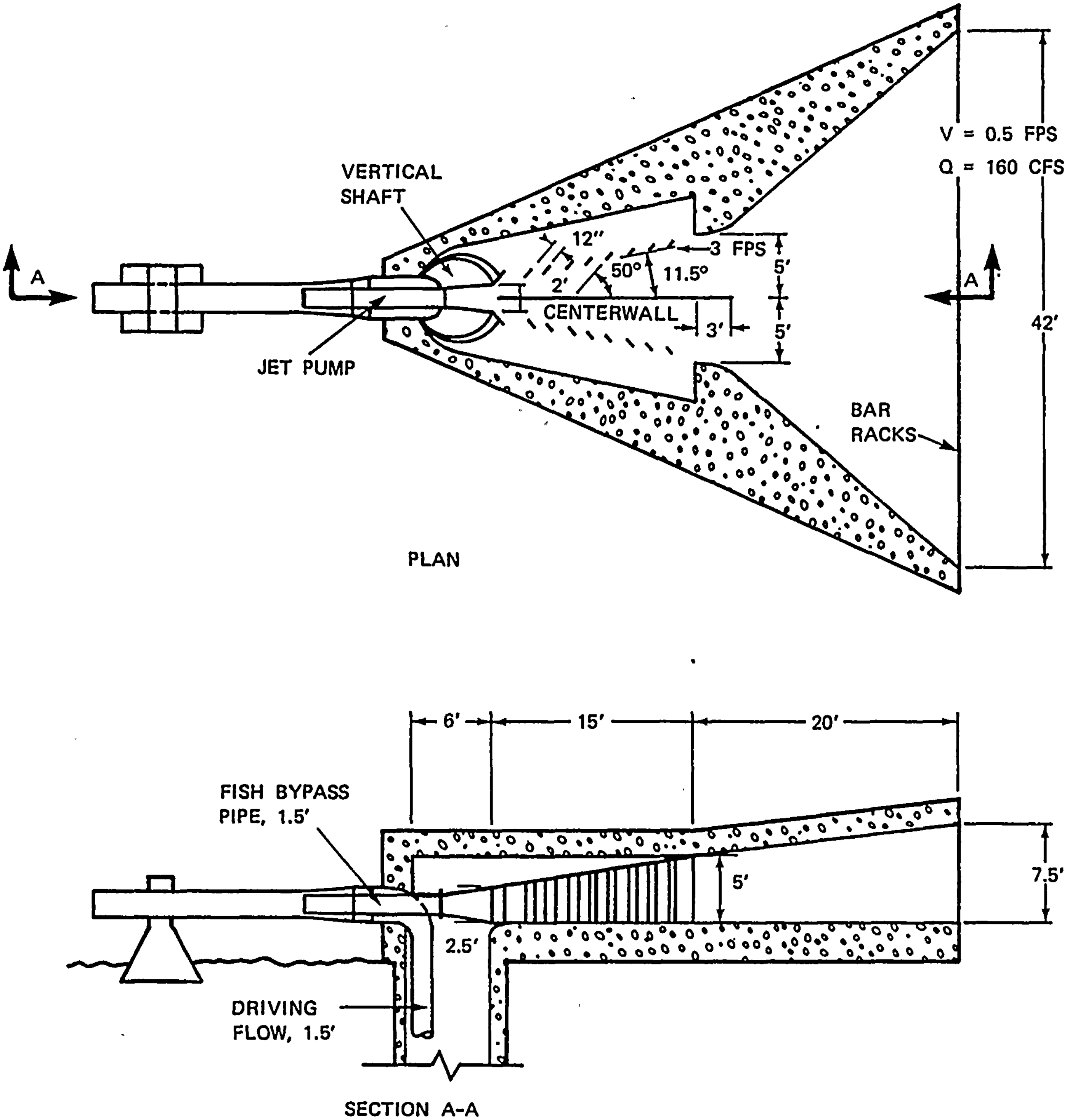


FIGURE 1 INTAKE STRUCTURE SEGMENT MODULE, CONCEPTUAL DESIGN

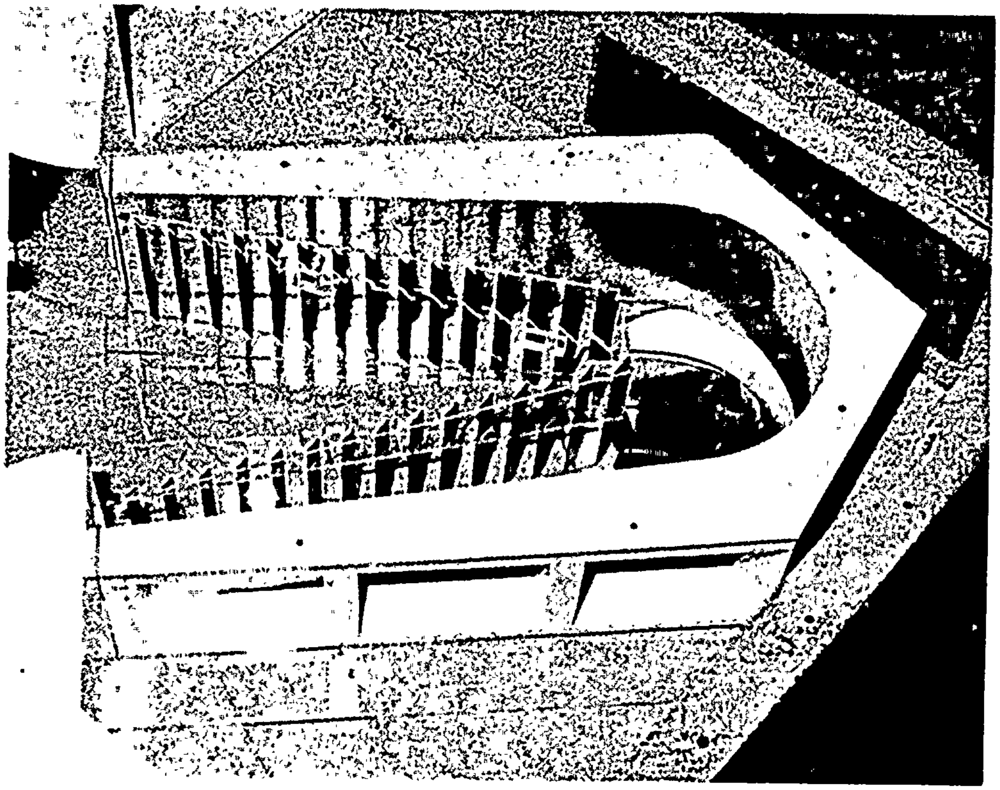
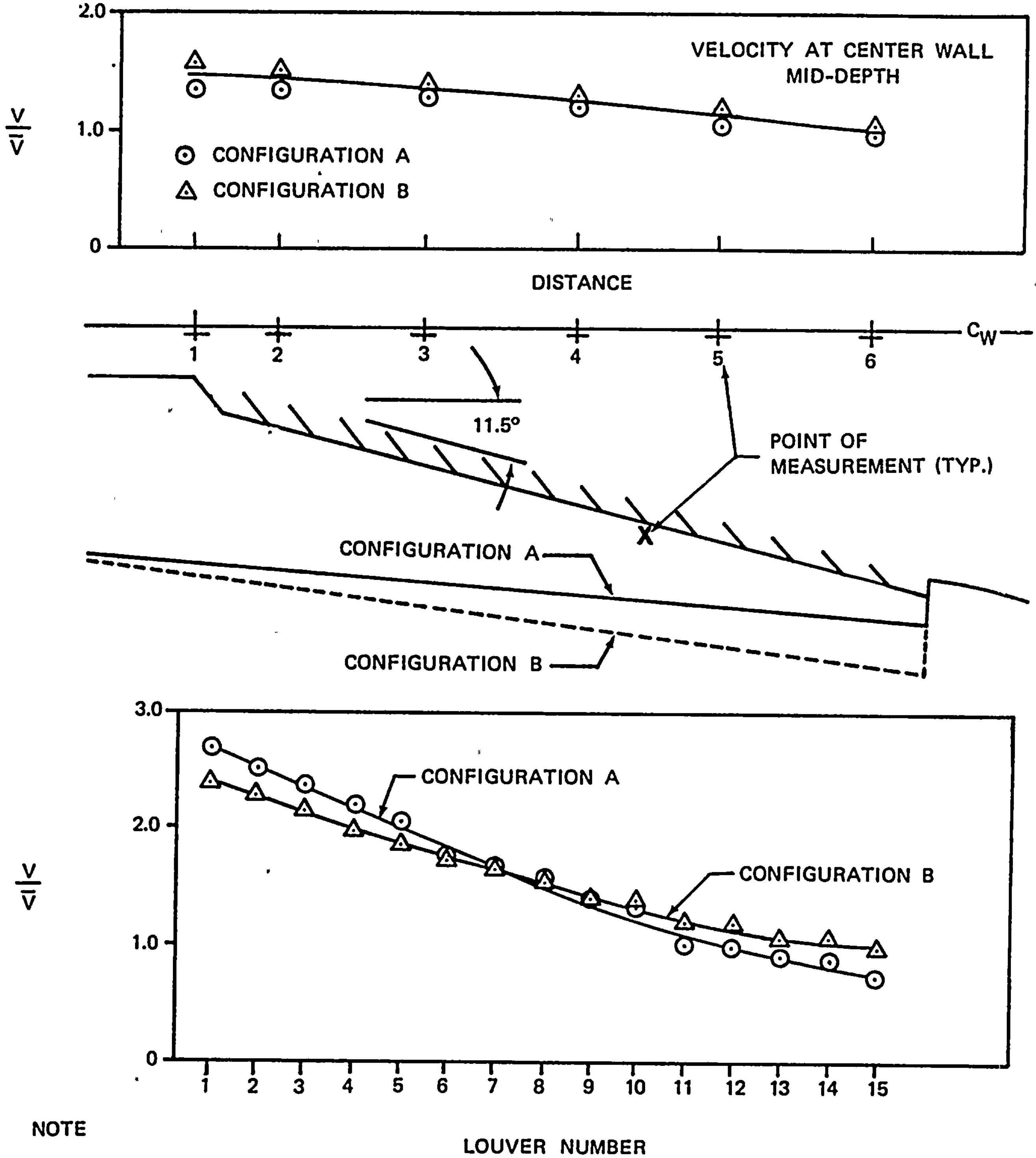


FIGURE 2 1:9 SCALE MODEL OF SEGMENT MODULE



NOTE

$$\frac{Q_{BYPASS}}{Q_{THROAT}} = 0.15$$

FIGURE 3 VELOCITY DISTRIBUTION, 1:9 SECTOR MODULE

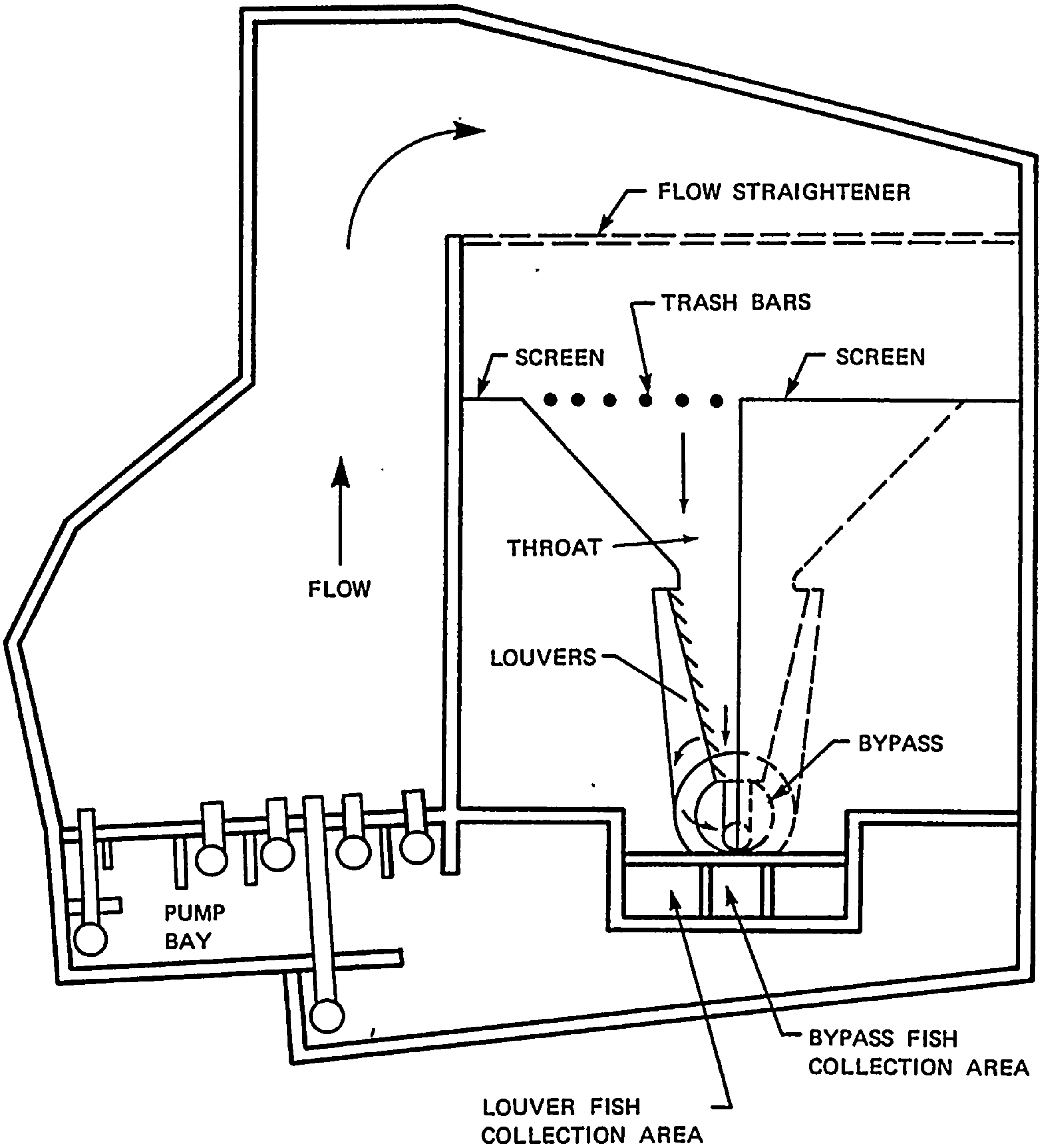
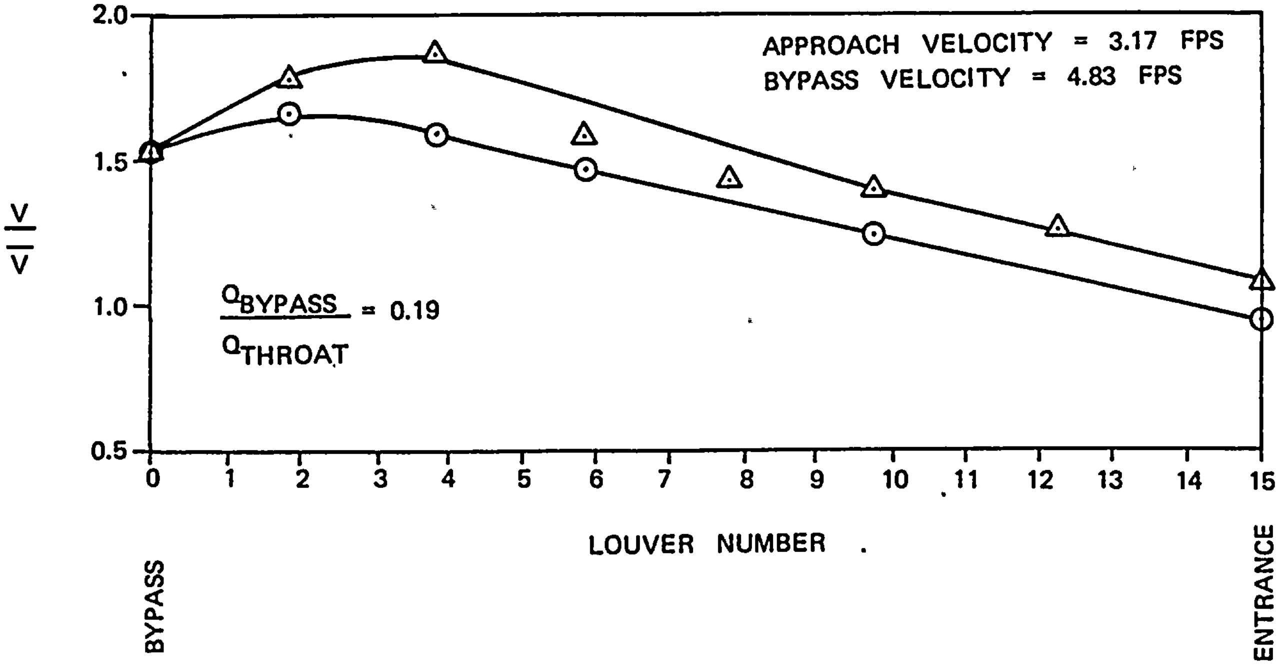
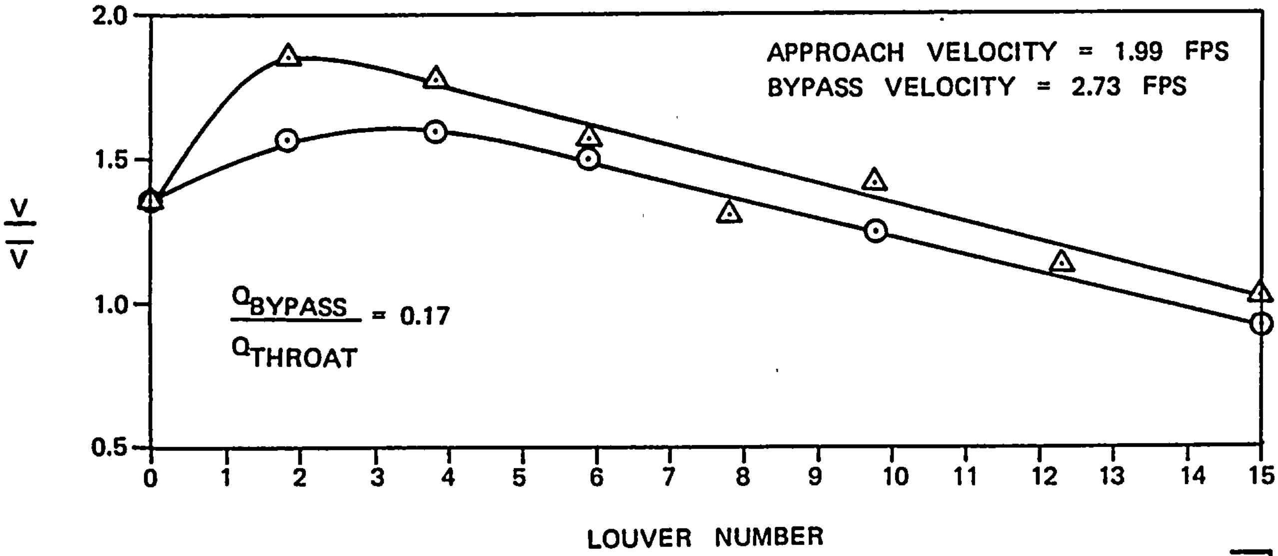


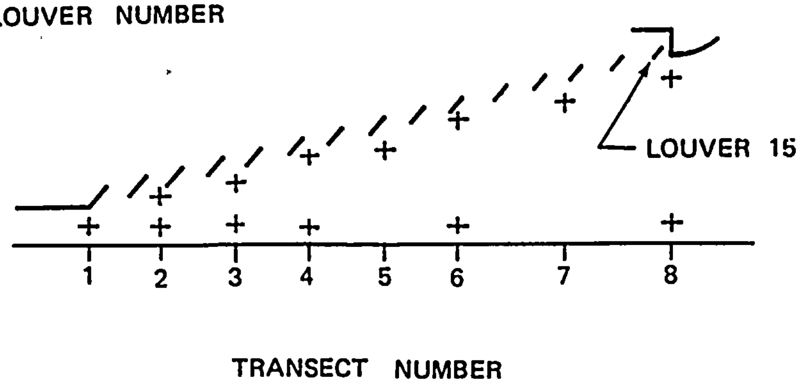
FIGURE 4 1:1 SCALE INTAKE SEGMENT MODULE





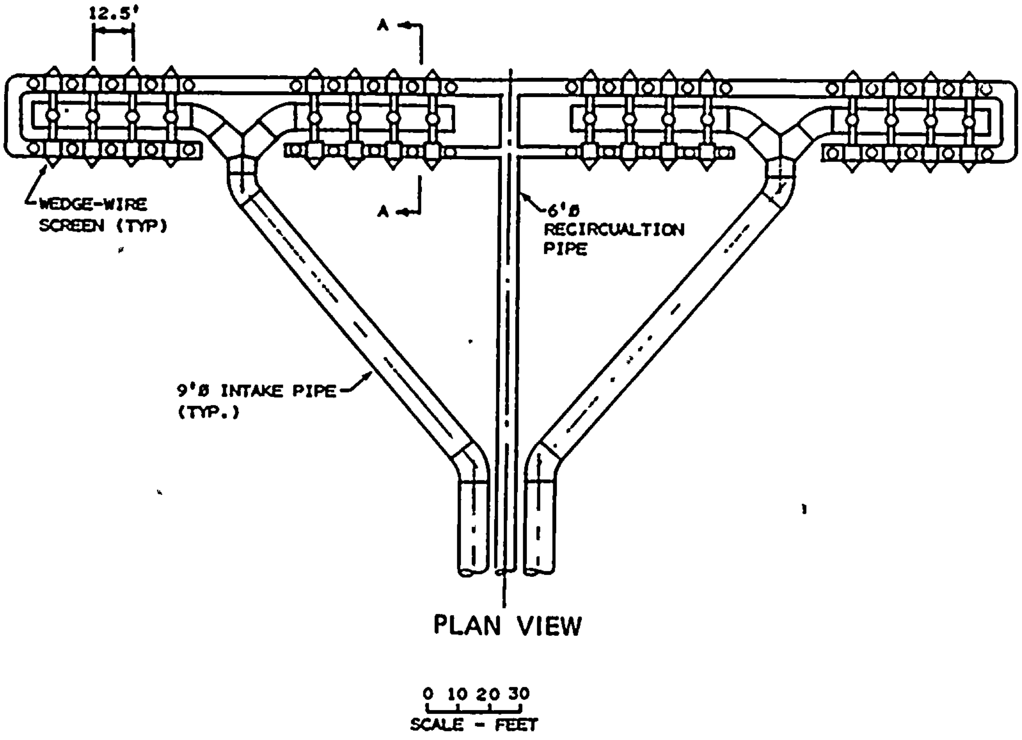
⊙ ALONG CENTERWALL

△ ALONG LOUVERS

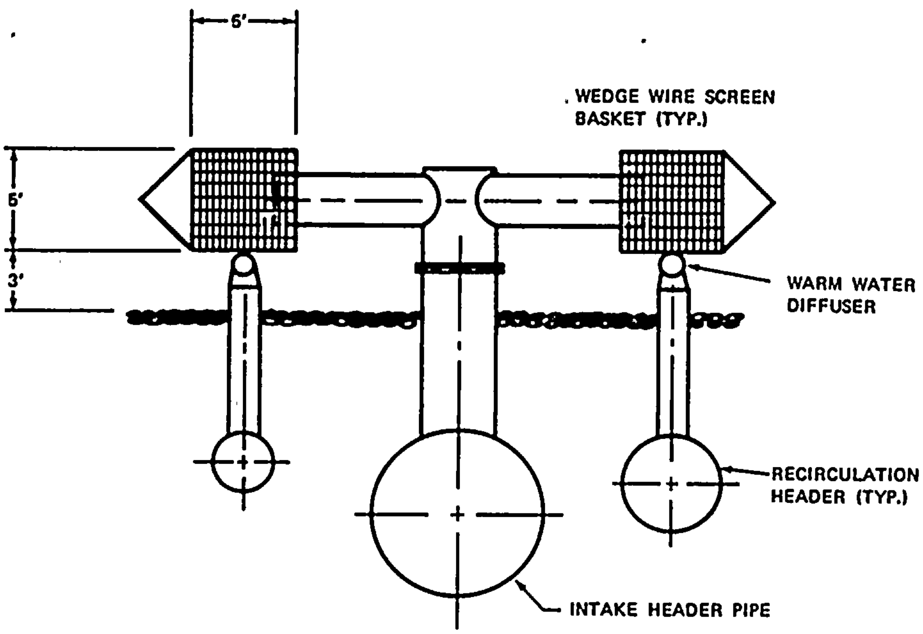


NOTE:
1) VELOCITY AT MID DEPTH

FIGURE 5 NORMALIZED VELOCITY GRADIENT, 1:1 INTAKE SEGMENT MODULE

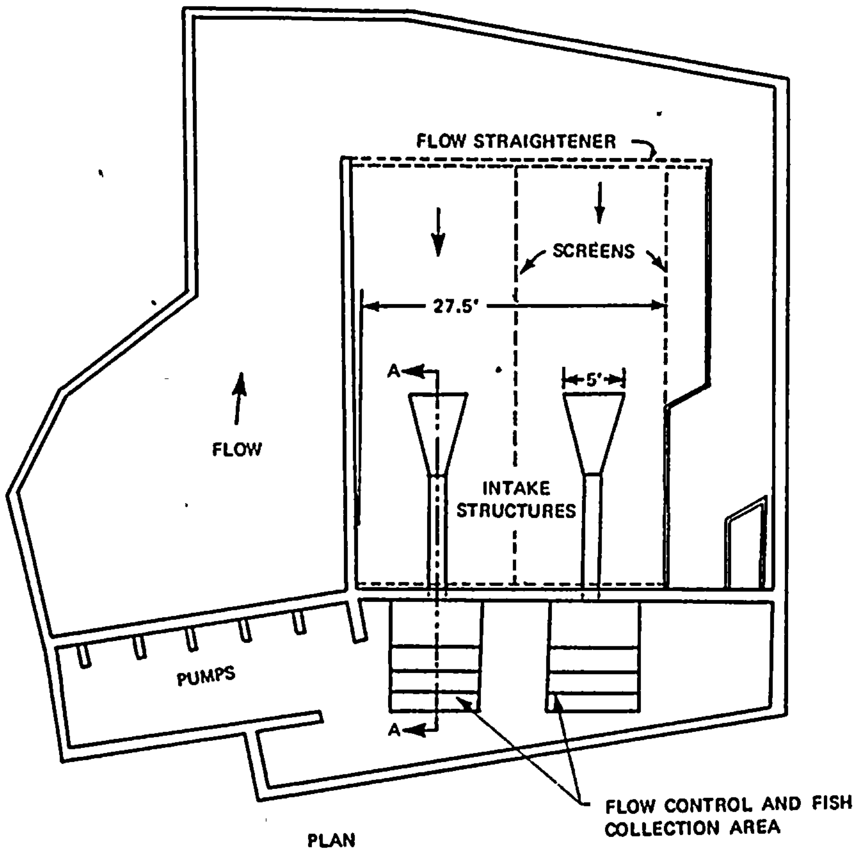


PLAN VIEW



SECTION A-A

FIGURE 6 OFFSHORE WEDGE WIRE SCREEN INTAKE



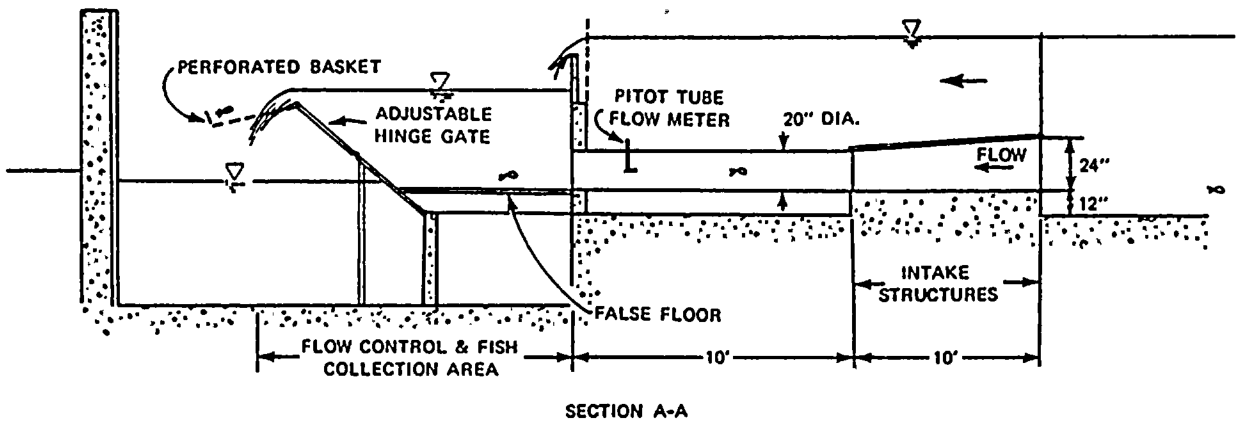
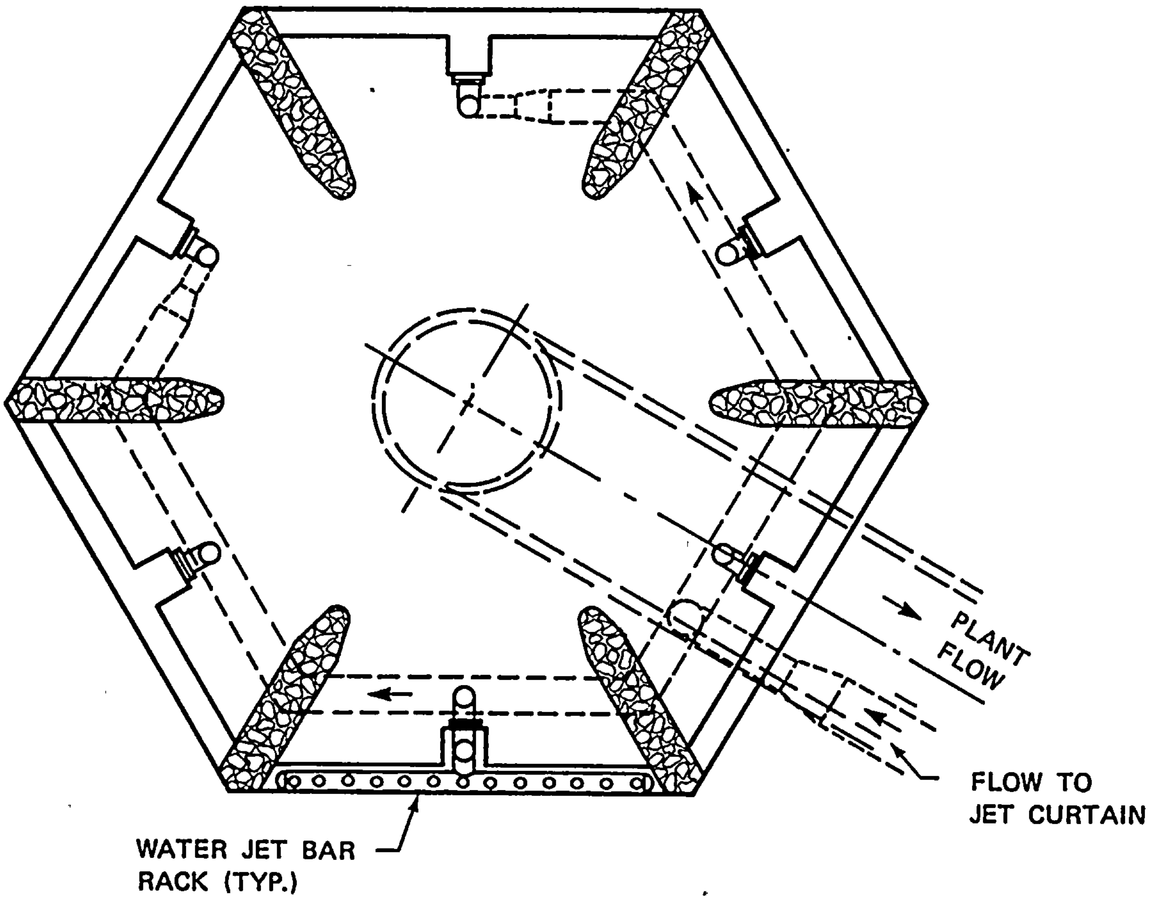
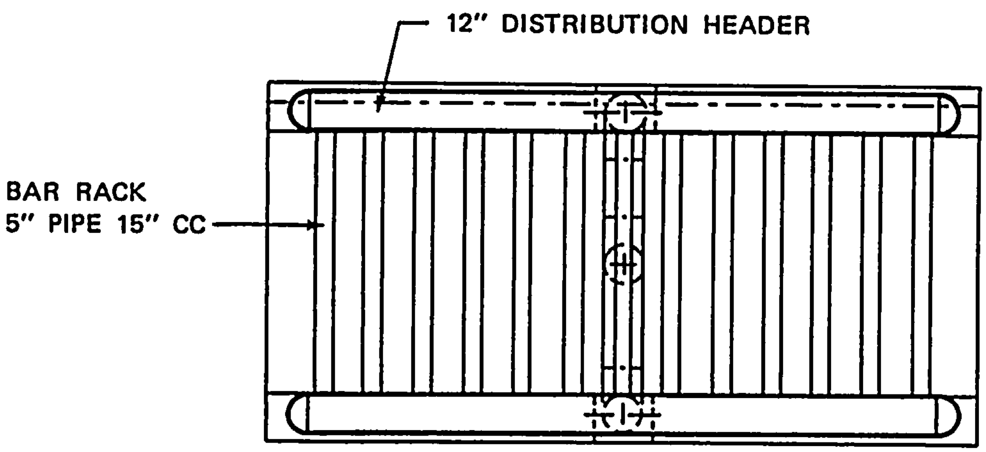


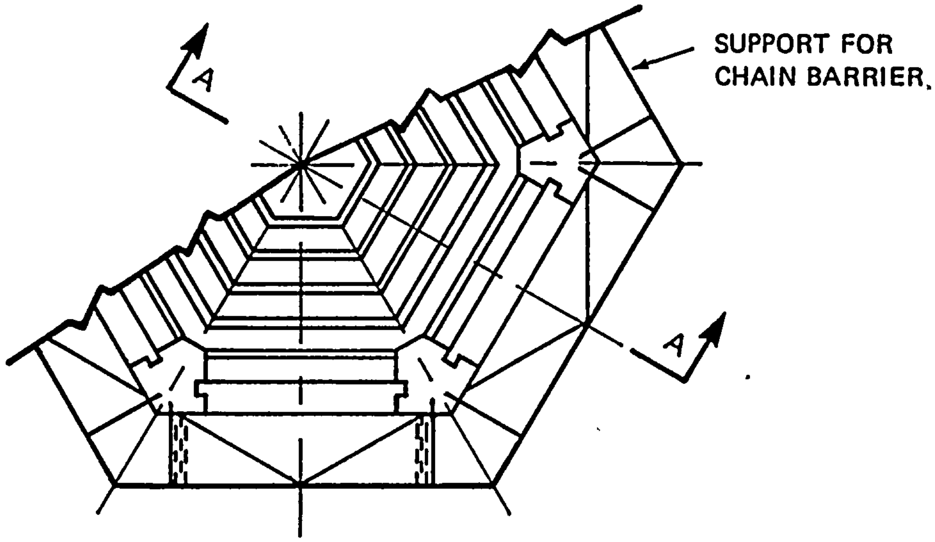
FIGURE 7 MODEL BASIN USED FOR TESTING BEHAVIORAL BARRIERS



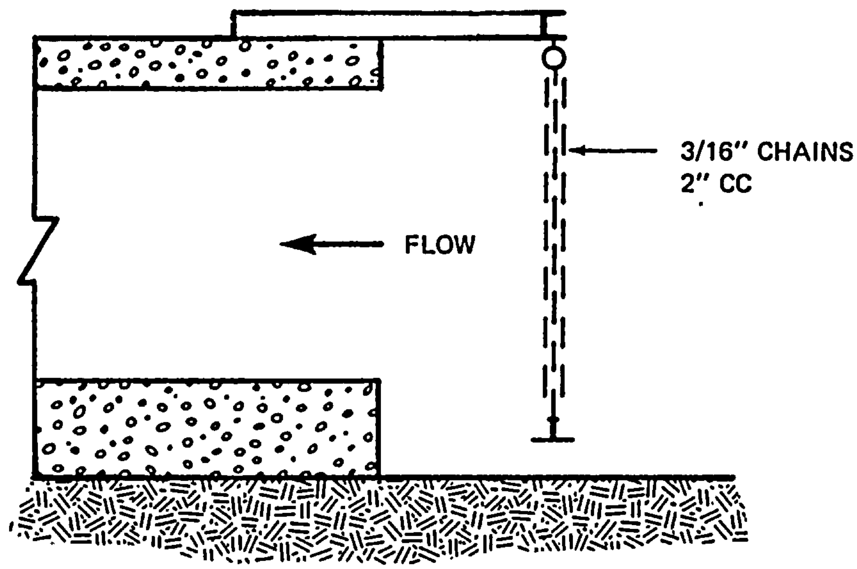


WATER JET BAR RACK

FIGURE 8 OFFSHORE INTAKE WITH WATER JET CURTAIN



PLAN



SECTION A-A

FIGURE 9 OFFSHORE INTAKE WITH HANGING CHAIN BARRIER