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Fish protection technologies: a status report

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Abstract

Section 316(b) of the Clean Water Act has required that "best technology available" (BTA) be used to minimize adverse environmental impacts resulting from operation of the cooling water intake structure (CWIS). The primary effects of CWIS operations are the entrainment of small aquatic organisms through the cooling water system and the impingement of larger life stages on traveling water screens. Extensive research has been conducted since the early 1970s in attempts to develop technologies that will minimize entrainment and impingement. As a result, a suite of technologies is available that can be considered for application as the BTA at the CWIS. Available technologies include fish collection systems, fish diversion systems, physical barriers and behavioral barriers. The ability of a given technology to meet BTA requirements is influenced by a wide variety of biological, environmental and engineering factors that must be evaluated on a site-specific basis. The status of systems and devices in each category of fish protection alternatives is presented.

Keywords: Fish protections; Water intakes; 316(b); Best technology available; Fish diversion; Fish collection; Behavioral barriers

1. Introduction

Section 316(b) of the Clean Water Act has required that "best technology available" (BTA) be used to minimize adverse environmental impacts (AEI) resulting from operation of cooling water intake structures (CWIS). The primary effects of CWIS operations are associated with the entrainment of small aquatic organisms through the cooling water system and the impingement of larger life stages on traveling water screens. Extensive research has been conducted since the early 1970s in attempts to develop technologies that will minimize entrainment and impingement. As a result, a suite of technologies is available that can be considered for application as the BTA at the CWIS. An overview of the status of fish protection technologies is presented below. A comprehensive review of these technologies is presented in a recent Electric Power Research Institute report (EPRI, 1999).

2. Fish collection systems

2.1. Modified traveling water screens

Conventional traveling water screens have been modified to incorporate modifications that improve survival of impinged fish. Such state-of-the-art modifications act to enhance fish survival related to screen impingement and spraywash removal. Screens modified in this manner are commonly called "Ristroph Screens". Each screen basket is equipped with a water-filled lifting bucket which safely contains collected fish as they are carried upward with the rotation of the screen. The screens operate continuously to minimize impingement time. When each bucket passes over the top of the screen, fish are gently rinsed into a collection trough by a low-pressure spraywash system. Once collected, the fish are transported back to a safe release

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Table 1
Summary of modified coarse and fine mesh traveling screen sites

Plant, location	Operator	Mesh size	Screened flow; water source and debris type	Screen type	Predominant species[a]	Reference
Salem Station, Delaware River	Public Service Electric and Gas Company	6.3 mm × 12.7 mm rectangular mesh	140 m^3/s; brackish water with heavy debris loading	Through-flow	Weakfish	Ronafalvy et al. (1997), Ronafalvy (1999)
Calvert Cliffs, Chesapeake Bay	Baltimore Gas and Electric	8 mm	30.5 m^3/s; salt water with light debris loading	Dual-flow	Atlantic menhaden, spot, oyster toadfish, northern searobin, bay anchovy, summer flounder	Breitburg and Thomas (1986)
Roseton Station, Hudson River	Central Hudson Electric and Gas Company	3.2 mm × 12.7 mm smooth-tex	10.3 m^3/s; fresh water with seasonal heavy debris loading	Dual-flow	Blueback herring, alewife, American shad, white perch, bay anchovy, striped bass	LMS (1991)
Big Bend Station, Tampa Bay, FL	Tampa Electric Company	0.5 mm	30.5 m^3/s; salt water with light debris loading	Dual-flow	Bay anchovy, black drum, silver perch, spotted seatrout, scaled sardine, tidewater silverside, stone crab, pink shrimp, American oyster, blue crab	Taft et al. (1981a), Bruggemeyer et al. (1988)
Indian Point, Hudson River	Consolidated Edison	9.5 mm	133 m^3/s; brackish water with heavy seasonal debris loading	Through-flow	Alewife, striped bass, white perch	Consolidated Edison Company of New York Inc. (1985)
Danskammer Point, Hudson River	Central Hudson Gas and Electric Company	9.5 mm	Flow not reported; fresh water with heavy seasonal debris loading	Through-flow	Alewife, Atlantic tomcod, bay anchovy, blueback herring, shiners, striped bass, weakfish	Ecological Analysts (1982)
Surry Station, James River	Virginia Electric Power Company	9.5 mm	111 m^3/s; brackish water with moderate debris loading	Through-flow	American shad, alewife, croaker, menhaden, silversides, bay anchovy, spotted seatrout, silver perch, weakfish	White and Brehmer (1976)
Oyster Creek, Barnegat Bay	Jersey Central Power and Light	9.5 mm	116 m^3/s; marine with heavy seasonal debris loading	Through-flow	Atlantic menhaden, bay anchovy, blueback herring, weakfish, bluefish, blue crab	Thomas and Miller (1976)
Mystic Station	Boston Edison Company	Smooth-tex	Marine with seasonally heavy debris and jellyfish loading	Through-flow	Alewife, winter flounder	SWEC (1981)
Prairie Island Station, Mississippi River, MN	Northern States Power Company	0.5 mm	39.7 m^3/s; fresh water with moderate seasonal debris loading	Through-flow	Gizzard shad, carp, shiners, catostomids, channel catfish, white bass, freshwater drum	Kuhl and Mueller (1988)
Brayton Point Station, Mt Hope Bay, MA	US Generating Company	1.0 mm/9.5 mm	16.4 m^3/s; salt water with moderate, seasonal debris loading	Angled, through-flow	Bay anchovy, Atlantic silverside, winter flounder, northern pipefish	LMS (1985a)
Barney Davis Station, Laguna Madre, TX	Central Power and Light Company	0.5 mm	21.5 m^3/s; salt water with heavy loading of grasses	Passavant, center-flow	Gulf menhaden, bay anchovy, Atlantic croaker, penaeid shrimp	Murray and Jinnette (1978)
Kintigh Station, Lake Ontario, NY	NY State Electric and Gas Company	1.0 mm	12.3 m^3/s; fresh water with light debris loading	Through-flow	Alewife, rainbow smelt, shiners	NYSEG (1990)
Dunkirk Station, Lake Erie	Niagara Mohawk Power Company	3.2 mm	Unknown	Dual-flow	Alewife, shiners, rainbow smelt, white bass, white perch, yellow perch	Beak Consultants, Inc. (1988)
Indian Point, Hudson River	Consolidated Edison	2.5 mm	133 m^3/s; brackish water with heavy seasonal debris loading	Through-flow	Striped bass, white perch, *Alosa* spp., rainbow smelt	Ecological Analysts, Inc. (1977, 1979)

Brunswick Station	Carolina Power and Light Company	1.0 mm	17.1 m^3/s; salt water with heavy seasonal debris loading	Through-flow	Croaker, spot, bay anchovy, shrimp, crabs	Carolina Power and Light (1985)
Laboratory study	ESEERCO	0.5 mm	Not applicable	Through-flow	Striped bass, winter flounder, alewife, yellow perch, walleye, channel catfish and bluegill	Taft et al. (1981b), ESEERCO (1981b)

[a] Weakfish (*Cynoscion regalis*), Atlantic menhaden (*Brevoortia tyrannus*), oyster toadfish (*Opsanus tau*), spot (*Leiostomus xanthurus*), northern searobin (*Prionotus carolinus*), bay anchovy (*Anchoa mitchilli*), silver perch (*Bairdiella chrysura*), spotted seatrout (*Synosion nebulosus*), scaled sardine (*Harengula pensacolae*), tidewater silverside (*Menidia beryllina*), Atlantic croaker (*Micropogon undulatus*), yellow perch (*Perca flavescens*), white bass (*Morone americana*), black drum (*Pogonias cromis*), walleye (*Stizostedion vitreum*), bluegill (*Lepomis macrochirus*), channel catfish (*Ichtalurus puntatus*), American shad (*Alosa sappidissima*), blueback herring (*Alosa aestivalis*), golden shiner (*Notemigonus crysoleucas*), white bass (*Morone americana*), striped bass (*Morone saxatilis*), white perch (*Morone americana*), white bass (*Morone chrysos*), winter flounder (*Pseudopleuronectes americanus*), summer flounder (*Paralichthys dentatus*), Atlantic tomcod (*Microgadus tomcod*), alewife (*Alosa pseudoharengus*), bluefish (*Pomotomus saltatrix*), gizzard shad (*Dorosoma cepedianum*), freshwater drum (*Aplodinotus grunniens*), northern pipefish (*Sygnathus fuscus*), gulf menhaden (*Brevoortia petronus*), rainbow smelt (*Osmerus mordax*), pink shrimp (*Penaeus duororum*), stone crab (*Menippe mercenaria*), American oyster (*Crassostrea virginica*), blue crab (*Callinectes sapidus*).

location. Such features have been incorporated into through-flow, dual-flow and center-flow screens.

Ristroph screens have been shown to improve fish survival and have been installed and evaluated at a number of power plants, as presented in Table 1. Improvements have been made recently to the Ristroph screen design that have resulted in increased fish survival. The most important advancement in state-of-the-art Ristroph screen design was developed through extensive laboratory and field experimentation. A series of studies conducted by Fletcher (1990) indicated that substantial injury associated with these traveling screens was due to repeated buffeting of fish inside the fish lifting buckets as a result of undesirable hydraulic conditions. To eliminate these conditions, a number of alternative bucket configurations were developed to create a sheltered area within the bucket in which fish could safely reside during screen rotation. After several attempts, a bucket configuration was developed which achieved the desired conditions (Envirex, 1996). In 1995, PSE&G performed a biological evaluation of the improved screening system installed at the Salem Generating Station in the Delaware River (Ronafalvy et al., 1997; Ronafalvy, 1999). The results of this evaluation are presented elsewhere in this issue.

Modified traveling water screens continue to be an available technology that can reduce fish losses due to impingement. Unless modified to incorporate fine mesh, as discussed below, these screens do not reduce entrainment losses.

2.2. Fine-mesh traveling screens

In addition to the fish handling provisions noted above, traveling water screens have been further modified to incorporate screen mesh with openings as small as 0.5 mm to collect fish eggs and larvae and return them to the source water body. For many species and early life stages, mesh sizes of 0.5 to 1.0 mm are required for effective screening. Various types of traveling screens, such as through-flow, dual-flow, and center-flow screens, can be fitted with fine mesh screen material.

A number of fine mesh screen installations have been evaluated for biological effectiveness, as presented in Table 1. Results of these studies indicate that survival is highly species- and life stage-specific. Species such as bay anchovy and *Alosa* spp. (American Shad, alewife and blueback herring) have shown low survival while other species such as striped bass, white perch, yellow perch and invertebrates show moderate to high survival. Therefore, evaluating fine mesh screens for potential application at a CWIS requires careful review of all available data on the survival potential of the species and life stages to be protected as well as non-target species. Generally, fine mesh screen systems

Table 2
Summary of angled screen sites

Plant, location	Owner/ operator	Mesh size	Screened flow; water source and debris type	Screen type	Predominant species	Reference
Oswego Steam Station — Unit 6; Lake Ontario	Niagara Mohawk	9.5 mm	Freshwater lake with heavy seasonal debris loading	Modified through-flow screen	Alewife, rainbow smelt, shiners	LMS (1992)
Brayton Point Station, Mt Hope Bay, MA	US Generating Company	9.5 mm/ 1.0 mm	Salt water with moderate, seasonal debris loading	Modified through-flow screen with interchangeable coarse and fine mesh	Atlantic silverside, bay anchovy, northern pipefish	LMS (1985a), Davis et al. (1988)
Danskammer Station Prototype Test Facility, Hudson River	ESEERCO/ Central Hudson	9.5 mm/ 1.0 mm	Experimental facility; freshwater with heavy seasonal debris loading	Modified through-flow screen with interchangeable coarse and fine mesh	Weakfish, bay anchovy, white perch, blueback herring, alewife, American shad, shiners, sunfishes	LMS (1985b)
Laboratory studies	ESEERCO	9.5 mm	Experimental facility	Simulated angled traveling screen panels	Alewife, striped bass, white perch, Atlantic menhaden	ESEERCO (1981a)

have proven to be reliable in operation and have not experienced unusual clogging or cleaning problems as a result of the small mesh size.

In addition to these field applications, survival data on a variety of species and life stages following impingement on fine-mesh screens is available from extensive laboratory studies (Taft et al., 1981a). In these studies, larval life stages of striped bass (*Morone saxatilis*), winter flounder (*Pseudopleuronectes americanus*), alewife (*Alosa pseudoharengus*), yellow perch (*Perca flavescens*), walleye (*Stizostedium vitreum*), channel catfish (*Ictalurus punctatus*) and bluegill (*Lepomis macrochirus*) were impinged on a 0.5 mm screen mesh at velocities ranging from 0.15 to 0.91 m/s (0.5 to 3.0 ft/s) and for durations of 2, 4, 8 or 16 min. As in the field evaluations, survival was variable between species, larval stages and impingement duration and velocity.

The primary concern with fine mesh screens is that they function by impinging early organism life stages that are entrained through coarse mesh screens. Depending on species and life stage, mortality from impingement can exceed entrainment mortality. In order for fine mesh screens to offer a meaningful benefit in protecting fish, impingement survival of target species and life stages must be substantially greater than survival through the circulating water system.

2.3. Fish pumps

Several pumps have demonstrated an ability to transfer fish with little or no mortality, including the Hidrostal and Archimedes screw pumps that have recently undergone extensive research (Liston et al., 1993). These pumps by themselves do not represent a technology for protecting fish. However, when coupled with fish bypass systems, such as angled screens and louvers, fish pumps are biologically effective.

3. Fish division systems

3.1. Angled screens

A variety of species have been shown to guide effectively on screens given suitable hydraulic conditions. Angled screens require uniform flow conditions, a fairly constant approach velocity, and a low through-screen velocity to be biologically effective. Angled screen systems have been installed and biologically evaluated at a number of cooling water intakes on a prototype and full-scale basis, as presented in Table 2. Angled screen diversion efficiency varies by species, but has generally been relatively high for the many species evaluated. Survival following diversion and pumping (as required to return fish to their natural environment) has been more variable. Overall survival rates of relatively fragile species following diversion may not exceed 70%. Hardier species should exhibit survival rates approaching 100%.

In addition to the CWIS applications, angled fish diversion screens leading to bypass and return pipelines are being used extensively for guiding salmonids in the Pacific northwest. These screens are mostly of the rotary drum or vertical, flat panel (non-moving) types. They have provided effective downstream protection for juvenile salmonids at several diversion projects in the Pacific Northwest (Neitzel et al., 1991; EPRI, 1998). Like other angled screens, suitable hydraulic conditions at the screen face and a safe bypass system are required for the screens to effectively protect fish from entrainment and impingement and to divert them to a bypass for return to the source water body (Pearce and Lee, 1991).

Angled screens can be considered a viable option for protecting juvenile and adult life stages provided that proper hydraulics can be maintained and that debris can be effectively removed. To date, all angled screen applications at cooling water intakes have involved the use of conventional traveling water screens modified to provide a flush surface on which fish can guide to a bypass. Fish eggs, larvae, and small invertebrates are not protected by angled screens.

3.2. Eicher screen

The Eicher screen is a passive pressure screen that has proven effective in diverting salmon at hydroelectric projects. The first prototype of an Eicher Screen was constructed and installed in a 3-m (9-ft) diameter penstock at a hydroelectric project in the Pacific Northwest. Field testing of the screen conducted in 1990 and 1991 demonstrated that the Eicher screen effectively diverted over 98% of the steelhead (*Oncorhynchus mykiss*), coho (*Oncorhynchus kisutch*), and chinook (*Oncorhynchus tshawytscha*) smolts (EPRI, 1992). The first full-scale Eicher screen installation (two screens in two, 10-ft diameter penstocks; total flow of 28.32 m^3/s [1000 cfs]) at B. C. Hydro's Puntledge Project has shown similar results. Survival of chinook and coho salmon smolts exceeded 99%, and survival of steelhead, sockeye (*Oncorrhynchus nerka*) and chum (*Oncorhynchus keta*) salmon fry was 100, 96, and 96%, respectively, at penstock velocities up to 1.8 m/s (6 ft/s) (Smith, 1997).

While biologically effective, the Eicher Screen was not designed for use at steam electric station cooling water intakes.

3.3. Modular Inclined Screens

The Modular Inclined Screen (MIS) has recently been developed and tested by the Electric Power Research Institute (EPRI, 1994a; EPRI, 1996). The MIS is intended to protect juvenile and adult life stages of fish at all types of water intakes. An MIS module consists of an entrance with trash racks, dewatering stop logs in slots, an inclined screen set at a shallow angle (10–20°) to the flow, and a bypass for directing diverted fish to a transport pipe. The module is completely enclosed and is designed to operate at relatively high water velocities ranging from 0.61 to 3.0 m/s (2–10 ft/s), depending on species and life stages to be protected.

The MIS was evaluated in laboratory studies to determine the design configuration which yielded the best hydraulic conditions for safe fish passage and the biological effectiveness of the optimal design in diverting selected fish species to a bypass (EPRI, 1994a). Biological tests were conducted in a large flume with juvenile walleye, bluegill, channel catfish, American shad (*Alosa sapidissima*), blueback herring (*Alosa aestivalis*), golden shiner (*Notemigonus crysoleucas*), rainbow trout (*Oncorhynchus mykiss*) (two size classes), brown trout (*Salmo trutta*), chinook salmon, coho salmon, and Atlantic salmon (*Salmo salar*). Screen effectiveness (diversion efficiency and latent mortality) was evaluated at water velocities ranging from 0.61 to 3.0 m/s (2–10 ft/s). Diversion rates approached 100% for all species except American shad and blueback herring at water velocities up to at least 1.8 m/s (6 ft/s). Generally, latent mortality of test fish that was adjusted for control mortality was low (0–5%).

Based on the laboratory results, a pilot scale evaluation of the MIS was conducted at Niagara Mohawk Power Corporation's Green Island Hydroelectric Project on the Hudson River near Albany, NY (EPRI, 1996). The results obtained in this field evaluation with rainbow trout, largemouth and smallmouth bass (*Micropterus salmoides* and *M. dolomieui*), yellow perch, bluegill and golden shiners were similar to those obtained in laboratory studies (Taft et al., 1997).

The combined results of laboratory and field evaluations of the MIS have demonstrated that this screen is an effective fish diversion device that has the potential for protecting fish at water intakes. Studies to date have only evaluated possible application at hydroelectric projects. Further, no full-scale MIS facility has been constructed and operated. As a result, the potential for effective use at cooling water intakes is unknown. Any consideration of the MIS for CWIS application should be based on future large-scale, prototype evaluations.

3.4. Louvers/angle bar racks

A louver system consists of an array of evenly spaced, vertical slats (similar to bar racks) aligned across a channel at a specified angle and leading to a bypass. Bar racks can be angled to act as louvers. Results of louver studies to date have been variable by species and site. Most of the louver installations in the US are in the Pacific Northwest at water supply intakes. Louvers generally are not considered acceptable by the fishery resource agencies in that region since they do not meet the current 100% effectiveness criterion. However, numerous studies have demonstrated that louvers can be on the order of 80–95% effective in diverting a wide variety of species over a wide range of conditions (EPRI, 1986; EPRI, 1994b; Stira and Robinson, 1997). Studies sponsored by EPRI are currently being conducted at Alden Research Laboratory with various fish species and louver/bar rack configurations. Results are expected to be available in late 2000.

Most of the louver applications to date have been with migratory species in riverine environments. No studies have been conducted to determine the potential for effective use at CWIS. Therefore, the ability of this alternative to protect species commonly impinged at CWIS is largely unknown. Further, due to the large spacings between louver slats, louver systems do not protect early life stages of fish. Future consideration of louver systems for protecting fish at cooling water intakes is warranted, but will require large-scale evaluations.

4. Physical barriers

4.1. Traveling (through-flow, dual-flow, center-flow, drum)

The traveling water screen is a standard feature at most CWIS. The ability of traveling screens to act as a barrier to fish while not resulting in impingement is dependent on many site-specific factors, such as size of fish, flow velocity, location of the screens and presence of escape routes. It is considered advantageous to locate screens flush with the shoreline at the point of water withdrawal. Traveling screens, as barrier devices, cannot be considered for protection of early life stages or aquatic organisms that have little or no motility (EPRI, 1999).

4.2. Cylindrical wedge-wire screens

Wedge-wire screens reduce entrainment and impingement at water intakes due to their small screen slot sizes, low slot velocities and appropriate location in the water column. They are designed to function passively; that is, to be effective, ambient cross-currents must be present in the water body to carry waterborne organisms and debris past the screens. Wedge-wire screens utilize "V" or wedge-shaped, cross-section wire

Table 3
Summary of cylindrical wedge wire screen sites

Plant, location	Owner/operator	Mesh size	Screened flow (cfs); water source and debris type	Screen type	Predominant species	Reference
J. H. Campbell Plant — Unit 3; Lake Michigan	Consumers Power Company	10 mm	340,000 gallons per min; light debris loading	Submerged, offshore structure with 28 individual screens	Gizzard shad, smelt, yellow perch, alewife, shiner species	EPRI (1994)
Eddystone Station, Delaware River	Philadelphia Electric Company	6.4 mm	440,000 gallons per min; heavy seasonal debris loading	Shoreline, bulkhead structure with 16 screens	Spot, Atlantic menhaden, blueback herring, white perch	Veneziale (1991)

welded to a framing system to form a slotted screening element. In order for cylindrical wedge-wire screens to reduce impingement and entrainment, the following conditions must exist: (1) sufficiently small screen slot size to physically block passage of the smallest lifestage to be protected (typically 0.5–1.0 mm); (2) low through-slot velocity; (3) relatively high velocity ambient current cross-flow (to carry organisms around and away from the screen); and (4) ambient currents providing high velocity cross-flow (to provide continuous flushing of debris). Where all of these conditions are present, wedge-wire screens can reduce entrainment and impingement (Hanson et al., 1978; Lifton, 1979).

Full-scale CWIS applications of wedge-wire screens to date have been limited to two plants (Table 3). These screens have been biologically effective in preventing entrainment and impingement of larger fish and have not caused unusual maintenance problems. This technology can be considered for application at CWIS. However, there are major concerns with clogging potential and biogrowth. Since the only two large CWIS to employ wedge-wire screens to date use 6.4 and 10 mm slot openings, the potential for clogging and fouling that would exist with slot sizes as small as 0.5 mm, as would be required for protection of many entrainable life stages, is unknown. In general, consideration of wedge-wire screens with small slot dimensions for CWIS application should include *in situ* prototype scale studies to determine potential biological effectiveness and identify the ability to control clogging and fouling in a way that does not impact station operation (EPRI, 1999; Smith and Ferguson, 1979).

4.3. Infiltration intakes

Radial wells and artificial filter beds are successfully used to supply small quantities of water. While such systems have little if any biological impact, they have not been developed for screening large flow volumes as required for CWIS application (EPRI, 1999).

4.4. Porous dike

Rock dikes which allow water to pass while preventing fish passage have been shown to be effective on an experimental basis. The effectiveness of porous dike and leaky dam systems in minimizing impingement and entrainment at power plant intakes was assessed from monitoring studies conducted by the Wisconsin Electric Power Company (Michaud, 1981). The results of this study indicated that, for several species of adult and larval fish, the impingement and entrainment rates of the porous dike and leaky dam structures were lower than the rates at nearby onshore intake structures. The accuracy of these results was limited by the variable densities of Lake Michigan ichthyoplankton populations; data interpretation was also limited by differences in operating characteristics and environmental conditions among the four plants. Results of additional laboratory and small-scale pilot studies have indicated that these dikes might be effective in preventing passage of juvenile and adult fish. However, entrainable organisms will generally be trapped in the porous medium or entrained into the pump flow. Such dikes have not been used to filter large quantities of water and generally are not considered a viable option for use at CWIS.

4.5. Gunderboom

The Gunderboom is a full-water-depth filter curtain consisting of polyester fiber strands which are pressed into a water-permeable fabric mat. Optimum performance requires flow rates below 0.002 m^3/s per square meter (10 gpm per square foot) of fabric mat (MEM, 1999). Beginning in 1995, Orange and Rockland Utilities, Inc. has sponsored an evaluation of the Gunderboom to determine its ability to minimize ichthyoplankton entrainment at the Lovett Generating Station on the Hudson River (LMS, 1997). Despite difficulties in keeping the boom deployed and providing adequate cleaning in 1995–1997 studies, results of studies in 1998 show a large reduction in entrainment and it appears that deployment and cleaning problems may have been resolved for this site. At this time, the Gunderboom system is still considered to be experimental, but its successful use at Lovett may change that status within several years. Debris loading and anchoring system requirements must be carefully evaluated at any site considered for possible installation of the Gunderboom system. Given the low flow per unit area required for optimal biological performance, a relatively large deployment area is required in the vicinity of the intake.

4.6. Barrier nets

Barrier nets have been effectively applied at several power plant cooling water systems, as well as a number of hydroelectric projects. Under the proper hydraulic conditions (primarily low velocity) and without heavy debris loading, barrier nets have been effective in blocking fish passage into water intakes. The mesh size must be selected to block fish passage, but not cause fish to become gilled in the net. Debris cleaning and biofouling control can be labor-intensive. Several recent applications in the mid-West are presented elsewhere in this paper (Michaud and Taft, 1999).

A barrier net was originally deployed at Chalk Point Station in July 1981 to combat condenser blockage problems due to seasonal invasion of blue crabs and to reduce impingement of fish and crabs on the traveling water screens. The initial barrier net had a poor performance due to fouling and clogging of the net and an inadequate anchoring system. The barrier net system at Chalk Point has undergone several modifications, including the addition of a second barrier net in 1984. The system has been successful in reducing blue crab impingement numbers. Clogging and fouling of the net is controlled through regular changing of the barrier net panels (Loos, 1986).

At the Ludington Pumped Storage Plant on Lake Michigan, a 4.02-km (2.5-mile) long barrier net, set in open water around the intake jetties, has been successful in reducing entrainment of all fish species that occur in the vicinity of the intake (Reider et al., 1997). The net was first deployed in 1989. Modifications to the design in subsequent years led to a net effectiveness for target species [five salmonid species, yellow perch, rainbow smelt (*Osmerus mordax*), alewife and bloater (*Coregonus hoyii*)] of over 80% since 1991, with an effectiveness of 96% in 1995 and 1996.

In 1993 and 1994, Orange and Rockland Utilities, Inc. sponsored a study of a 3.0-mm, fine mesh net at its Bowline Point Generating Station on the Hudson River (LMS, 1996). In 1993, clogging with fine suspended silt caused the net to clog and sink. In 1994, spraying was not effective in cleaning the net when it became fouled by the algae *Ectocarpus*. Excessive fouling caused two of the support piles to snap, ending the evaluation (LMS, 1996). In both years, an abundance of the target ichthyoplankton species, bay anchovy, was too low to determine the biological effectiveness of the net. On the basis of studies to date, the researchers conclude that a fine mesh net may be a potentially effective method for preventing entrainment at Bowline Point (LMS, 1996). However, pending further evaluation, this concept is considered to be experimental.

In conclusion, barrier nets can be considered a viable option for protecting fish provided that relatively low velocities [generally less than 0.3 m/s (1 ft/s)] can be achieved and debris loading is light. A thorough evaluation of site-specific environmental and operational conditions is generally recommended.

5. Behavioral barriers

5.1. Strobe lights

Strobe lights have been shown to effectively and consistently repel a number of lacustrine, riverine, and anadromous fish species in both laboratory and field experiments. Conversely, other studies have indicated that other species do not respond to strobe lights. Therefore, the potential use of strobe lights requires site- and species-specific evaluation. A review of recent strobe light applications is presented elsewhere in this issue (Brown, 2000).

5.2. Air bubble curtains

These curtains have generally been ineffective in blocking or diverting fish in a variety of field applications. Air bubble curtains have been evaluated at a number of sites on the Great Lakes with a variety of species. In no case have air bubble curtains been shown to effectively and consistently repel any species. Therefore, the potential for application of this technology appears limited. All air bubble curtains at these sites have been removed from service. It is possible that air bubble curtains combined with other behavioral technologies, such as light sources, might indicate improved potential for this hybrid technology in the future (GLEC, 1994; McCauley et al., 1996).

5.3. Sound

The focus of recent fish protection studies involving underwater sound technologies has been on the use of new types of low- and high-frequency acoustic systems that have not previously been available for commercial use. High-frequency (120 kHz) sound has been shown to effectively and repeatedly repel members of the Genus *Alosa* at sites throughout the US (Ploskey et al., 1995; Dunning, 1995; Consolidated Edison Company of New York Inc., 1994). Other studies have not shown sound to be consistently effective in repelling species such as largemouth bass, smallmouth bass, yellow perch, walleye, rainbow trout (EPRI, 1998), gizzard shad (*Dorosoma cepedianum*), Atlantic herring (*Clupea harengus harengus*), and bay anchovy (*Anchoa mitchilli*) (Consolidated Edison Company of New York, Inc., 1994).

Given the species-specific responses to different frequencies that have been evaluated, and the variable results that have often been produced, additional research is warranted at sites where there is no or limited data to indicate that the species of concern may respond to sound.

5.4. Infrasound

In the near field, fish response to "sound" is probably more related to particle motion than acoustic pressure (Kalmijn, 1988). Particle motion is very pronounced in the near field of a sound source and is a major component of what fish most likely sense from infrasound (frequencies less than 50 Hz). In the first practical application of infrasound for repelling fish, Knudsen et al. (1992, 1994) found a piston-type particle motion generator operating at 10 Hz to be effective in repelling Atlantic salmon smolts in a tank and in a small diversion channel.

Following the success of Knudsen et al. (1992, 1994), there was a general belief in the scientific community that infrasound could represent an effective fish repellent since there was a physiological basis for understanding the response of fish to particle motion. The potential for currently available infrasound sources to effectively repel fish has been brought into question by the results of more recent studies. Given these results, it appears that infrasound sources need to be further developed and evaluated before they can be considered an available technology for application at CWIS.

5.5. Mercury light

Response to mercury light has been shown to be species specific; some fish species are attracted, others repelled, and others have demonstrated no obvious response (EPRI, 1999). Therefore, careful consideration must be given for any application of mercury lights to avoid increasing impingement of some species. The use of mercury lights as a primary or sole fish protection device has not been supported by the results of past studies.

5.6. Electric screens

Electric barriers have been shown to effectively prevent the upstream passage of fish. However, a number of attempts to divert or deter the downstream movement of fish have met with limited success (Bengeyfield, 1990; Kynard and O'Leary, 1990). Consequently, past evaluations have not led to permanent applications. Given their past ineffectiveness and hazard potential, electric screens are not considered a viable technology for application at CWIS.

5.7. Other behavioral barriers

Devices such as water jet curtains, hanging chains, visual cues and chemicals have been suggested, and in some cases evaluated, as fish protection measures. However, no practical applications of these devices have been developed and they are not considered available technologies for application at CWIS.

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