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Fish Protection at Cooling Water Intake Structures: A Technical Reference Manual

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EPRI Project Manager

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CYLINDRICAL WEDGEWIRE SCREENS

Introduction

Wedgewire screens have the potential to reduce both entrainment and impingement at water intakes. Wedgewire screens use V or wedge-shaped cross-section wire welded to a framing system to form a slotted screening element (Figure 5-1). In order to effectively reduce impingement and entrainment, the following conditions must exist:

- Sufficiently small screen slot size to physically block passage of the smallest life stage to be protected (typically 0.5 to 1.0 mm);
- Low through-slot velocity;
- Ambient currents that are sufficient for sweeping aquatic organisms and debris past a screen

Wedgewire screens (Figure 5-2) have been effective in preventing entrainment and impingement of ichthyoplankton and juvenile fish at different types of water intakes (mainly irrigation, municipal water supply, and cooling water intakes) without any major maintenance problems. However, as with any screening technology, the potential for clogging and biofouling is a concern and needs to be addressed in the design and operation this technology. When all conditions for effective operation are met, wedgewire screens can reduce entrainment and impingement to levels that usually meet existing regulations and resource agency criteria. Furthermore, the now suspended EPA Rule identified submerged cylindrical wedgewire screens in freshwater river under certain hydraulic conditions as a pre-approved technology to meet impingement mortality. In other water body types, wedgewire screens would have met compliance alternative 1 in the Phase II 316(b) Rule because of the low through screen velocity (0.5 ft/s).

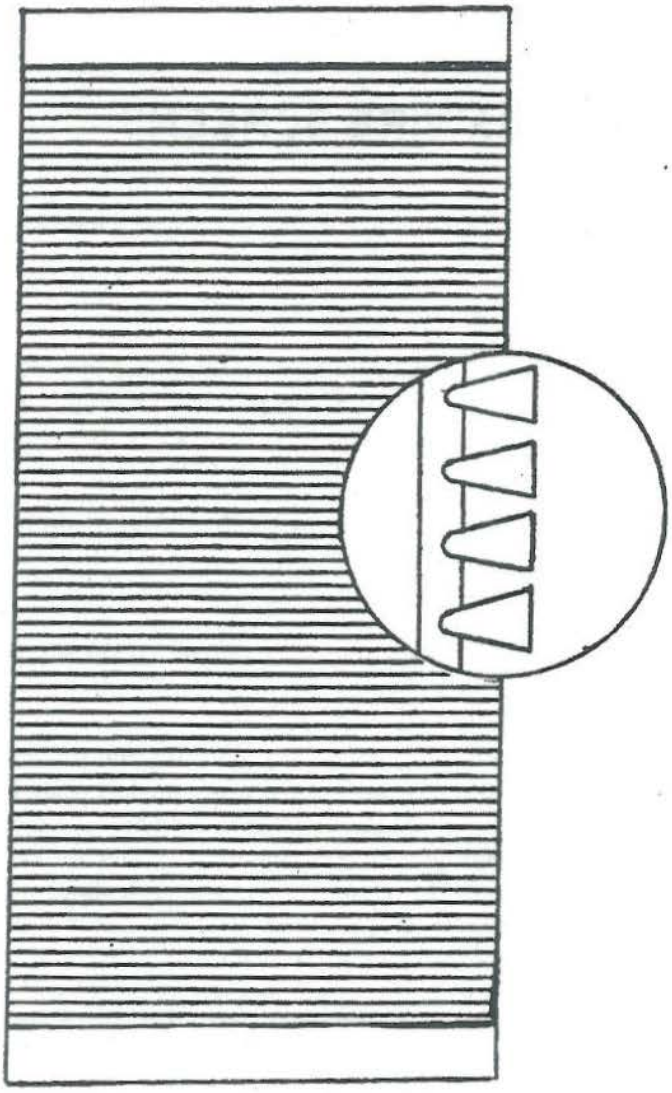


Figure 5-1
Cylindrical Wedgewire Screen Panel Detail (Modified from EPRI)

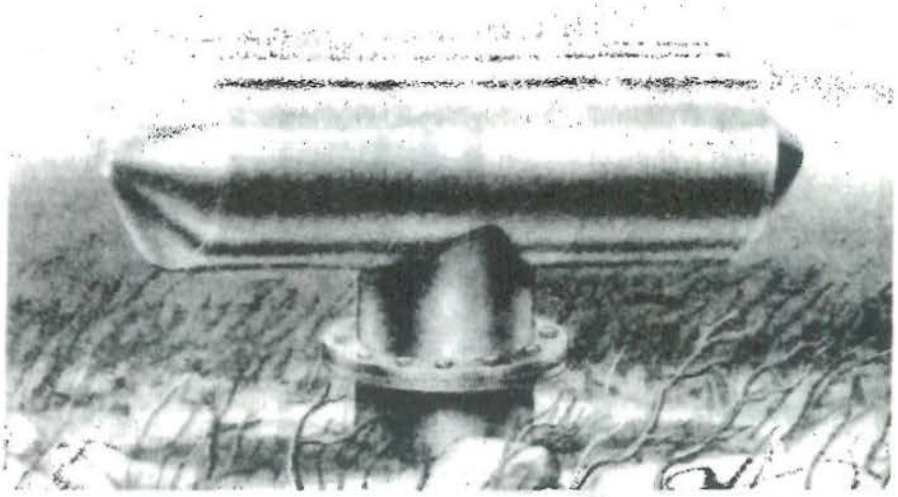


Figure 5-2
Cylindrical Wedgewire Screen Intake (Courtesy of Johnson Screens)

Case Studies – CWIS Application

Logan Generating Plant

A study was conducted to evaluate the performance of 1-mm (0.039 in.) slot wedgewire screens at the Logan Generating Plant (LGP; Ehrler and Raifsnider 2000) (Figure 5-3). The plant is located on the Delaware River in Gloucester County, New Jersey. Water is drawn from the river to replace evaporative water losses from the plant's closed-cycle cooling system.

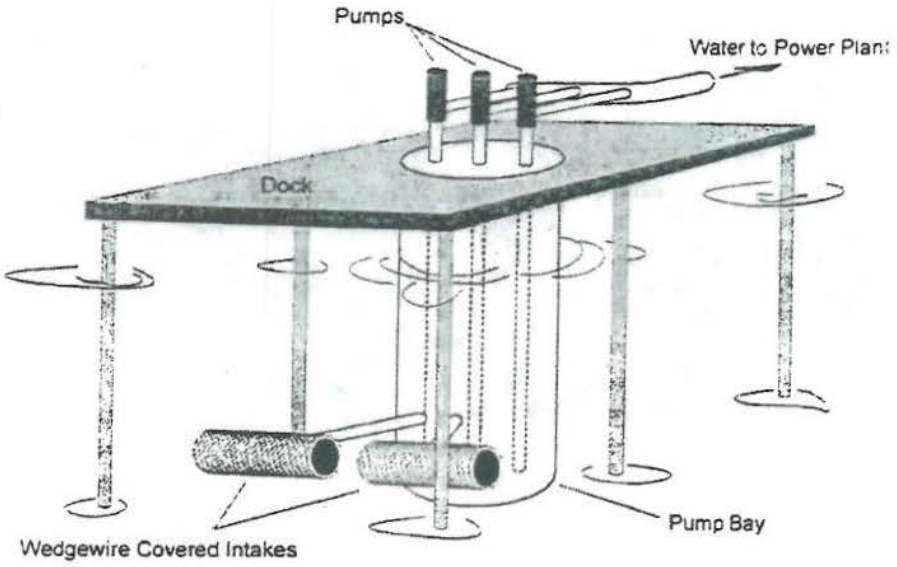


Figure 5-3
Wedgewire Screen Intake at the Logan Generating Plant (Ehrler and Raifsnider 2000)

Samples were collected from the Delaware River adjacent to the plant and from water that had passed through the wedgewire screens for comparison of larval densities. River water was sampled by towing a plankton net at water depths of 10.3, 8.5, and 6.7 m (34, 28, and 22 ft). Samples from the river were collected by towing a 30-cm (1-ft) diameter, 335-μ mesh plankton net at constant speed. Three sampling transects were established: one was located upriver of the station, another was aligned with the plant's fuel dock, and one was located downstream of the plant. Water that had passed through the screened intake was sampled by pumping water from the plant's intake wet well. A total of 30 towed net and entrainment samples were collected.

The most abundant species collected during tow samples in the deep stations (9.1 m [30 ft]) were striped bass (39%), white perch (28%), carps/minnows and suckers (19%), and herrings (13%). The most abundantly collected species at the shallow stations (0.9 m [3 ft]) were river herring (80%), white perch (17%), striped bass (2%), and minnows/carps and suckers (1%).

A comparison between the densities of striped bass in the Delaware River and in the plant's makeup water was used to determine the effectiveness of the wedgewire screen intake system. It was estimated that an unscreened intake would entrain approximately 0.03% of the local striped bass larval population. The intake screens were expected to exclude 90% of the striped bass larvae (Ehrler and Raifsnider 1999). The results of the comparison study resulted in an average proportional withdrawal of striped bass larvae of 0.003%.

Cope Station

A cylindrical wedgewire screen intake system is in operation at the 385 MW, coal-fired Cope Station located on the South Fork Edisto River in Orangeburg County, South Carolina (Cumbie and Banks 1997). The station withdraws 0.3 m^3/s (10 cfs) for closed-cycle cooling purposes. Engineering and model studies were conducted to demonstrate the system's potential to minimize impingement and entrainment of fish (including eggs, and larvae). Species of primary interest included redbreast sunfish, striped bass, and shortnose sturgeon.

The intake structure consists of two 2-mm (0.079 in.) slot cylindrical wedgewire screens. The screens are affixed to two 61-cm (24-in.) diameter pipes that project out from a caisson intake structure. They are arranged in line, with their long axis parallel to the river flow. Through-slot velocities were found to be less than 0.15 m/s (0.5 ft/s). It was concluded that potential negative impacts of the screens on eggs and larvae was low because the cross-sectional area of the river was large relative to area influenced by the intake (i.e., probability of organisms encountering the intake screens was low). The lateral distance over which the screens exert an entraining influence on the river was determined to be approximately 8% of the stream width at the intake location. No data were presented with respect to the biological effectiveness of the screen (i.e., impingement or entrainment rates).

Eddystone Generating Station

Cylindrical wedgewire screens were installed for fish protection purposes at the Eddystone Generating Station located on the Delaware River (within the tidal influence) near Philadelphia, Pennsylvania (Veneziale 1992). The four-unit Eddystone station has a generating capacity of 1,400 MW. The screens were installed in front of the cooling-water intakes of Units 1 and 2, which have a combined flow of about 980 cfs (27.8 m^3/s). The Eddystone Station originally had trash racks and traveling water screens for collecting fish and debris. Impingement and entrainment studies revealed that over 3,000,000 fish were impinged on the traveling screens during a single 20-month period. It was concluded that Delaware River resident and migratory fish populations were being adversely affected by the Eddystone Plant. Consequently, resource agencies requested that steps be taken to reduce fish impingement at Eddystone as part of the facility's 316(b) requirements. After an extensive review of available fish protection technologies, the facility chose cylindrical wedgewire screens to replace the existing screens on the basis of past experience and low maintenance costs.

To support the wedgewire screens, a sheetpile bulkhead was installed at the intake. Sixteen cylindrical screens were placed in front of the Unit 1–2 intake structure and perpendicular to the bulkhead (Figure 5-4). The screens are arranged in two rows: eight inboard screens extend 7 ft (2.1 m) out from the bulkhead and eight outboard screens extend 19 ft (5.8 m) out. The screens can be removed for manual cleaning, and an air-burst cleaning system was installed to facilitate debris flushing without removing the screens. Since the screens have been installed, minimal debris accumulation has occurred and there has been no visible damage. The air-burst cleaning system is used infrequently and the screens have experienced no problems with ice buildup. It has been concluded that fish impingement and screen fouling have been eliminated at Eddystone (Veneziale 1992).

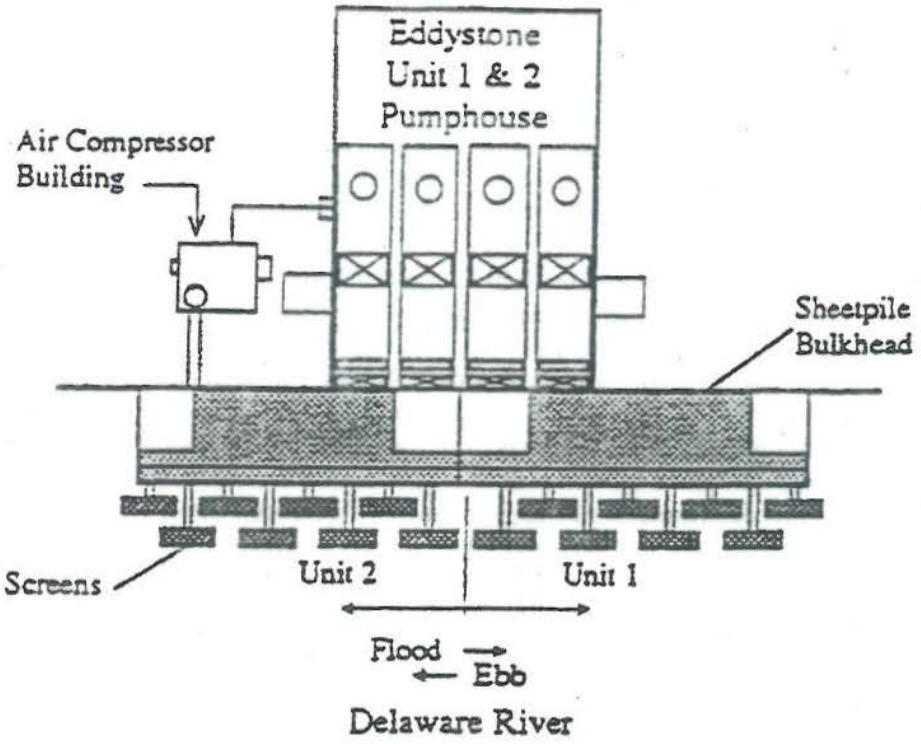


Figure 5-4
Wedgewire Intake System at Eddystone Station (Veneziale 1992)

Jeffrey Energy Center

A cylindrical wedgewire screen cooling water intake system has been operating since 1982 at the Jeffrey Energy Center (JEC) located on the Kansas River in Kansas (Johnson and Ettema 1988). The JEC has three 670 MW units that employ a closed-cycle cooling system. Replacement water for the cooling system is withdrawn from the Kansas River. The river intake system was designed to withdraw up to 111 cfs (3.1 m^3/s), remain free of floating debris, have a sediment-free area around the screens, withdraw water during low flow periods, and have low maintenance requirements (Figure 5-5).

Two screen types were considered for installation at the JEC intake: traveling screens (active screening) and cylindrical wedgewire screens (passive screening). Through-flow traveling screens have been installed at other Kansas River water intakes. These screens have operated efficiently, however, wearing of key parts has contributed to extensive maintenance requirements. Passive screen systems possess no moving parts that can wear or require extensive maintenance. Also, low water velocity between screen wires of cylindrical screens reduces the potential for fish impingement and entrainment. For these reasons, the cylindrical wedgewire screens were chosen for installation with the new intake system at JEC.

The screen system that was installed at JEC comprises three cylindrical wedgewire screens placed along the face of the intake structure (Figure 5-5). The screens are 4 ft (1.2 m) in diameter, about in 3.4 m (11 ft) in length, have slot openings of 10 mm (0.375 in.), and have a flow capacity of 11.3 m/s (37 ft/s), which maintains a 0.15 m/s (0.5 ft/s) through-slot velocity. The screens are capable of being removed for inspection and maintenance. An air backwash system was installed for screen cleaning. The intake system has been operating for several years with minimal problems. The screens have been free of sedimentation and debris accumulation. Maintenance has consisted of daily sediment sluicing and air backwashing and annual sediment basin dredging. No information was provided with respect to the biological effectiveness of the screens.

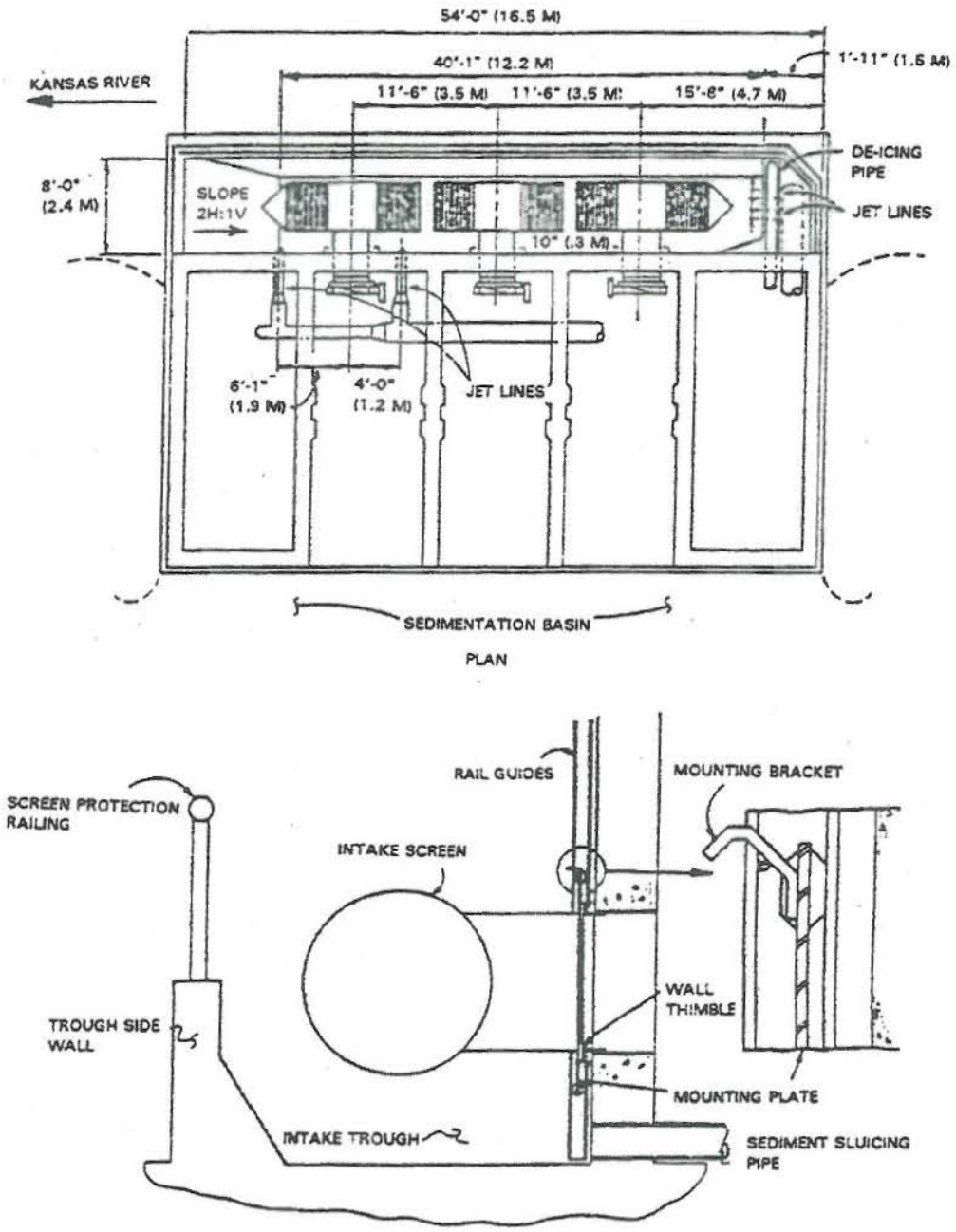


Figure 5-5
Wedgewire Screen Intake System — Jeffrey Energy Center (Johnson and Ettema 1988)

Chalk Point Station

A field evaluation of cylindrical wedgewire screens was conducted at the Chalk Point Station from 1982 to 1983. A modular barge testing facility was placed in the intake canal of the station. The barge had two separate but identical intake ports on which 76-cm diameter cylindrical wedgewire test screens and an open port were attached (Figure 5-6). During testing in 1982, the pumps withdrew approximately 7.7 m^3/min (4.5 cfs), while in 1983, after refurbishing, the pumps withdrew 12 m^3/min (7.1 cfs). The intakes were positioned 1 m below the surface. Screens with slot sizes measuring 1, 2, and 3 mm were evaluated. Average through slot velocities for all of the screens together in 1982 and 1983 were 13 cm/s (0.43 ft/s) and 20 cm/s (0.66 ft/s) respectively.

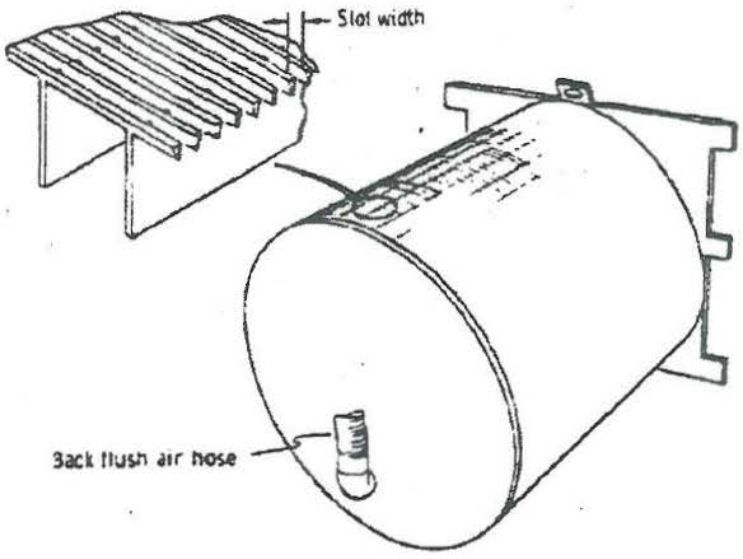


Figure 5-6
Drawing of a Bulkhead-Mounted Screen with Cut Away of Wedgewire Configuration

Samples were collected at night using a 505-μ mesh plankton net located at the discharge from each pump. A total of 24 samples was collected during testing in 1982 and 88 samples were collected in 1983. Ambient ichthyoplankton samples were collected just upstream from the testing barge by towing a bongo net measuring 0.5 m in diameter with a 505-μ mesh at the surface and at depths of 1 and 2 m.

The most abundant fish species collected were bay anchovy and naked goby. Bay anchovies were grouped by length classes of ≤ 4 mm, 5–7 mm, 8–10 mm, 11–14 mm, and ≥ 15 mm. Naked gobies were grouped by length classes of ≥ 4mm, 5–6 mm, 7–8 mm, and ≥ 9 mm. Numbers of fish entrained are presented in Table 5-1.

Table 5-1
Mean Densities (Numbers/1,000 m³ of Water) of Bay Anchovies and Naked Gobies Collected in the Bongo Net from the Canal, Through Each Wedgewire Exclusion Screen, and Through an Open Port in 1982 and 1983 (Weisberg et al. 1987)

Fish Class Size (mm)	August 1982				July 1983				
	Bongo Net	Open Port	Screen		Bongo Net	Open Port	Screen		
			2 mm	1 mm			3 mm	2 mm	1 mm
Bay Anchovy									
Eggs	0.0	0.0	0.0	0.0	19,610	2,341	1,707	18,435	10,966
• 4	2.0	0.0	0.0	0.0	60.0	9.6	13.6	21.0	9.2
5 – 7	4.5	4.1	0.0	0.0	37.6	20.1	11.3	9.2	10.8
8 - 10	6.2	1.6	1.5	0.0	11.2	7.7	2.6	1.6	1.0
11 - 14	152.9	31.1	10.5	0.0	3.5	1.3	0.3	0.0	0.0
• 15	2,469.4	57.3	15.0	1.5	9.3	3.3	0.5	0.4	0.0
Naked Goby									
• 4	95.3	17.2	13.5	1.5	223.5	535.7	557.1	513.4	562.5
5 – 6	117.6	22.9	19.5	6.0	514.8	148.7	87.6	81.6	66.5
7 – 8	95.5	38.5	16.5	5.8	370.5	49.7	11.2	9.6	3.9
• 9	342.3	201.5	64.6	35.8	243.7	49.1	7.8	4.4	1.9

For bay anchovy, the screens had no significant effect (i.e., exclusion) on eggs and larvae measuring ≤ 4mm. Exclusion became apparent at the 5–7-mm length class in 1983, as nearly twice as many anchovy were entrained into the unprotected open intake than into any of the screens. Exclusion increased in with increasing fish length. Although more fish were entrained through the larger slot sizes, the differences were not significant, which may have been due to the small sample sizes.

Although there was a tenfold decrease in entrainment of naked goby measuring ≤ 4mm between the unprotected and 1 mm screen in 1982, the difference was not statistically significant. Exclusion by the 1 mm screen became apparent at the 5–6 mm length in 1983. Further, both years of sampling yielded a significant decrease in the entrainment of fish measuring 7–8 mm and larger.

The authors cite physical exclusion and hydrodynamic exclusion as the two principal modes by which wedgewire screens protect ichthyoplankton from entrainment. Evidence for the physical exclusion caused by the screens is that the smallest slot size (1 mm) excluded more fish than either the 2 or 3 mm screens. Further evidence of physical exclusion is that a head capsule depth of 1 mm was not reached until a length of 9 mm, and there were essentially no fish over 10 mm entrained in the samples. Evidence for the hydrodynamic exclusion is that fish of both species measuring 5 mm in length were not entrained by the 3 mm screen, indicating their ability to swim away from the low-velocity flow near the screen.

Charles Point Recovery Facility

Environmental monitoring studies were conducted at the Charles Point Resource Recovery Facility to evaluate the number, species, and life stage of organisms impinged and entrained by the facility's cooling water system (EA Science and Technology 1986). This wedgewire screen facility has been operating since the early 1980s with little maintenance required (Radle pers. comm. 1999). The biological studies were performed as a requirement of Westchester RESCO's SPDES permit. The facility is located on the east bank of the Hudson River near Peekskill, New York.

The Charles Point Resource Recovery Facility has a design capacity of 60 MW generated by the combustion of municipal solid waste. The once-through cooling system has a flow rate of 2.4 m³/s (85 cfs). The cooling water system consists of an offshore (26.8 m [800 ft]) intake fitted with four pairs of cylindrical wedgewire screens mounted on T-stands approximately 1.5 m (5 ft) above the river bottom. The cylindrical wedgewire screen are 1.4 m (4.6 ft) long, 1.4 m (4.6 ft) in diameter, and constructed of a copper-nickel alloy. The slot width of the screens is 0.5 mm (0.02 in.), resulting in a design through-slot velocity of 0.15 m/s (0.5 ft/s).

The monitoring study was designed to sample ichthyoplankton entrainment and impingement. Entrainment monitoring was conducted using an Automated Abundance Sampler (AUTOSAM). Six samples were collected on each date for a 4-hour duration at approximately 1% of the total flow. A combined total of 15,287 ichthyoplankton was collected by the AUTOSAM from May through October in 1985 and March through April in 1986. The most abundant species collected during entrainment sampling from mid-June through September 1985 was bay anchovy (93.5%). Other ichthyoplankton collected were striped bass (4.2%), white perch (0.9%), and Atlantic tomcod (0.7%). The most abundant lifestage collected in entrainment samples was eggs (67.3%) and post-yolk-sac larvae (31.2%).

Impingement sampling was conducted from May 1985 through April 1986. Organisms were removed from the intake screens by a specially designed apparatus. A series of guide bars were welded lengthwise across each of the screen intake structures to allow a vacuum head to move over the screens and remove impinged organisms. The vacuum head was operated by a diver and attached to a pump that transported impinged organisms into a collection facility. Vacuumed materials were screened though a 500-μ mesh net in order to separate impinged organisms from those that had already passed through the wedgewire screens (Radle pers. comm. 1999).

A total of 175 organisms were collected during 37 samples. Bay anchovy was the most abundant species (70.3%) collected. Atlantic tomcod, striped bass, and white perch comprised 25.7, 1.1, and 0.6% of the total impingements collected, respectively. Similar to entrainment samples, eggs were the most abundant life stage (61.1%) collected during impingement sampling, followed by larvae (33.7%).

Oyster Creek Nuclear Generating Station

A field study was conducted in 1978 to assess the engineering and biological performance of cylindrical wedgewire screens (Brown 1979) at the Oyster Creek Nuclear Generation Station.

The test screens were mounted on a floating test facility that was moored in the intake canal of the the station. The test facility had two 2,000-gpm (7.6 m³/s) vertical pumps. Screens with slot widths of 1, 2, and 3 mm were tested. The screens measured 30 in. (75.6 cm) in diameter, were set at a depth of 3.3 ft (1 m), and were designed to generate an average through slot velocity of 0.5 ft/s (15.2 cm/s) during their evaluation. The screens were also outfitted with air backflushing mechanisms that would activate when a set pressure differential occurred across the screen face. If backwashing did not maintain a differential of less than 1.3 ft (40.6 cm), the screens were raised to the test facility's deck for high-pressure spray washing.

Results of the engineering evaluation revealed that, despite high debris loads during the spring and early summer, all the screens functioned well with respect to the removal of debirs by air backflushing. Overall down time associated with cleaning the screens was 0.02–1.30% and 0.29–1.40% for the 1 and 2 mm screens, respectively. The author suggested that these estimates would be decreased substantially by the addition of an automatic cleaning system.

The biological evaluation of the test screens included entrainment and impingement sampling. Entrainment samples were collected from the pump discharge pipes using 0.5 m diameter plankton nets with 500 µm mesh. Impingement of larger organisms and fish behavior near the screens was monitored concurrently to entrainment sampling.

Organisms were not entrained in large enough numbers to draw any significant conclusions. However, the data that was collected did indicate that fewer target species were entrained through the 1-mm slot screen than through the 2-mm screen and an unscreened intake. Also, target species entrained through the 1-mm screen were generally smaller and narrower than those entrained through the 2-mm screen and the unscreened intake, and densities of target species entrained through the 2-mm screen were sometimes equal to and occasionally greater than densities entrained through the unscreened intake. Entrainment data for opossum shrimp are presented in Table 5-2.

Monitoring of the screens in situ revealed that impingement was negligible for organisms near the screens. However, American eel elvers were observed impinged on the screens or entrapped in the slots during observations made from January to April. Various invertebrates were also found impinged on the screen face, though many crabs, amphipods, and isopods were also seen moving freely along the screen face, possibly feeding on the other impinged organisms. Larval fish (20–25 cm TL), such as silversides, were also seen swimming in the immediate vicinity of the screen in ambient currents of 0.5–0.7 ft/s (15 – 20 cm/s) without any signs of difficulty. Further, impingement of adult fish did not appear to be an issue.

The amount of biofouling on different screen material revealed that, of the four samples tested, the steel containing the highest amount of copper possessed the best antifouling characteristics.

Table 5-2
Density (No./m^3) Length (mm), and Width (mm) of Mysidacea (Opossum Shrimp) in Entrainment Sample Sets Collected January 3, 1979.

	1-mm Screen	2-mm Screen	No screen (control)
Sample Set 1			
Density No./m^3	8.9	22.4	19.3
Density relative to no screen density (%)	46.0	116.0	100.0
Length range (mm)	3.2–7.8	3.3–9.7	3.8–10.1
Mean length (mm)	5.0	6.0	5.7
Width range (mm)	0.4–0.8	0.4–1.1	0.4–1.2
Mean width (mm)	0.6	0.7	0.7
Sample Set 2			
Density No./m^3	16.2	26.6	20.0
Density relative to no screen density (%)	81.0	133.0	100.0
Length range (mm)	3.0–9.3	3.3–10.6	3.5–8.7
Mean length (mm)	5.2	5.6	5.2
Width range (mm)	0.3–1.1	0.4–1.2	0.4–1.0
Mean width (mm)	0.6	0.6	0.6

St. John's River, FL

A study similar to those conducted by Brown (1979) was conducted by Lifton (1979) on the St. John's River in northeastern Florida. The investigations were conducted as a requirement of Section 316(b) during the construction of a coal-fired electric generating station in Putnam County, Florida. In this study, entrainment through 1-mm and 2-mm (0.04 and 0.08 in.) slot wedgewire screens was compared to entrainment through an open pipe and concurrent plankton tows. Entrainment collections were made from March through September for a total of 134 samples. The study was conducted in three phases. Phase I involved in-river sampling to identify species and life stages vulnerable to entrainment. Phase II involved the collection of data on the exclusion differences between 1 and 2-mm screens, and Phase III examined operational feasibility, biofouling, and entrainment mitigation.

Individual egg and larvae fish collections for Phase I were conducted by net tow sampling using a 363-μ mesh plankton net. The wedgewire screen test facility used in Phase II and Phase III was located on an existing dock at the power plant site. Sampling was conducted over an 8-day period, and included visual observations of the wedgewire screens, in-river larval tows, and open pipe entrainment tests to provide control data.

The majority of fish entrained through the 1 and 2-mm screens were unidentified Atherinidae (silverside) species, tidewater silversides, naked goby and clown goby. The predominant species entrained through the open pipe were bay anchovy, tidewater silverside, sunfish, naked goby, and clown goby. Fish eggs and larvae were collected in the 1-mm screen samples. The 2-mm screen also entrained two juveniles and some adult fish were entrained through the open pipe. Results of statistical analyses showed no significant difference in entrainment between the 1 and 2-mm screen with respect to organism densities for all species and life stages. Comparisons of total numbers entrained showed that the screened intakes entrained at least 30 percent fewer fish than the open pipe in 16 of 20 comparisons. In 13 of 20 comparisons, the number of fish entrained was at least 50% less than the open pipe.

J. H. Campbell, Unit 3

Consumers Energy's J. H. Campbell Unit 3 screen system has functioned effectively since 1979. Unit 3 withdraws 21.5 m^3/s (757 cfs) from an offshore location (1,067 m from shore in 10.7 m of water) through 28 fixed wedgewire screening units with 9.5-mm (3/8-in.) wide screen slots. Units 1 and 2 withdraw cooling water from Pigeon Lake, which empties into Lake Michigan adjacent to the station. It was believed that locating the Unit 3 intake in the relatively unproductive lake environment would decrease the potential for entrainment and impingement. When compared to Units 1 and 2, the Unit 3 screens have reduced impingement of gizzard shad, smelt, yellow perch, alewife, and shiner species and have required minimal maintenance (Gulvas and Zeitoun 1979). The screens are cleaned manually by water jets to reduce biofouling (algae). The plant was forced to shut down once (spring 1984) due to anchor ice. Because the screen mesh is 9.5 mm (3/8 in.), this installation achieves no reduction in entrainment other than by virtue of its deep offshore location in an area of low abundance of entrainable-sized fish. Operating experience to date has been satisfactory, due to the large screen slot size and the relatively low debris loading in Lake Michigan.

Case Studies – Hydroelectric Application

Arbuckle Mountain Hydroelectric Project

A cylindrical wedgewire screen system was installed in 1986 at the Arbuckle Mountain Hydroelectric Project located on the Middle Fork of Cottonwood Creek near Redding, California (Ott et al. 1988). The project operates in a run-of-the-river mode, diverts a maximum of 115 cfs (3.3 m^3/s), has a design head of 55 ft (16.8 m), and a generating capacity of about 400 kW. Cylindrical wedgewire screens were selected for Arbuckle Mountain to prevent entrainment of resident and migratory fish and to provide for continuous cleaning to eliminate sediment and debris buildup. Also, a vertical-axis configuration was selected because material and construction costs were less than for a horizontal deployment.

The final design of the screen system installed at Arbuckle Mountain consisted of eight screens, with an intake flow of 0.4 m^3/s (15.7 cfs) per screen. At maximum capacity, the approach velocity component (normal to the screen face) is 0.1 m/s (0.33 ft/s). The screen V-wire was 1.8 cm (0.71 in.) wide with slot openings 2 mm (0.079 in.), yielding an open area of 57%. The screens are mounted on a concrete manifold/plenum chamber and placed in the project forebay.

An internal flow modulator was designed to create uniform flow distribution across the face of the screen cylinders. For debris management, a pneumatically operated programmable controller was developed to automatically initiate cleaning of the eight cylindrical screens with an air burst backwash system. An annular air distributor is mounted outside the flow modulator that introduces air within a cylinder to backflush water for removal of any debris collected on the exterior of the cylinder. Also, a conical deflector mounted internally at the top of each cylinder provides even distribution of the air burst during the backflush cycle. After backflushing, ambient currents remove accumulated debris. Biological evaluations of the screen system have not been performed.

Case Studies – Laboratory and Field Evaluations

Laboratory Test EPRI/EPA, Alden Research Laboratory

The Electric Power Research Institute (EPRI) with Water Quality Cooperative Grant (#X829108010) support from the U.S. Environmental Protection Agency (EPA) sponsored the biological evaluation of cylindrical wedgewire screens. The testing was conducted in a laboratory flume with striped bass larvae and a surrogate egg type in 2001 and with eight additional species in 2002. The tests conducted in 2001 were primarily designed to determine if the test facility and procedures functioned as needed for accurately evaluating the relative effectiveness of the wedgewire screens. These tests also provided the initial set of data on relative impingement and entrainment rates of the organisms that were evaluated.

The section of the test facility flume where testing is performed has a maximum depth and width of 2.1 m and 3.0 m, respectively. For 2001 testing, the width of the flume channel was about 1.5 m and water depth was 1.3 m. Flume width and water depth for 2002 tests were both 1.8 m (a temporary wall was removed and the plexiglass window was repositioned to widen the flume prior to 2002 testing). Channel velocities up to 0.9 m/sec can be maintained at full depth. Flow is re-circulated through the flume by a bow thruster that is driven by an electric motor.

The location of the screens was about 11.4 m downstream of where water is returned to the flume from the bow thruster (Figure 5-7). At this location, one side of the flume consists of a plexiglass window that allows for real-time visual and video observations to be recorded during testing. The wedgewire screen test facility consists of a fish larvae and egg release system, the wedgewire screens, an entrainment collection system, and a downstream collection system. The design of the test facilities used in 2001 and 2002 are presented in Figure 5-8and Figure 5-9, respectively.

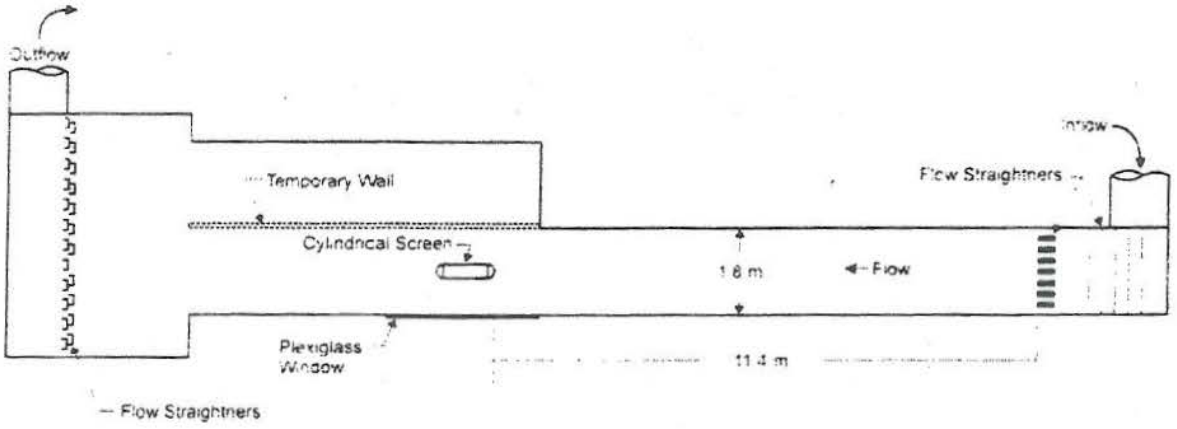


Figure 5-7
Fish Testing Facility and Approximate Location of Cylindrical Wedgewire Screens

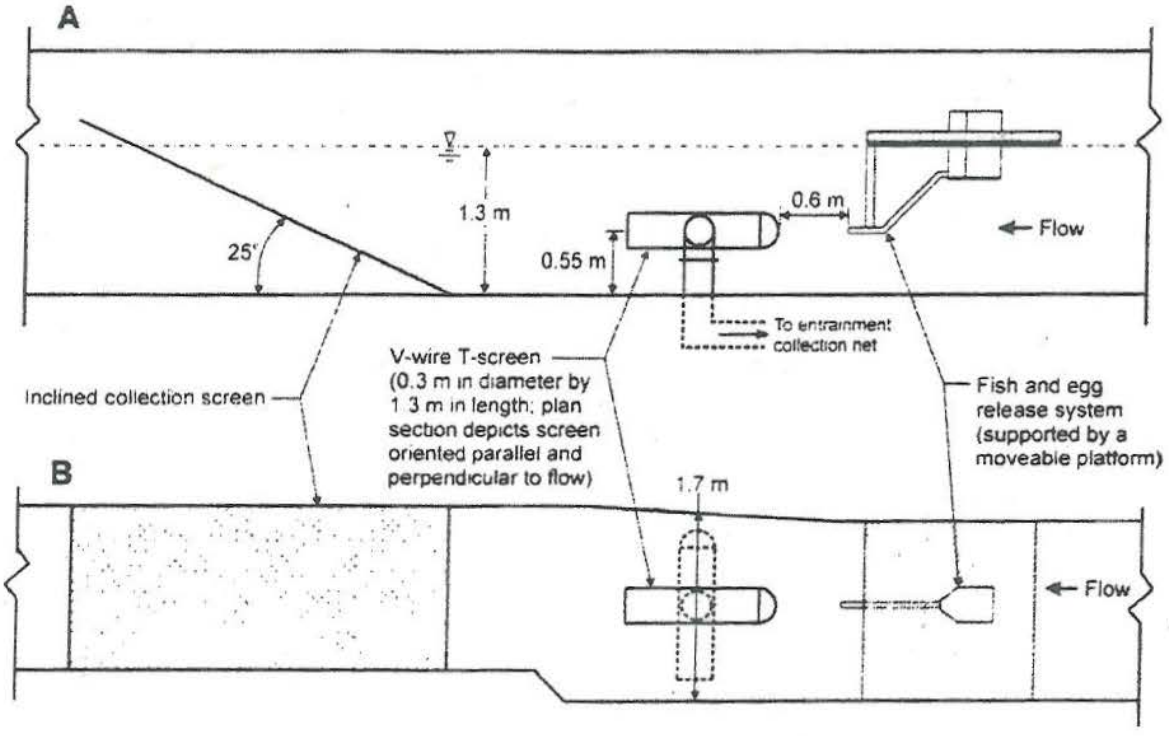


Figure 5-8
2001 Wedgewire Screen Test Facility

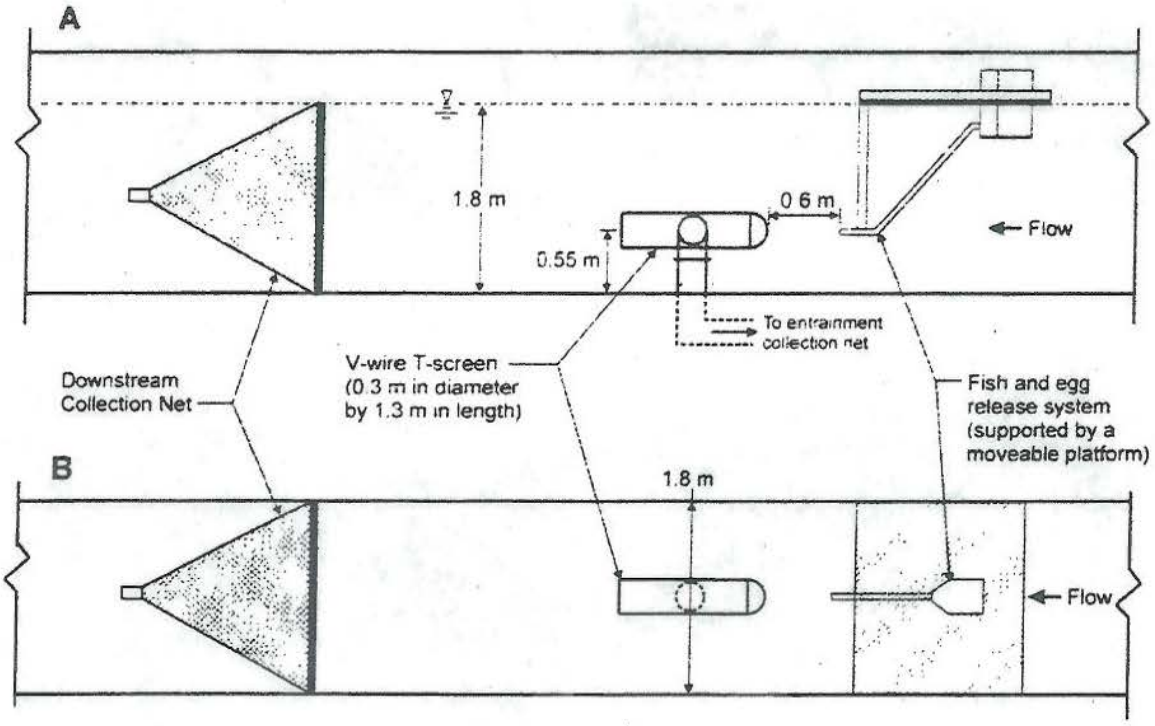
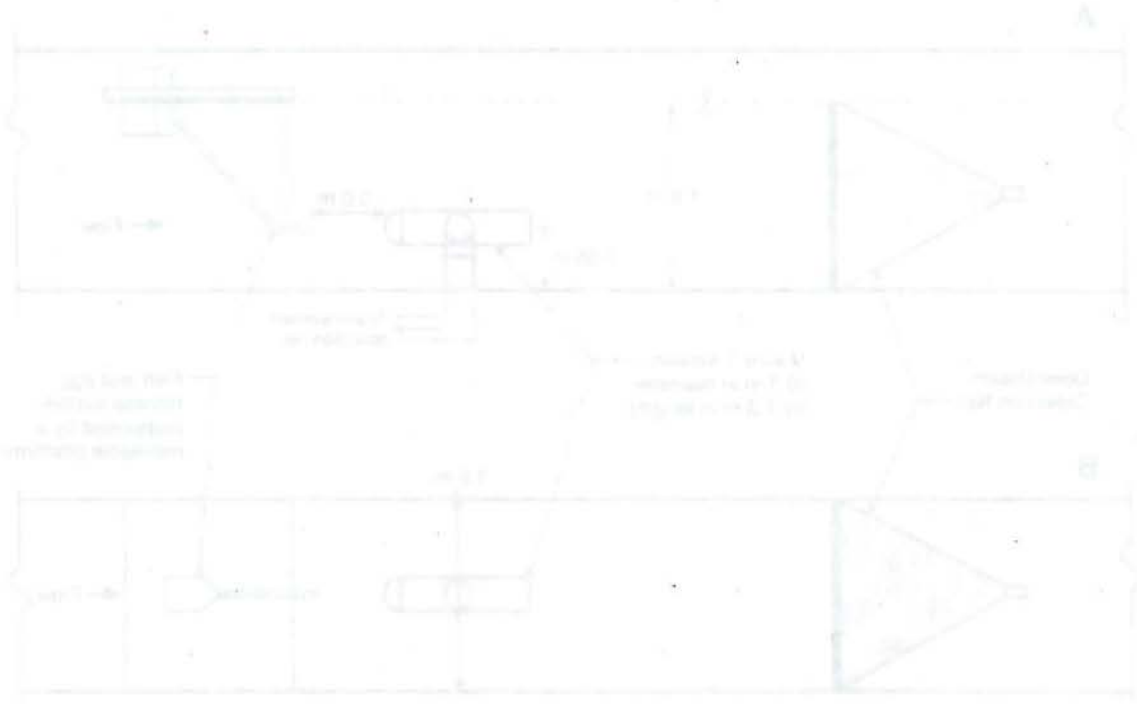


Figure 5-9
2002 Wedgewire Screen Test Facility

The screens that were used for the laboratory evaluation were T-12 (12-inch diameter [30.5 cm]) cylindrical wedgewire screens supplied by Johnson Screen (Figure 5-10). The T-12 screens have two 31-cm long sections through which water is withdrawn. Three screens constructed with different slot sizes (0.5, 1.0, and 2.0 mm) were evaluated to determine fish egg and larval entrainment and impingement rates under different channel and screen flow conditions. All three screens had 1.5-mm wide wedgewire bars. The porosities of the screens were 24.7% for the 0.5-mm slot screen, 39.6% for the 1.0-mm screen, and 56.8% for the 2.0-mm screen. Design information and flow rates at each through-slot velocity that was evaluated are presented in Table 2-1.



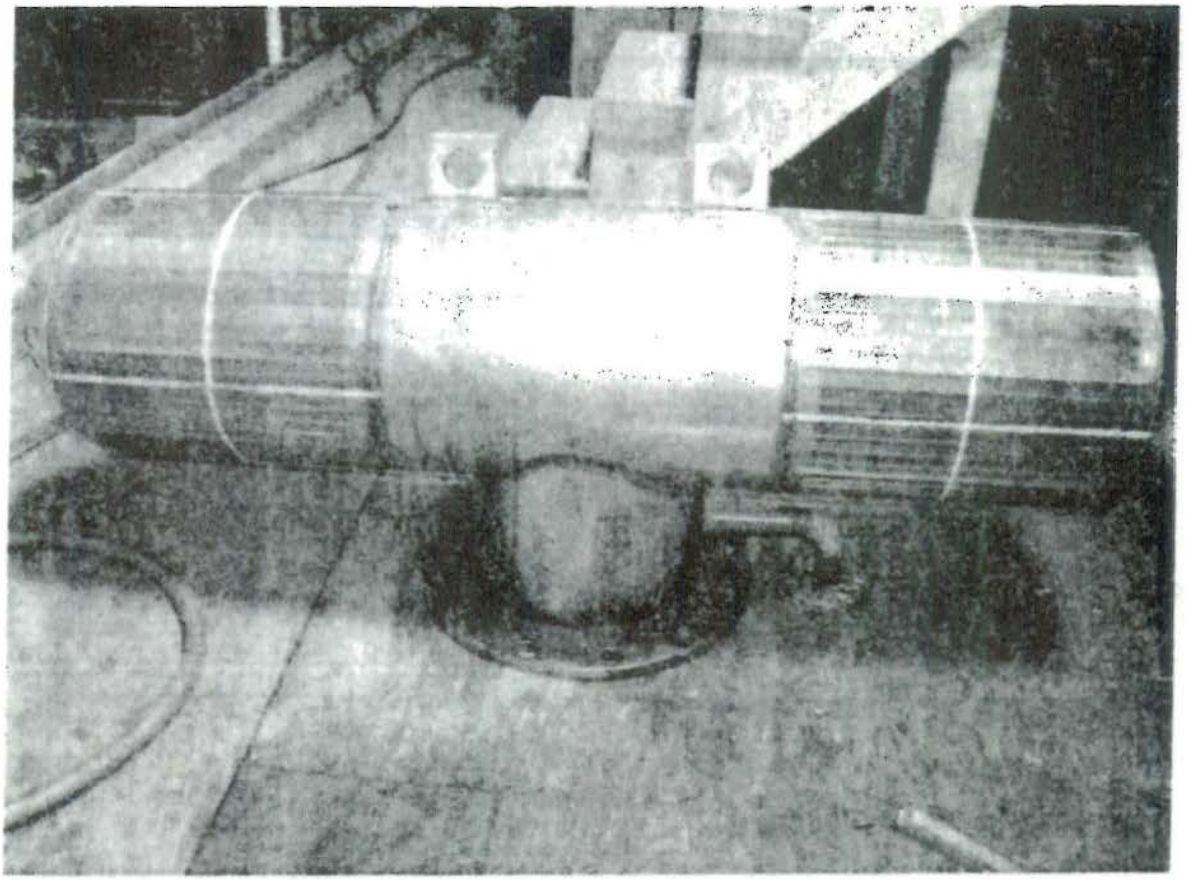


Figure 5-10
Johnson T-12 Cylindrical Wedgewire Screen (White Lines Delineate Sections of the Screen for Which Impingement Locations Were Recorded)

Table 5-3
Wedgewire Screen Design and Operation Parameters Evaluated During the Laboratory Study

Slot size (mm)	Screen Open Area (m^2)	Screen Porosity (%)	Slot Velocity (m/s)	Screen Withdrawal Rate		Channel Velocity (m/s)	Channel Flow Rate			
							2001		2002	
				m^3/s	gpm		m^3/s	gpm	m^3/s	gpm
0.5	0.15	24.7	0.15	0.023	363	0.08	0.15	2376	0.26	4039
						0.15	0.30	4753	0.51	8078
						0.30	0.60	9506	1.02	16,157
			0.30	0.046	726	0.08	0.15	2376	0.26	4039
						0.15	0.30	4753	0.51	8078
						0.30	0.60	9506	1.02	16,157
1.0	0.24	39.6	0.15	0.037	582	0.08	0.15	2376	0.26	4039
						0.15	0.30	4753	0.51	8078
						0.30	0.60	9506	1.02	16,157
			0.30	0.073	1164	0.08	0.15	2376	0.26	4039
						0.15	0.30	4753	0.51	8078
						0.30	0.60	9506	1.02	16,157
2.0	0.35	56.8	0.15	0.053	834	0.08	0.15	2376	0.26	4039
						0.15	0.30	4753	0.51	8078
						0.30	0.60	9506	1.02	16,157
			0.30	0.105	1667	0.08	0.15	2376	0.26	4039
						0.15	0.30	4753	0.51	8078
						0.30	0.60	9506	1.02	16,157

The biological evaluation of cylindrical wedgewire screens successfully identified several important relationships associated with the various factors that effect impingement and entrainment of aquatic organisms. However, these relationships were not always straightforward or easily detectable due to interactions among the test variables and the inability to collect data for all species and life stages with all combinations of test conditions. The following are general conclusions from the analysis of the entrainment and impingement data that were collected:

1. Impingement decreased with increases in slot size
2. Entrainment increased with increases in slot size
3. Entrainment and impingement increased with increases in through-slot velocities

4. Entrainment and impingement decrease with increases in channel velocity

This study identified several biological factors that can influence wedgewire screen impingement and entrainment rates, including life stage, size, and swimming ability. These factors appeared to be strongly related; although for larvae, life stage is probably inconsequential compared to size and swimming ability. Specifically, as fish mature during early life stages, they grow larger and swimming ability improves, allowing for greater physical and behavioral exclusion to occur. The most pronounced effect of life stage is associated with differences between passive eggs and actively swimming larvae. The entrainment and impingement of eggs during our study were related to the size of eggs and hydraulic conditions that influenced downstream movement of eggs along the screen surface. Alewife eggs, which averaged 0.7 mm in diameter, did not impinge on the 0.5 mm slot screen but were entrained at rates of 10 to 20% for the two channel velocities evaluated. The entrainment rate at the lower channel velocity was nearly 50% greater than at the higher velocity. In contrast to alewife, white sucker and surrogate striped bass eggs were not entrained but were susceptible to impingement depending on the hydraulic conditions being evaluated. For both these species, egg impingement rates increased with slot velocity and decreased with channel velocity.

Based on the estimates of entrainment and impingement for larvae and eggs, protection of aquatic organisms using cylindrical wedgewire screens will be optimized by minimizing slot size and slot velocity and maximizing ambient currents approaching a screen or screen array. Design and operation criteria that result in optimization of these parameters will be dependent on the target species and life stages. Older and larger organisms will not require as stringent criteria as younger and smaller organisms that do not possess the size or swimming ability to avoid impingement and entrainment. Using less than optimum slot size and velocity criteria may be appropriate if wedgewire screens are located where species and life stages that are potentially susceptible to entrainment and impingement are not abundant.

The data that was gathered during the biological and CFD components this study clearly demonstrate that this technology can effectively protect early life stages of fish from entrainment and impingement when designed according to appropriate biological and hydraulic criteria. It was concluded that future studies, whether conducted in the laboratory or field, should focus on interrelationships among a smaller set of design criteria or for specific species and life stages. Such studies are expected to provide more specific descriptions and a better understanding of the relationships between biological and engineering design parameters that maximize fish protection effectiveness.

Laboratory Evaluation – Delmarva Power and Light

Laboratory studies were conducted Delmarva Power and Light to assist in the development of a surface water intake using wedgewire screens that would be effective in protecting the early life stages of fishes (Hanson et al. 1977). These studies were initially conducted to determine the entrainment and impingement of striped bass eggs, larvae, and juveniles but were later expanded to include other fish species. Additional studies were also performed to investigate potential egg mortality associated with screen contact and impingement.

The majority of the experiments were carried out in a 9.1 by 4.6 m (30 by 15 ft) oval flume (Figure 5-11). The flume was constructed of aluminum and plywood and was 8.4 m (2.6 ft) wide and 12.2 m (4 ft) deep. The test screens were placed in the flume and were evaluated under both static (no flume flow) and dynamic (flume flow past the screens) conditions. A 5 hp horizontal pump was used to withdraw flow through the screens with a maximum pump rate of 0.03 m^3/s (1.13 cfs).

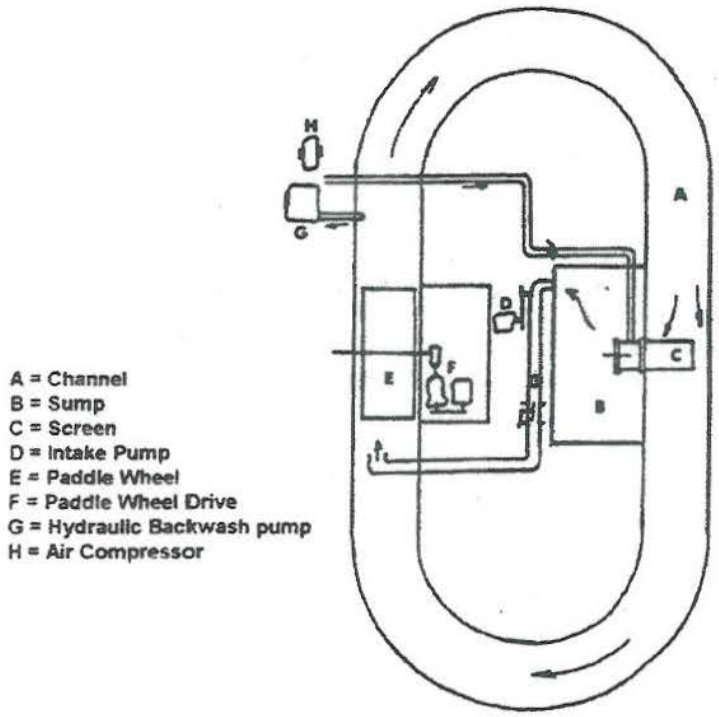


Figure 5-11
Schematic Diagram of Wedgewire Test Flume (Hanson et al. 1977)

Egg mortality studies were conducted with a flat 30.5 cm (12 in.) square screen panel with a 0.5-mm (0.020 in.) slot width. The panel screen was placed on the flume wall orientated perpendicular to the flow. The test screens used to evaluate the exclusion of striped bass eggs, larvae, and juveniles had slot widths of 1 mm (0.040 in.) or less. Tests with larval striped bass employed cylindrical wedgewire screens with a diameter of 30.5 cm (12 in.) and a length of 61 cm (24 in.). The cylindrical screens were placed horizontally across the flume channel at about mid-depth (Figure 5-11).

Striped bass eggs used in the mortality studies were obtained from an onsite hatchery. The experiments consisted of 30-, 60-, and 120-second impingement trials using live eggs. Trials had one replicate and one control for each duration. The number of dead eggs was counted and recorded every 30 minutes. Egg impingement trials were conducted by releasing a known number of live eggs into a 0.15 m/s (0.5 ft/s) current approximately 1.2 m (4 ft) upstream of the test screen panel. After the eggs had been impinged for the specified duration, they were

siphoned off the screen into a jar and observed for mortality at 5, 20, 45, and 60 minutes for the first two tests and at 5, 30, and 60 minutes for the remaining tests. A total of 6,945 striped bass eggs were used in 26 tests. The eggs ranged in developmental stage from gastrula to fully developed embryo.

Statistical tests revealed significant differences between control and test mortality at the 30-minute impingement observations. The gastrula and early embryo developmental stages suffered higher mortality than other stages in both test and control specimens. Mortality resulting from impingement ranged from none to 11.9%. Overall, mean mortality from impingement was 1.4%. Most mortality occurred within the first 30 minutes of impingement.

Experiments were performed to determine swimming ability and avoidance behavior of striped bass larvae exposed to a wedgewire screen in static mode (i.e., all flow withdrawn through test screen with no channel cross-flow). Groups of 50 or less larvae were introduced into the flume and allowed to acclimate for up to 3 hours. The specimens were then released into the test area, which was formed by the screen and a cage that kept them in close proximity to the screen. For each test, a velocity of 0.04–0.15 m/s (0.13–0.50-ft/s) was established through the test screen and subsequent behavior of test organisms was noted. The tests were run until all of the larvae were entrained, which generally occurred in less than 5 minutes. The larvae were recovered from the screen discharge pipe in a 500 μ mesh net. Condition and length of the recovered specimens was then recorded and the surviving larvae were held separately for later experiments.

More than 1,000 larval striped bass were used in 42 tests. Swimming performance and ability to avoid entrainment was rated on an individual and group basis. Avoidance behavior was displayed in all the experimental trials. Many specimens exhibited resistance even when contact was made with the screen. Specimens that did not contact the screen were entrained more passively.

Larger fish were acquired in seine collections from nearby sources. Some striped bass were also supplied by the onsite hatchery. The larger test specimens were given 4–16 hours to acclimate to the test flume water and another 5–20 minutes to acclimate to the test cage. Two different testing procedures were used for the tests with larger fish. In the first procedure, the screen velocity was started at a set rate and then increased 0.06 m/s (0.2 ft/s) at 10-minute intervals until the maximum rate was reached. The second procedure used a similar incremental increase in velocity, however, the velocities were held constant for 30-minute intervals. The specimens were monitored continuously throughout the testing period for impingement, entrainment, and behavior.

The major factors that influenced impingement included intake velocity, fish size, and behavior. The impingement study of larger fish used a total of 1,387 fish representing 20 species (Table 5-4). Intake velocities up to 0.5 m/s (1.53 ft/s) were tested with the 10.2 mm (0.40 in) slot width screen. The majority of the experiments were conducted in the static mode (i.e., no channel flow) with fish contained in close proximity to the screen. The authors assumed that these were worst-case conditions due to constant exposure and lack of bypass currents to lessen entrainment and impingement. Fish interactions with the screens were rare in tests conducted in the dynamic mode (i.e., with channel flow). Impingement and interaction of fish with the screens varied by species. Of the 1,318 fish tested in the static mode, only 20% of the 261 fish that became impinged failed to escape the screen after impingement. The authors suggest that handling stress

may have contributed to fish that experienced prolonged impingement. Thirty-four specimens died as a result of testing. The authors note that most of these fish were in poor condition prior to the impingement trials (Hanson et al. 1977).

Table 5-4
Impingement Occurrence (Hanson et al. 1978)

Species	n	FL (mm)	Intake Velocity (ft/s)	I.O.[a]	Escapes	Fish-min.[b]	Mean Impingement Duration (min.)	Susceptibility Index[c]
alewife	37	37-65	0.50-1.50	0	--	--	--	0.0000
Atlantic menhaden	77	38-145	0.50-1.50	15	12	34.25	2.28	0.0164
bay anchovy	68	25-71	0.50-1.50	85	73	214.95	2.53	0.1202
carp	39	17-30	0.00-0.79	7	7	26.00	3.71	0.0118
silvery minnow	4	30-31	0.50-1.50	0	--	--	--	0.0000
golden shiner	14	35-56	0.21-1.42	0	--	--	--	0.0000
spottail shiner	34	23-77	0.50-1.50	5	1	186.01	37.20	0.2989
banded killifish	10	34-89	0.96-1.42	0	--	--	--	0.0000
mummichog	7	37-75	0.98-1.42	0	--	--	--	0.0000
tidewater silverside	44	27-81	0.41-1.50	5	5	0.29	0.06	0.0001
Atlantic silverside	136	34-95	0.50-1.50	7	7	0.09	0.01	T[d]
threespine stickleback	1	23	1.00	2	2	0.04	0.02	0.0013
white perch	96	21-41	0.50-1.50	24	24	4.79	0.20	0.0017
striped bass	648	8-151	0.31-1.50	77	49	996.96	12.95	0.0335
pumpkinseed	3	70-91	1.50	0	--	--	--	0.0000
bluegill	30	25-98	0.20-1.50	0	--	--	--	0.0000
yellow perch	18	34-40	0.50-1.50	0	--	--	--	0.0000
bluefish	4	64-135	0.41-1.25	0	--	--	--	0.0000
weakfish	53	31-93	0.50-1.50	13	13	0.70	0.05	0.0004
spot	64	36-98	0.50-1.50	23	19	71.65	3.12	0.0427

[a] I.O. = Impingement Occurrence
Fish-min = the sum of the products of the number of fish and the time exposed to any event
Susceptibility Index = [I.O.-E.S./I.O. + 1] [F.M./T.F.M.]
where:

I.O. is the number of impingement occurrences
E.S. is the number of escapes
F.M. is fish-min impinged
T.F.M is total fish-min exposed

[d] T<0.00005

These laboratory studies were followed by in situ tests on the Chesapeake and Delaware Canal. A test facility was installed with a single 1-mm slot wedgewire screen capable of withdrawing up to 4.4 m/s (154 cfs) with a corresponding slot velocity of 0.24 m/s (0.8 ft/s). A series of 24-hr studies was conducted once each month from June through September. Samples were taken every 3 hours in conjunction with concurrent ichthyoplankton tows at a nearby station. The majority of eggs collected were bay anchovy. White perch and bay anchovy accounted for the majority of larvae collected. Statistical analysis showed that the density of prolarvae, post-larvae, juvenile, and all life stages combined was significantly lower in entrainment samples than in towed ichthyoplankton samples (Hanson et al. 1978).

Field Evaluation - Narragansett Bay, RI; Portage River, OH; and Chesapeake Bay, VA

EPRI conducted field evaluations of narrow-slot wedgewire screens to examine entrainment rates of naturally-occurring fish species and life stages at three sites with unique hydraulic and environmental conditions. The previous EPRI laboratory study (EPRI 2003) identified key aspects of design and operation that affect the biological performance of narrow-slot wedgewire screens. The subsequent EPRI field studies were conducted as follow-up testing to quantify the effects of environmental variables, such as non-uniform flows, debris, and biofouling, on entrainment of ichthyoplankton. Specifically, the initial objective was to estimate entrainment rates of naturally-occurring fish species from one estuarine site and one freshwater site through 0.5 and 1.0-mm wedgewire screens. A second estuarine site was selected for testing after the first year of study was completed at the first two sites.

A floating barge test facility was constructed specifically for the field evaluations of wedgewire screens (Figure 5-8). The barge had intakes for two wedgewire screens and an open port on the bow. The port-side intake was capped with a 0.5-mm slot cylindrical screen and the starboard-side intake was capped with a 1.0-mm slot cylindrical screen. The open port was capped with a 9.5-mm (3/8-in) coarse debris screen and was located between the two wedgewire screen intakes. Two hydraulically driven fish pumps were used to withdraw water through the open port (control) intake and either one of the two wedgewire screen (treatment) intakes. Water was discharged into 330-μ mesh plankton nets to collect entrained ichthyoplankton. Ambient ichthyoplankton density was determined by sampling from the side of the barge with a 335-μ mesh plankton net.

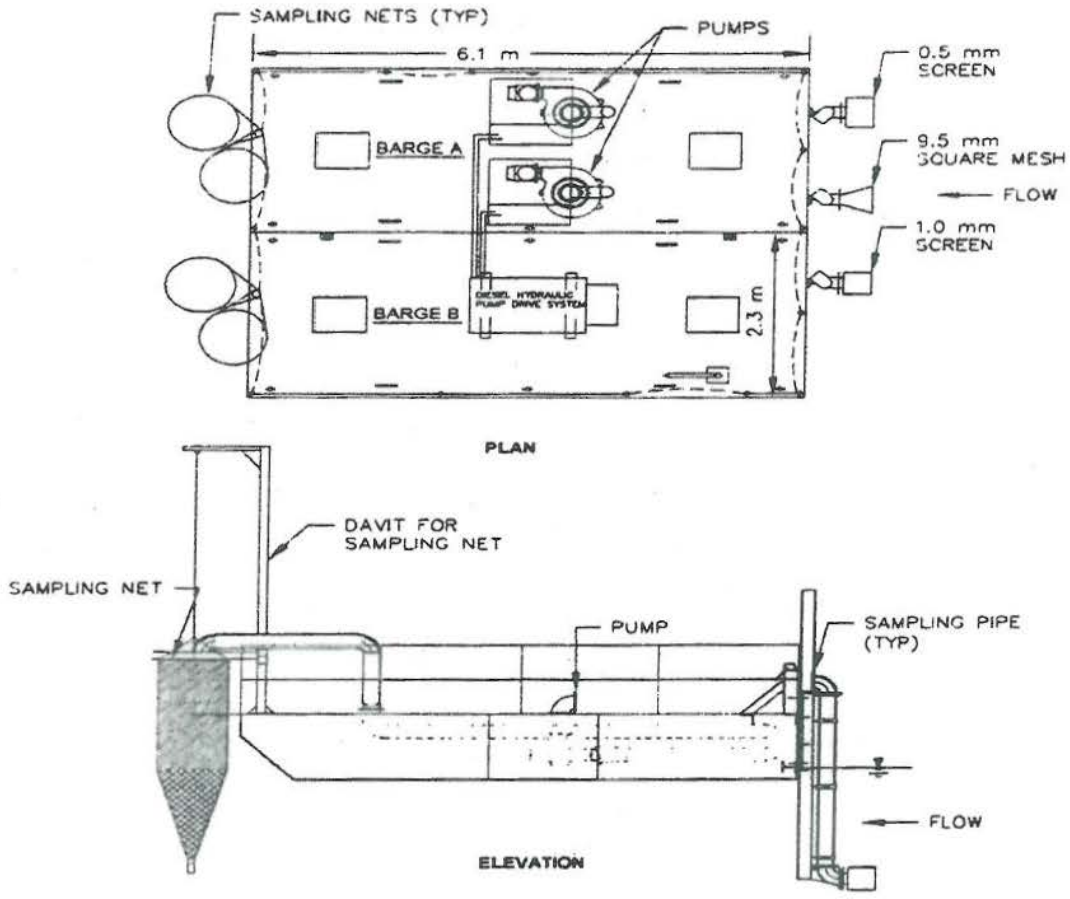


Figure 5-12
Test Facility in Plan and Elevation View. Note That Flexible Hoses Connecting Pumps to Sampling Pipes Have Been Omitted from Both Views For Clarity.

The two test screens were constructed of single-screen, stainless steel, wedgewire (Johnson Screens). The control intake simulated the conical intakes found at the majority of conventional traveling water screens. The 0.5-mm screen was 41 cm (16.1 in) in diameter and 46 cm (18.1 in) in length with a discharge diameter of 20 cm (7.9 in). The 1.0-mm screen was 30 cm (11.8 in) in diameter and 36 cm (14.2 in) in length with a discharge diameter of 15 cm (5.9 in). Porosities of the 0.5-mm screen, 1.0-mm screen, and the 9.5-mm mesh-covered control port were 23.8, 38.5, and 70.6% respectively. Sizing of the wedgewire screens and control intake were such that respective through-slot velocities were equal at a given flow rate.

The first estuarine site seletcted for testing was on the Sakonnet River within Narragansett Bay and was selected for its abundance of target species and absence of dredging activity. Testing was conducted five to seven days per week in April and May of 2004. The barge was moored approximately 100 m from the eastern shore of the river in 15.7-m deep water. The intakes were positioned at a depth 1.5 m (on center) below the water surface. Six trials averaging 55 minutes in duration were completed daily. Sampling was conducted from one hour after high tide until one hour after low tide.

The independent variables evaluated in this study included slot width (0.5 and 1.0 mm), screen slot velocity (0.15 and 0.30 m/s), and ambient velocity (0 to 1.1 m/s). Each combination of treatment conditions was replicated 10 times. All collected larvae were enumerated, identified to species when possible, and preserved for subsequent analysis. A subset of individuals was measured for length and head capsule depth (HCD). An ambient sample averaging 60 m^3 was collected with a plankton net towed 20 m downstream of the test facility at a depth of 1.5 m. This ambient sample served to characterize species composition and densities. Comparative densities of entrained eggs and larvae between paired test and control intakes provided relative effectiveness measurements of entrainment reduction.

The freshwater site was located on the Portage River approximately 600 m upstream of Lake Erie. This site was selected for its high concentrations of target great lakes species. Testing was conducted seven days a week in May and June of 2004 and is procedurally similar to the Sakonnet River site unless otherwise noted. The barge was moored in 2.4-m deep water. The intakes were positioned 1.2 m below the water surface. Unlike the tidal estuarine sites, the effects of ambient water velocity could not be ascertained due to the absence of any predictable variation in water velocities. Therefore, two trials, averaging 4 hours in duration, were conducted daily to maximize sample sizes. Each pair of trials evaluated the same slot size, but different slot velocities. Each test condition was replicated 10 times. To minimize mechanical damage to larvae, entrainment nets were rinsed hourly during each 4-hr trial. All collected larvae were enumerated, identified to species when possible, and preserved for subsequent analysis. An ambient ichthyoplankton sample averaging 60 m^3 was collected for each trial by towing a plankton net 20 m behind a john boat. Comparisons between treatment and control entrainment densities were analyzed as described above for the Sakkonet River site.

A total of 11 species of larval fish were collected during the Sakonnet River sampling. Sand lance, winter flounder, and grubby comprised 51, 34, and 13%, respectively, of all larval fish collected. These were the only species collected in sufficient quantity for statistical analysis. A total of 15 species of larval fishes were collected during the Portage River sampling. While 93% of all larvae collected at this freshwater site were shad species (Clupeidae), sufficient numbers of Carp (Cyprinidae), freshwater drum, and temperate basses (Morone spp.) were collected to allow statistical analysis.

The mean densities of all larvae and eggs collected in treatment, control, and ambient samples during Sakonnet River testing are presented in Table 5-5 through Table 5-8. For grubby, the 0.5-mm screen significantly reduced entrainment by more than 92% for all length classes combined. For larvae greater than 7 mm in length, the reduction increased to 100%. The 1.0-mm screen significantly reduced entrainment of grubby over 7 mm by 84%. The 0.5-mm screen significantly reduced the entrainment of sand lance by 80 and 93% for all length classes combined. The 1.0-mm screen offered no significant reduction in entrainment for sand lance. For winter flounder, which were considerably smaller than other species, the 0.5-mm screen significantly reduced entrainment of all combined length classes by 44 -56%. The 1.0-mm screen did not offer any significant reduction in entrainment to winter flounder. Both the 0.5- and 1.0-mm screens significantly reduced entrainment of 4 to 6-mm shad by 62 and 47%, respectively, at the higher slot velocity (0.30 m/s), but not at the lower slot velocity (0.15 m/s). Overall, the 0.5-mm screen reduced the entrainment of all larvae at the Sakonnet River site by 82 and 72% at the 0.15 and 0.30 m/s slot velocities, respectively. For all larvae combined, the 1.0-mm screen offered no significant reduction in entrainment at either slot velocity. The 0.5-mm screen significantly reduced the entrainment of eggs by 93 and 100% at slot velocities of 0.15 and 0.30 m/s, respectively (Table 5-13). Although mean densities were lower in treatment samples, no significant reduction in the entrainment of eggs was observed with the 1.0-mm screen.

The mean densities of all larvae and eggs collected in treatment, control, and ambient samples during Portage River testing are presented in Table 5-9 through Table 5-14. For shad, the 0.5-mm screen only produced a significant reduction in entrainment (98% reduction) at a slot velocity of 0.15 m/s for fish between 7 and 9 mm. Similarly, the 1.0-mm screen only produced a significant reduction in entrainment under one test condition, a 47% reduction at a slot velocity 0f 0.30 m/s for fish between 4 and 6 mm. For carp, the 0.5-mm screen produced no significant reduction in entrainment, while the 1.0-mm screen did at 0.30 m/s. For freshwater drum, there were no significant reductions in entrainment at any test conditions despite large differences between treatment and control densities. For temperate basses, despite reductions over controls of over 65% for each test condition, the statistical analysis revealed no significant differences in densities. The paucity of carp, freshwater drum, and temperate bass collected during this study (less than 5% of the total) limited the statistical power of the analysis. The 0.5-mm screen significantly reduced the entrainment of eggs by 98 and 93% at slot velocities of 0.15 and 0.30 m/s, respectively (Table 5-14). Although the mean density of eggs at 0.15 m/s with the 1.0-mm screen was considerably lower, no significant reduction was detected in the analysis.

Table 5-5
Mean density and standard deviation (SD) of grubby larvae collected at the Sakkonet River site in ambient, control, and test samples during trials with 0.5 and 1.0 mm screens at slot velocities of 0.15 and 0.30 m/s. C-T is the percent difference between test and control densities.a Asterisks indicate a statistically significant difference between test and control densities ($p<0.05$).

Slot Width (mm)	Slot Velocity (m/s)	Larval Length (mm)	Mean Number Entrained per 100 m^3 (SD)			C-T Percent Difference (Valid Trials)
			Ambient	Control	Test	
0.5	0.15	≤3	0.7 (2.4)	0.9 (2.4)	0.1 (0.4)	92.5 (7)
		4-6	12.2 (15.5)	8.9 (14.0)	0.4 (0.9)	95.8 (19)*
		7-9	5.9 (7.9)	3.2 (7.2)	0.0 (0.0)	100.0 (10)*
		≥10	0.8 (1.3)	0.7 (1.7)	0.0 (0.0)	100.0 (5)*
		All	19.5 (23.2)	13.7 (23.2)	0.4 (1.2)	96.7 (19)*
	0.30	≤3	0.0 (0.0)	0.1 (0.5)	0.0 (0.2)	77.8 (4)
		4-6	8.9 (9.2)	7.6 (13.8)	0.7 (1.1)	90.2 (23)*
		7-9	1.6 (3.3)	2.3 (4.9)	0.0 (0.0)	100.0 (12)*
		≥10	0.5 (0.7)	0.4 (0.8)	0.0 (0.0)	100.0 (7)*
		All	12.5 (11.4)	10.4 (18.0)	0.8 (1.1)	92.5 (23)*
1.0	0.15	≤3	0.6 (2.0)	1.5 (3.9)	0.8 (2.5)	44.6 (13)
		4-6	6.5 (5.8)	7.3 (16.6)	4.8 (9.3)	33.7 (26)
		7-9	1.8 (4.8)	1.8 (4.4)	0.3 (1.6)	83.8 (9)*
		≥10	0.8 (2.1)	0.2 (0.9)	0.0 (0.0)	N/A[b]
		All	9.9 (10.3)	10.8 (22.8)	6.0 (11.8)	44.5 (26)*
	0.30	≤3	0.3 (0.9)	0.5 (0.9)	0.2 (0.4)	63.2 (7)
		4-6	3.7 (6.4)	5.2 (12.0)	3.3 (6.2)	35.9 (18)
		7-9	2.6 (5.6)	1.7 (3.5)	0.2 (0.9)	89.1 (10)*
		≥10	2.0 (4.9)	0.0 (0.2)	0.0 (0.0)	N/A[b]
		All	8.6 (16.5)	7.3 (15.3)	3.7 (7.0)	50.1 (21)*

a "C-T Percent Difference" is calculated as [(control density minus test density) divided by control density]. Thus, positive values indicate lower densities in test samples.
b *Insufficient data for meaningful comparison*

Table 5-6
Mean density and standard deviation (SD) of sand lance larvae collected at the Sakkonet River site in ambient, control, and test samples during trials with 0.5 and 1.0 mm screens at slot velocities of 0.15 and 0.30 m/s. C-T is the percent difference between test and control densities.[a] Asterisks indicate a statistically significant difference between test and control densities ($p<0.05$).

Slot Width (mm)	Slot Velocity (m/s)	Larval Length (mm)	Mean Number Entrained per 100 m^3 (SD)			C-T Percent Difference (Valid Trials)
			Ambient	Control	Test	
0.5	0.15	≤5	0.0 (0.0)	0.8 (1.7)	0.2 (0.6)	78.6 (6)*
		6-10	57.6 (80.2)	43.6 (102.9)	2.9 (7.5)	93.4 (16)*
		11-15	34.9 (45.0)	4.7 (13.6)	0.1 (0.3)	98.8 (8)*
		≥16	0.7 (1.4)	0.1 (0.5)	0.0 (0.0)	100.0 (2)
		All	91.6 (114.6)	47.5 (112.6)	3.2 (7.5)	93.3 (17)*
	0.30	≤5	0.0 (0.0)	1.1 (3.0)	0.9 (1.9)	15.0 (11)
		6-10	38.5 (56.0)	20.0 (35.9)	4.0 (9.1)	80.0 (20)*
		11-15	28.8 (97.4)	1.3 (2.4)	0.1 (0.2)	95.9 (12)*
		≥16	5.8 (17.4)	0.3 (1.0)	0.0 (0.0)	100.0 (4)
		All	87.5 (134.4)	24.9 (38.9)	4.9 (9.8)	80.2 (23)*
1.0	0.15	≤5	0.0 (0.0)	0.9 (2.1)	1.0 (3.1)	-15.3 (8)
		6-10	41.5 (49.3)	10.3 (16.1)	13.4 (20.0)	-29.8 (23)
		11-15	32.6 (49.8)	1.4 (2.9)	1.1 (3.6)	23.9 (11)
		≥16	7.6 (25.3)	0.2 (1.1)	0.0 (0.0)	N/A[b]
		All	81.8 (89.8)	12.8 (18.8)	15.5 (23.0)	-20.8 (24)
	0.30	≤5	0.0 (0.0)	0.8 (1.7)	0.9 (2.3)	-13.2 (9)
		6-10	61.0 (88.4)	20.0 (40.1)	19.5 (33.3)	2.5 (14)
		11-15	50.1 (51.9)	1.0 (1.6)	1.4 (2.5)	-43.7 (9)
		≥16	29.8 (39.5)	0.2 (0.3)	0.0 (0.0)	100.0 (4)
		All	111.8 (122.1)	19.0 (35.4)	18.6 (33.1)	2.2 (21)

[a] "C-T Percent Difference" is calculated as [(control density minus test density) divided by control density]. Thus, positive values indicate lower densities in test samples.
[b] Insufficient data for meaningful comparison

Table 5-7
Mean density and standard deviation (SD) of winter flounder larvae collected at the Sakkonet River site in ambient, control, and test samples during trials with 0.5 and 1.0 mm screens at slot velocities of 0.15 and 0.30 m/s. C-T is the percent difference between test and control densities.[a] Asterisks indicate a statistically significant difference between test and control densities ($p<0.05$).

Slot Width (mm)	Slot Velocity (m/s)	Larval Length (mm)	Mean Number Entrained per 100 m^3 (SD)			C-T Percent Difference (Valid Trials)
			Ambient	Control	Test	
0.5	0.15	≤3	13.5 (12.9)	12.3 (12.0)	8.2 (11.8)	33.6 (24)*
		4-6	16.0 (14.0)	13.4 (18.3)	3.1 (5.4)	76.9 (20)*
		7-9	1.9 (2.3)	0.0 (0)	0.0 (0.0)	N/A[b]
		≥10	0.0 (0.0)	0.0 (0)	0.0 (0.0)	N/A[b]
		All	31.4 (19.5)	25.7 (26.0)	11.3 (14.7)	56.2 (24)*
	0.30	≤3	17.5 (16.9)	6.0 (5.3)	5.3 (5.9)	10.9 (26)
		4-6	45.6 (82.5)	11.4 (12.4)	4.4 (6.6)	61.2 (24)*
		7-9	5.0 (13.5)	0.0 (0.2)	0.0 (0.2)	-30.6 (2)
		≥10	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	N/A[b]
		All	77.0 (89.9)	17.4 (15)	9.8 (11.0)	43.8 (26)*
1.0	0.15	≤3	30.0 (22.0)	10.1 (8.8)	12.0 (9.0)	-18.6 (30)
		4-6	34.5 (19.8)	10.0 (10.2)	9.4 (12.0)	5.8 (31)
		7-9	3.1 (8.0)	0.3 (1.1)	0.3 (1.5)	-16.4 (4)
		≥10	0.1 (0.4)	0.0 (0.0)	0.0 (0.0)	N/A[b]
		All	67.7 (29.8)	20.4 (16.2)	21.7 (17.0)	-6.7 (31)
	0.30	≤3	18.2 (16.5)	5.9 (6.1)	4.3 (4.9)	26.6 (24)
		4-6	14.7 (12.6)	9.0 (8.8)	8.0 (11.0)	11.0 (22)
		7-9	0.7 (1.4)	0.2 (0.6)	0.1 (0.3)	44.2 (4)
		≥10	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	N/A[b]
		All	33.3 (20.6)	14.5 (14.7)	12.1 (13.1)	16.9 (25)

[a] "C-T Percent Difference" is calculated as [(control density minus test density) divided by control density]. Thus, positive values indicate lower densities in test samples.
[b] Insufficient data for meaningful comparison

Table 5-8
Mean density and standard deviation (SD) of larvae (all species) collected at the Sakkonet River site in ambient, control, and test samples during trials with 0.5 and 1.0 mm screens at slot velocities of 0.15 and 0.30 m/s. C-T is the percent difference between test and control densities.[a] Asterisks indicate a statistically significant difference between test and control densities ($p<0.05$).

Slot Width (mm)	Slot Velocity (m/s)	Larval Length (mm)	Mean Number Entrained per 100 m^3 (SD)			C-T Percent Difference (Valid Trials)
			Ambient	Control	Test	
0.5	0.15	≤3	13.5 (11.7)	12.7 (12.2)	7.7 (11.1)	39.2 (28)*
		4-6	32.7 (28.6)	24.6 (30.6)	4.6 (7.2)	81.2 (25)*
		7-9	39.8 (56.4)	28.1 (69.5)	1.7 (5.3)	93.8 (18)*
		≥10	49.5 (70.4)	15.8 (46.0)	0.2 (0.8)	98.8 (13)*
		All	135.5 (133.5)	81.1 (144.8)	14.5 (19.6)	82.2 (29)*
	0.30	≤3	18.1 (16.4)	6.1 (5.5)	5.0 (5.7)	17.2 (29)
		4-6	52.1 (82.0)	23.8 (29.5)	6.4 (9.1)	73.2 (27)*
		7-9	30.0 (45.0)	17.3 (28.3)	2.6 (6.6)	85.2 (23)*
		≥10	88.6 (177.5)	5.3 (8.1)	0.1 (0.6)	97.2 (19)*
		All	210.5 (194.7)	52.6 (65.2)	14.5 (17.7)	72.4 (29)*
1.0	0.15	≤3	30.2 (21.9)	11.7 (9.8)	12.7 (9.5)	-8.4 (31)
		4-6	41.6 (18.6)	18.2 (21.2)	16.2 (20.0)	10.7 (32)
		7-9	32.9 (43.2)	10.0 (15.8)	10.1 (16.3)	-0.3 (23)
		≥10	61.7 (79.1)	3.6 (7.7)	3.1 (8.9)	14.5 (16)
		All	166.4 (96.8)	43.5 (44.7)	42.2 (42.1)	2.9 (32)
	0.30	≤3	18.8 (15.6)	5.8 (6.2)	4.7 (5.0)	18.9 (29)
		4-6	18.0 (15.7)	18.5 (24.4)	15.1 (22.1)	18.5 (28)
		7-9	41.2 (79.1)	14.3 (27.8)	12.4 (23.8)	13.0 (24)
		≥10	75.1 (89.1)	3.7 (4.1)	2.8 (5.3)	23.1 (25)
		All	153.2 (147.0)	43.3 (56.5)	35.7 (49.3)	17.6 (30)

[a] "C-T Percent Difference" is calculated as [(control density minus test density) divided by control density]. Thus, positive values indicate lower densities in test samples.

Table 5-9
Mean density and standard deviation (SD) of carp spp. larvae collected at the Portage River site in ambient, control, and test samples during trials with 0.5 and 1.0 mm screens at slot velocities of 0.15 and 0.30 m/s. C-T is the percent difference between test and control densities.[a] Asterisks indicate a statistically significant difference between test and control densities ($p<0.05$).

Slot Width (mm)	Slot Velocity (m/s)	Mean Number Entrained per 100 m^3 (SD)			C-T Percent Difference (Valid Trials)
		Ambient	Control	Test	
0.5	0.15	0.3 (0.9)	2.2 (5.6)	2.7 (7.2)	-22.1 (7)
	0.30	0.0 (0.0)	1.5 (2.9)	1.1 (1.5)	22.3 (6)
1.0	0.15	3.6 (7.4)	1.3 (2.5)	2.1 (3.7)	-65.5 (6)
	0.30	12.4 (25.2)	6.0 (9.3)	2.7 (5.1)	54.3 (7)*

[a] "C-T Percent Difference" is calculated as [(control density minus test density) divided by control density]. Thus, positive values indicate lower densities in test samples.

Table 5-10
Mean density and standard deviation (SD) of freshwater drum larvae collected at the Portage River site in ambient, control, and test samples during trials with 0.5 and 1.0 mm screens at slot velocities of 0.15 and 0.30 m/s. C-T is the percent difference between test and control densities.[a] Asterisks indicate a statistically significant difference between test and control densities ($p<0.05$).

Slot Width (mm)	Slot Velocity (m/s)	Mean Number Entrained per 100 m^3 (SD)			C-T Percent Difference (Valid Trials)
		Ambient	Control	Test	
0.5	0.15	1.6 (4.2)	2.5 (5.5)	0.1 (0.2)	96.4 (4)
	0.30	43.1 (131.5)	14.2 (36.4)	0.6 (1.6)	95.9 (4)
1.0	0.15	19.7 (52.0)	0.0 (0.0)	0.1 (0.3)	N/A[b]
	0.30	199.3 (549.6)	9.9 (19.9)	2.8 (5.5)	71.7 (2)

[a] "C-T Percent Difference" is calculated as [(control density minus test density) divided by control density]. Thus, positive values indicate lower densities in test samples.