Downstream Fish Passage Technologies: How Well Do They Work? 4

The implementation of downstream mitigation for fish passage at hydropower facilities has three distinct goals: to transport fish downstream; to prevent fish from entrainment in turbine intakes; and to move fish, in a timely and safe manner, through a reservoir.[1]

A range of mitigation methods for downstream passage and for prevention of turbine entrainment exist, and some have been applied with more success than others. The so-called "standard" or "conventional" technologies are mainly structures meant to physically exclude or "guide" fish to a sluiceway or bypass around the project and away from turbine intakes by means of manipulating hydraulic conditions. Other "alternative" technologies attempt to "guide" fish by either attracting or repelling them by means of applying a stimulus (i.e., light, sound, electric current). Many theories have been applied to the design of downstream passage systems and further experimentation is underway in some cases (see box 4-1).

For downstream migrating species, including the juveniles of anadromous upstream spawners, it is important that a safe route past hydropower facilities be made available. For these fish, a means of preventing turbine entrainment, via a diversion and bypass system, is often needed (242,243) (see box 4-2). For some resident fish, downstream movement may not be critical or desirable. Philosophies of protection vary across the country depending on target fish, magnitude of the river system, and complexity of the hydropower facility. For example, practitioners in the Northwest tend to prefer exclusion devices that physically prevent entrainment, while those in the Northeast tend to recommend structural devices that may alter flow and rely on fish behavior for exclusion.[2] Much of the variance in protection philosophy may be linked to differences in target fish in these regions. The Northwest hosts a number of endangered or threatened species (mainly salmonids), while the Northeast does not have quite the same history of concern. In the Northwest, fish protection is mainly focused on salmonids. Downstream migrants

[1] The main difference between up- and downstream passage is that upstream moving fish may keep trying until they find a means of passage (i.e., a fishway). A downstream migrating juvenile has one chance to find the proper passage route, otherwise it becomes entrained.

[2] The mechanism that causes fish to be guided by angled bar racks is not well understood.

BOX 4-1: Chapter Findings—Downstream Technologies

- There is no single solution for designing downstream fish passage. Effective fish passage design for a specific site requires good communication between engineers and biologists and thorough understanding of site characteristics.
- Physical barrier screens are often the only resource agency-approved technology to protect fish from turbine intake channels, yet they are perceived to be very expensive.
- The ultimate goal of 100 percent passage effectiveness is most likely to be achieved with the use of physical barrier technologies, however site, technological, and biological constraints to passing fish around or through hydropower projects may limit performance.
- Structural guidance devices have shown to have a high level of performance at a few studied sites in the Northeast. The mechanism by which they work is not well understood.
- Alternative behavioral guidance devices have potential to elicit avoidance responses from some species of fish. However, it has not yet been demonstrated that these responses can be directed reliably; behavioral guidance devices are site- and species-specific; it appears unlikely that behavioral methods will perform as well as conventional barriers over a range of hydraulic conditions and for a variety of species.

SOURCE: Office of Technology Assessment, 1995.

tend to be small and have limited swimming ability. In the Northeast, fish protection is focused on a variety of species. In some cases downstream migrants are of fairly good size and possess fairly good swimming ability (e.g., American shad).

Physical barriers are the most widely used technology for fish protection. These technologies include many kinds of screens (positioned across entrances to power canals or turbine intakes) providing physical exclusion and protection from entrainment. In some parts of the country, *behavioral guidance devices* such as angled bar racks (modified versions of conventional trashracks) are used to protect fish from turbine entrainment. For both categories of downstream passage technologies, careful attention to dimensions, configurations and orientations relative to flow is required to optimize fish guidance.[3]

In most cases, structural measures to exclude or guide fish are preferred by resource agencies. Screens and angled bar racks providing structural measures for physical guidance are preferred by resource agencies, however, the screens can be expensive to construct and maintain. As a result, the development of alternatives to these technologies, such as *alternative behavioral guidance devices* (e.g., light, sound), continues to be explored. These devices have not been proven to perform successfully under a wide range of conditions as well as properly designed and maintained structural barriers. Thus, the resource agencies consider them to be less reliable in the field than physical barriers. In addition, other methods for downstream passage are also being explored. New turbine designs that will be not only more efficient but more "friendly" to fish are under proposal. And in the Columbia River Basin, a surface collector system which intends to guide fish past hydropower facilities by better accommodating natural behavior is being experimented with at a number of sites.

DESIGN OF CONVENTIONAL STRUCTURAL MEASURES

Progress in developing effective downstream fish passage and protection mechanisms has occurred over the past 50 years (203,205,221). Physical barrier screens and bar racks and lou-

[3] Fish impingement on screens or trashracks can stress, descale and otherwise injure fish, particularly juveniles (168, 190).

BOX 4-2: Complements to Exclusion, Diversion, and Guidance Technologies

Once fish are diverted by physical screens, angled bar racks, or louvers, a means of passing them around hydropower projects is needed. This is achieved through the use of bypasses and sluiceways. These measures would also be required for any emerging behavioral guidance technologies.

Bypasses

Engineered bypass conduits are needed for downstream-migrating fish at hydropower facilities and are the key to transporting fish from above to below a hydropower project. Most early downstream mitigation efforts only marginally improved juvenile fish survival. Today, juvenile bypass structures are more efficient due to lessons learned and a better understanding of the interaction of hydraulics and fish behavior (190). In some instances bypasses must provide efficient and safe passage for both juvenile and adult life stages (175).

Despite efforts at designing mitigation systems for specific sites, efforts may fail due to inadequately designed fish bypasses (204). Bypass design should be based on the numbers, sizes, and behaviors of target species (204). The entrance to such channels may be their most important feature. Smooth interior surfaces and joints, adequate width, absence of bends and negative pressures, proper lighting, and appropriate hydraulic gradients should be considered when designing an effective bypass system (239). High-density polyethylene, PVC, or concrete cylinders are all appropriate bypass materials (175).

Bypass entrances and the velocity of the flow are critical to success. For example, fish may be less likely to enter a bypass if met with extremely high flows. Typically, bypass entrances consist of a sharp-crested weir configuration which causes an increase in velocity. The development of a new weir, which may be able to be retrofitted at some applications, will result in gradual velocity acceleration intended to be more attractive to fish.[a]

Bypass outfalls are also critical in achieving safe downstream passage of target fish. The potential for predation at bypass exits where fish are concentrated is a particular concern (204). Gulls, squawfish, otters, herons, and other predators often congregate at these outfalls. Submerged outfalls may allow for avoidance of strong currents, bottom injury, and predation by birds; but they may cause disorientation and have debris problems (175,190). Elevated outfalls may greatly subject fish to predation and disorientation, but avoid problems with debris. Injury and mortality associated with various bypass structures has rarely been studied, although in some cases it has been high.

Sluiceways

Sluiceways are typically used to bypass ice and debris at hydropower projects, but they can also provide an adequate and generally successful means of downstream passage provided fish are able to locate them. Small hydropower projects often rely on sluiceways for passage. This type of passage may work well for surface or near-surface oriented fish (i.e., clupeids, salmonids, and some riverine species) but may not work as well for fish distributed elsewhere in the water column.

Entrance location, adequate flow, and thorough maintenance and debris removal are critical factors to sluiceway success. The sluiceway should be located to one side of the powerhouse, generally at the most downstream end, with its outfall located so as not to interfere with the attraction flow of the upstream fishway. The greatest problem associated with sluiceways is the potential for predation at the entrance or exit.

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[a]The NU-Alden Weir was developed by Alden Research Laboratory with funding from Northeast Utilities, Inc. Testing of the weir took place at the Conte Anadromous Fish Research Center during the spring of 1995. Results were promising.

SOURCE: Office of Technology Assessment, 1995.

vers have been used to exclude fishes from turbine intakes and are considered to be standard, conventional technologies.[4] In cases where there is a large forebay area, water velocities are high, or site specifications are limiting, these types of systems may not be feasible, or the costs may be exceedingly high. Physical barrier screens may provide nearly 100 percent protection for migrating (target) fish, but for the aforementioned reasons, the development of alternative behavioral guidance techniques (e.g., sound and light) has been, and continues to be, pursued in the public and private sector.

The design of effective structural measures for assisting in downstream passage of juvenile outmigrants and riverine species is dependent on behavioral criteria, and the knowledge of physical, hydraulic, and biological information which are critical to success (13,185). Lack of knowledge of fish behavior tends to lead to disagreement on what the best available method or technology for a particular site might be. This type of information is also necessary for the design of alternative behavioral guidance devices. For example, the limited swimming ability exhibited at the juvenile stage is a critical design concern. Flow data, species and population size, and where the target species tend to exist within the water column will help determine location and type of passage system necessary.

Downstream passage design must take into consideration the lack of or limited swimming ability of outmigrating (anadromous) juvenile and smolt fishes. Other catadromous and riverine species may have limited swimming ability as well, depending on age and size. Where larger catadromous fishes and anadromous adult repeat spawners are concerned, entrainment avoidance might be more related to behavior than to physical swimming ability. Where hydropower projects exist in series, a system of reservoirs may be created where velocities are low and water temperatures elevated. These conditions may alter fish behavior and slow outmigration of juveniles that are dependent on water flow to assist their movement. The series of four dams (McNary, The Dalles, John Day, Bonneville) on the lower Columbia River, for example, can add up to 20 to 30 days to the travel time for juvenile fish due to alteration in flow conditions (230).

Screens as well as bar racks generally are designed to work with site hydraulics to help or encourage fish in moving past or away from turbine intakes. Well-designed screen facilities may result in a guidance efficiency of over 95 percent (see appendix B) (236,236A). The effectiveness of bar racks is less conclusive. The size and cost of screen and bar racks systems depends on the site. However, water velocities in the forebay in general, and the approach velocity[5] in front of the system in specific, are of primary concern. The idea is to maintain approach velocities within the cruising speed of all target fishes to be screened in order to achieve protection (58).

Physical Barriers

Screens

Outmigrating juvenile salmonids depend a great deal on hydrology and hydraulics to guide their movement. These fish have limited swimming ability and orient themselves into the flow.[6] Therefore, downstream protection devices must take advantage of natural fish behavior. At many hydropower projects a physical barrier is used in conjunction with a bypass to facilitate passage. The flow characteristics that are generated by the particular placement of a screen and the physical parameters of the screen itself help to guide fish

[4] Bar racks and louvers are considered standard technologies for application in the Northeast, but not in the Northwest.

[5] “Approach velocity” is the velocity component of flow normal to and approximately three inches in front of the screen face. Fisheries agencies determine this value based on the swimming capabilities of the smallest and/or weakest fish present (239).

[6] Some salmonid pre-smolts have good swimming ability (i.e., sockeye, coho, steelhead), while others (i.e., pink and chum) smolt shortly after emergence and their swimming ability does not change significantly during smoltification. Not as much is known about how other migratory species (e.g., American shad, blueback herring) behave during outmigration (187).

to the bypass. The key to successful downstream passage is to employ the fish's behavior to guide them to a safe bypass. The hydraulics of the structure must be benign enough that the fish can be guided to safety before they fatigue or are injured.

Physical barrier screens can be made of various materials based on the application and type of screen (i.e., perforated plate, metal bars, wedgewire, or plastic mesh). Screens are designed to slow velocities and reduce entrainment and impingement (78). Smooth flow transitions, uniform velocities, and eddy-free currents just upstream of screens are desirable. Adequate screen area must be provided to create a low flow velocity that enables fish to swim away from the screen.

The positioning of the screening device is critical. It must be in appropriate relationship to the powerhouse to guide fish to the bypass by creating the appropriate hydraulic conditions. Fish then enter a bypass which either deposits them in a canal that eventually rejoins the main channel, releases them into the main flow downstream of the project via an outfall pipe or sluiceway, or leads them to a holding facility for later transport. Outfall pipes typically release fish above the water's surface to avoid creation of a hydraulic jump or debris trap within the closed pipe. Releasing fish above the water may also alleviate disorientation and help to prevent schooling. However, predation at the outfall can be a problem and there is no consensus on how to avoid this, though multiple outfalls might alleviate the situation in some cases (188).

The screen must be kept clean and clear of debris or it will not function properly. Debris is commonly the biggest problem at any screen and bypass facility. Debris loading can disrupt flow and create high-velocity hot spots, or cause injury to fish (238). In addition, a partially blocked bypass entrance can reduce the efficiency of fish passage and cause injury or mortality (190) (see box 4-2). Installation and operation of a screen cleaning system and regular inspections to ensure proper operation of screens may be the most important activities to increase effectiveness. Mechanical cleaning systems are preferable over manual ones and often more reliable, provided they are functioning properly. Very frequent cleaning may be needed where there is a lot of debris. California screen criteria require cleaning every five minutes. Ideally, screens should be cleaned while in place, and temporary removal of a screen for cleaning is usually not acceptable (12).

A variety of physical barrier screens has been developed to divert downstream migrants away from turbine intakes.[7] Years of design, experimentation, evaluation, and improvement have alleviated some problems but others still remain, and no physical barrier is 100 percent effective in protecting juveniles. Few studies have been able to demonstrate conclusively a guidance efficiency exceeding 90 percent; and although the effectiveness of these facilities is probably close to 100 percent at many sites, losses of fish may occur due to predation or leakage of fish past faulty or worn screen seals (59). However, improvements in screen components have been made and designs have begun to reflect new knowledge about hydraulics. Some specifics of design and function of a variety of low-velocity[8] physical barrier screens are highlighted below.

The *drum screen* is often found to provide the best fish protection at sites with high debris loads. Comprehensive evaluation of large drum screen facilities has demonstrated nearly 100

[7] Between 1985 and 1989, a series of evaluation reports on the performance of diversion screens in use at irrigation and hydroelectric diversions in the Yakima River Basin, Washington, were jointly produced by the U.S. Department of Energy, Bonneville Power Administration, and Batelle PNW Laboratory. The reports evaluate flow characteristics of the screening facilities. A discussion of these sites is not included in OTA's report; however, they were used by resource agencies in developing screen criteria in the Northwest and therefore the reports deserve mention (244, 245, 246, 247, 248, 249, 250).

[8] The physical barrier screens discussed in this section are considered to be low-velocity screens, meaning that they can function at velocities (perpendicular to the screen) between 0.33 to 0.5 feet per second (59).

percent overall efficiency and survival (12). The drum rotates within a frame and is operated continuously for cleaning. Debris is carried over the drum and passed down a channel or into a bypass (175). Drum screens can be expensive to construct and install, but relatively economical to operate; however, application criteria are site specific. These screens have been proven to be reliable at sites in California and the Pacific Northwest (204). Relatively constant water levels in the forebay are necessary for operation, and maintenance and repairs to seals can be problematic and costly.

Simple fixed screens can be an economical method of preventing fish entry into water intakes at sites where suspended debris is minimal; however, costs are site specific. Though fixed panel screens can and have been built in areas with substantial debris, automatic screen cleaners are required. These screens have demonstrated greater than 95 percent overall efficiency and survival at sites in the Columbia River Basin (12). Several types of simple fixed screen are available. The stationary panel screen is a vertical or nearly vertical wall of mesh panels installed in a straight line or "V" configuration. Fish-tight seals are easily maintained around this fixed screen, and the design accommodates a range of flows and forebay water elevations (175).

Inclined plane screens are also stationary, but are tilted from the vertical to divert fish up or down in the water column to a bypass. A conceivable problem with this design is the potential for dewatering of the fish and debris bypass route if water levels should fall below either end of the tilted screen. Also, cleaning is a primary concern for both stationary panel and inclined plane screens (175). Manual brushing is usually required to keep surfaces debris-free. The design is practical for water intakes drawing up to 38 cubic meters per second (175,204); however, application depends more on the site than on the flow.

Submersible traveling screens (STSs) are expensive to construct and install, and subject to mechanical failures, although in some cases they have been considered by the U.S. Army Corps of Engineers to be the best available technology for diverting downstream migrating fish in the Columbia River Basin (204). STS configurations operate continuously during the four- to nine-month salmonid migration period in the Columbia River; they are capable of screening extremely large flows in confined intakes but do not screen the entire powerhouse flow (175,204). At hydropower facilities where the fish are concentrated in the upper levels of the water column, good recoveries have been achieved (65). However, intakes at projects in the Basin tend to be very deep (i.e., greater than 90 feet) and flows are high. Under these conditions, fish have been seen to try to move away from STSs, especially if they are deeper in the intake. Also, the potential for impingement is greater due to high through-screen flow velocities (175). These screens seem to work better for some species than others.

Vertical traveling screens were originally designed to exclude debris from water intakes but were found to be effective at guiding or lifting fish past turbine intakes. The screen may consist of a continuous belt of flexible screen mesh or separate framed screen panels (baskets). Vertical traveling screens are most effective for sites where the intake channel is relatively deep. If approach velocities are kept within the cruising speed of the target fish, impingement can be greatly reduced (175,204). However, traveling screens that lift fish are not recommended for fish that are easily injured, such as smolting salmonids.

Structural Guidance Devices

Fish passage devices designed with the goal of guiding fish by eliciting a response to specific hydraulic conditions are described below.

Angled Bar or Trash Racks and Louvers

Angled bar racks and louvers are used to direct juvenile fish toward bypasses and sluiceways at hydropower plants. These structural guidance systems are devices that do not physically exclude fish from intakes, but instead create hydraulic conditions in front of the structures. Theoretically, fish respond to this condition by moving along the turbulence toward a bypass system. The success of these systems is dependent on fish response to hydraulic conditions, which means their performance can be poor under changing hydraulic conditions and for different fishes of non-target sizes and species (12,65).

Angled bar and trash racks have become one of the most frequently prescribed fish protection systems for hydropower projects, particularly in the northeastern United States (59,243), to prevent turbine entrainment of down-migrating juvenile anadromous species (e.g., alosids and salmonids) (194,242). Most of the angled bar racks installed to date consist of a single bank of racks placed in front of the turbine intake at a 45-degree angle to flow. Although design can vary from site to site, most racks consist of 1-inch spaced metal bars with a maximum approach velocity of two feet per second (15,59).

The angled bar rack is set at an acute angle to flow and with more closely spaced bars than conventional trashracks. It can divert small downstream migrating fish, and larger fish cannot typically pass through the bars. However, the use of close-spaced bar racks creates the potential for impingement of fish. This is of greatest concern for species with weak swimming ability and/or compressed body shapes (59). Most of the angled bar racks have been installed at small hydropower projects, the majority of which have not been evaluated for their performance in effectively diverting fish.

Proper cleaning and maintenance of the bar and trash rack systems on a regular basis is a critical element of operational success. Racks can be equipped with mechanical cleaning systems or can be pulled out of the water for manual cleaning; trash booms can also be helpful in mitigating debris loading. The ideal trash boom is designed to carry debris past the fishway exit to the spillway or falls and out of the forebay area (15).

A louver system consists of an array of evenly spaced, vertical (hard plastic) slats aligned across a channel at a specified angle and leading to a bypass (59). The louver system, like the angled bar rack, attempts to take advantage of the fact that fish rely mainly on senses other than sight to guide them around obstacles. Theoretically, as fish approach louvers, the turbulence that is created by the system causes them to move laterally away from it toward a bypass (59).

Louvers have been installed at a small number of locations, but are not generally acceptable as a mitigation technology for protecting fish from turbine entrainment. If approach velocities do not exceed their swimming ability, fish generally assume a tail-first position and move parallel to the line of louvers guided by streamflow and hydraulics toward a bypass (204). However, louvers may be considered for sites with relatively high approach velocities, large uniform flow and relatively shallow depths (204), and for some sites with species requiring lesser levels of protection. Louver efficiency in fish diversion, although high for some species, is relatively low on average compared to true physical barriers.

Passage of Atlantic salmon smolts at the Vernon and Bellows Falls hydropower projects on the Connecticut River was evaluated during the spring outmigration in 1995. A newly designed angled louver system at the Vernon site, which was based on hydraulic modeling, is in place to guide fish to a primary bypass chute in the middle of the powerhouse. Smolts are spilled into the tailwater of the project. Preliminary data indicate that about half the smolts are being guided to the primary bypass, while the remainder are either sounding beneath the louvers and passing through the turbines, or going through the secondary bypass, or are never making it into the forebay due to downmigration behavior (94).

The system may not be as successful as hoped due to the fact that the actual hydraulic conditions in the forebay of the project are not consistent with the modeling. This is mainly a result of not replacing certain turbine units adjacent to the primary bypass. This decision, which was made based on economics, has led to a less than adequate flow regime in the forebay of the project. Data and evaluation have yet to be finalized.

Despite efforts to monitor performance at any of these hydropower sites on the Connecticut River, information regarding effects of the angled bar rack and louvers on the overall salmon population in the Connecticut River has yet to be generated. Though angled bar and trash racks are frequently used to prevent turbine entrainment, evaluations of performance and effectiveness are rare. As of the writing of this report, 36 trash racks have been installed at projects in the Northeast (U.S. Fish and Wildlife Service (FWS)–Region 5); however, few had been evaluated prior to the spring of 1995.[9]

Louvers operate most efficiently when they are designed for larger fish of a specific size (175). Tests of a louver system at the J.E. Skinner Fish Protective Facility in Tracey, California, showed good guidance for larger juveniles (i.e., greater than 70 percent) (100). However, this same system operated poorly under high debris conditions. Floating louver systems have shown excellent promise for protecting fish which migrate downstream near the water surface (204). However, excessive entrainment on louvers of smaller, weaker fish, including juveniles, has caused louvers to be rejected as a design concept at most new hydropower installations (190).

There is a great deal of variation in opinion regarding how well, or why, louvers work. A better understanding of fish behavior could lead to improved designs for these structural guidance devices. Currently, they are recommended for use by the FWS in the northeastern part of the country. They are not in use in the Pacific Northwest because they have not been found to provide a high enough degree of effectiveness. The degree of protection granted by a louver system is directly related to the target fish, the degree of protection being sought, the approach velocity, and the extent that debris is present or is a problem.

OTHER METHODS FOR PROVIDING DOWNSTREAM PASSAGE

Other methods for providing downstream fish passage include pumps, spilling, turbine passage, and transportation.

Pumps

The hydropower industry is currently examining the application of fish collection systems, or *pumps*, to collect and divert fish at intakes (220). There are air-lift, screw impeller, jet, and volute pumping systems. These pumps could be used to force fish into bypass pipes for downstream passage at hydropower projects. Pump size and speed, however, may affect fish survival (223).

Fish pumps are not widely used because they can lead to injury and de-scaling as a result of crowding in the bypass pipe and to disorientation once released back into the river environment, and do not allow the fish to move on their own (196). Historically, the conventional wisdom of the resource agencies is to use bypass methods which allow fish to move of their own volition. However, a major research effort spearheaded by the Bureau of Reclamation is underway at Red Bluff Diversion Dam on the Sacramento River. Tests are being done to evaluate the usefulness of pumps to pass juvenile salmonids. Both the Archimedes screw and the Hydrostal-Volute pumps are being tested for the effective and safe passage of fish.

Spilling

Spill flows, or water releases independent of power generation, are the simplest means of transporting juvenile fish past (over) a hydropower project and away from turbines (36). Increased spill to flush fish over a dam can be especially cost-effective when the downstream migration period of the target species is short, when migration occurs during high river flows,

[9] The trash rack at the Wadhams Project on the Boquet River in northeastern New York, in place to guide down-migrating Atlantic salmon smolts, has been evaluated. Others include Cabot Station and the Holyoke Canal Louver on the Connecticut River in Massachusetts, and the Pine Valley Project on the Souhegan River in New Hampshire (195).

or where spill flows are needed for other reasons (e.g., to increase dissolved oxygen levels to maintain minimal instream flows).

Care should be taken to ensure that spillway mortality does not exceed turbine passage mortality (36,243). Consideration of forebay flow patterns, location of spillway relative to turbine intake, and positive flow to attract fish to spillways are all features of effective spillway passage (175).

Spilling is a particularly controversial issue in the Columbia River Basin (see box 4-3). The U.S. Army Corps of Engineers (COE) maintains that spilling water to pass juvenile fish has been demonstrated to be the safest, most effective, and one of the lowest-mortality means of getting juvenile anadromous fish past hydropower projects in the Columbia River Basin. In addition, it is viewed as the only means of enhancing survival without additional flow augmentation or drawdown (229). However, spilling water to assist fish in downstream passage means lost revenue for the hydropower operator. The COE recognizes that spill has its own associated risks (231) and has modified some spillways and operations to reduce problems in the Columbia River Basin (49). Passing juvenile fish by spilling water can result in "gas bubble trauma," or cause pressure-induced injury. According to at least one study, juvenile anadromous fish that pass a hydropower project by means of spill have a significantly higher rate of survival (98 percent estimated) than do fish that pass through the turbines (85 percent estimated) (229). However, this 85 percent turbine survival is through low-head dams with Kaplan turbines; survival is much lower for high-head dams with Francis turbines (12).

Gas Bubble Trauma

As spill water plunges below the dam the hydrostatic pressure causes air, mostly nitrogen gas, to be entrained in the flows. The pressure at the bottom of the stilling basins forces the gases into solution, creating a supersaturated condition. The slack water and low flow velocities below the dam slow the escape of the gas back into the atmosphere (23).[10] When fish absorb this gas, bubbles can form in the bloodstream. This effect, coupled with the pressure changes experienced when fish plunge with the flow and then return to the surface, can cause traumatic effects and even death. This situation is referred to as *gas bubble trauma.*

Since the late 1960s, tests on exposure of adult salmonids to supersaturated water have been conducted to determine the effects of exposure. The impact that dissolved gas may have on fish at any given time cannot be simply determined from gas saturation measurements. Thus, monitoring of migrants for signs of gas bubble trauma is an important management tool for determining if dissolved gas levels are having an impact on populations (229).

In June of 1994 the National Marine Fisheries Service (NMFS) Northwest regional office convened a panel of experts to review the biological data concerning dissolved gas effects on fish. Their findings indicate that a dissolved gas level of 110 percent can protect fish on purely biological grounds, whereas levels above 110 percent have the potential to be damaging (231,234). COE policy calls for keeping gas supersaturation levels at less than 110 percent in the Columbia River Basin, the level set by Oregon and Washington State water quality standards (231). Some laboratory research indicates that total dissolved gas levels above 110 percent in shallow water increases mortality observed in laboratory animals. Yet, field responses may be very different, making it difficult to base in-river management criteria on laboratory results.[11] The NMFS Northwest office and the Intertribal Fish Commission, which represents tribes in the Columbia

[10] In the Columbia River Basin dams were built so that the reservoir of one project backs up on the tailwater of the next project upstream, exacerbating the supersaturation problem.

[11] For example, juveniles may dive to greater depths to avoid areas of high dissolved gas concentration.

BOX 4-3: Spilling to Facilitate Fish Passage: Debate Over the Effects on Juvenile Salmonids

Spilling water to pass downmigrating fish is being used as an alternative method for protecting juveniles and enhancing survival at mainstem dams in the Columbia River Basin.[a] Spilling would occur during high flow periods when juvenile salmonids are in the midst of their downstream migration. However, there is still debate over whether this method might do more harm than good.

A 1995 Spill and Risk Management report prepared for the Columbia River Basin notes that spill passage and associated damage caused by dissolved gases should not generate greater mortality than that caused by turbine passage. The report goes on to say that there is little doubt that increasing the total dissolved gas levels in laboratory studies results in increasing the levels of mortality observed in laboratory animals in shallow water. By the same token, the report recognizes that mortality levels experienced in the lab are in conflict with those that would be observed in the natural environment where fish can sound to a safer depth to avoid injury.

The incidence of Gas Bubble Trauma (GBT) has been observed in juvenile anadromous fish during periods of high flow and spill during the spring out-migration in the Columbia River Basin.[b] GBT occurs when gas bubbles or emboli develop in the circulatory systems and tissues of fishes as a result of supersaturated gaseous conditions in the tailrace waters of hydropower projects. GBT is considered a physical, not a pathological, response to an environmental condition (117). The occurrence of GBT has been shown to be dependent, in part, on water temperature, species, genetic composition, and physiological condition of fish, as well as proximity and length of exposure to the total gas pressure (3,117).

The data which have been collected in situ as well as in the laboratory are in conflict with some observations that have been made in the natural environment. Laboratory experiments have indicated that fish exhibit a high level of mortality when exposed to constant supersaturated conditions, but in contrast, observations made in the wild actually indicate that higher survival rates occur in populations migrating under higher spill/flow/TDG conditions. In some of the laboratory situations fish were held at a constant depth and exposed to a constant level of TDG. In the natural environment, fish would be sounding to different depths and therefore would probably exhibit a different response. As a result, the usefulness of these tests in the development of a spill management plan may be questionable.

The effect of supersaturated conditions on fish is dependent on the depths (i.e., spatial and temporal distribution) at which they swim and are present in the water column. Therefore, completing depth distribution studies would generate helpful information. According to scientists, each meter of depth affords adults a 10-percent reduction in adverse impacts of gas supersaturation. In addition, the length of time it takes for a fish to travel through a reach of the river, where nitrogen concentrations might be a concern, influences exposure to high levels of dissolved gas. This is the major factor in determining the impacts a high-level exposure might have on the fish (44a).

These concerns, and mounting political pressure, have led the federal and state governments to set standards for limits on the allowable levels of gas supersaturation in the tailraces of mainstem dams in the Columbia River Basin. Washington and Idaho have set water quality standards with maximum levels at 110 percent for the Columbia and Snake Rivers, while Oregon has adopted a 105-percent standard. Some have contested that these standards were set without adequate biological research and information regarding the effects of supersaturation on fish. In addition, there is concern over the lack of information regarding fish response to the combination of supersaturated conditions and reaction with other gases, varying water temperatures, exposure time, and swimming depth.[c] In general, a 110-percent standard is considered conservative because this level is typically observed, if not exceeded, in the Columbia River Basin with no discernible impacts on fish. Therefore, scientists and resource managers argue that the impacts that supersaturated conditions have on fish can only be determined by monitoring migrants for signs of trauma, and monitoring natural environmental conditions.

(continued)

BOX 4-3: Spilling to Facilitate Fish Passage:
Debate Over the Effects on Juvenile Salmonids (Cont'd.)

It is difficult to monitor the response of fish to supersaturated conditions because mortality may occur before any physical characteristics are evident. After death, the external signs of GBT (i.e., large body blisters) may disappear within 24 hours, leaving dissection the only option by which to make determinations regarding cause of mortality (52). However, swimming performance, physical growth, and blood chemistry can be adversely affected, leaving weaker fish more susceptible to predation, disease, and migration delay (47).

The National Biological Survey's research lab in the Columbia River Basin has instituted a Smolt Monitoring Program (SMP) to be implemented in 1995. The SMP will monitor biological parameters in both the tailwater and the reservoir of a number of dams on the Lower Snake and Lower- and Mid-Columbia. Ideally, data resulting from the SMP will give managers a sense of what the existing levels of supersaturation are so that an appropriate spill management plan can be developed.

Recently, a study of hatchery Chinook test fish (juvenile fall Chinook salmon) being in net-pens below Ice Harbor Dam on the Snake River resulted in mortality during a study of the effects of high quantities of dissolved nitrogen. While the exact cause of mortality was not known, an uncontrolled spill of heavy spring runoff was occurring at the dam and all the dead fish had signs of GBT.

Events such as these have kept the debate over spilling to facilitate passage of juvenile outmigrants at a premium. And despite all past studies, there is still great disagreement and many unanswered questions that remain regarding the level of dissolved gases that can be safely tolerated by juvenile salmonids.

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[a]Juvenile salmon passed via spill as opposed to going through the turbines have a higher survival rate (98 percent) than those exposed to turbine passage (85 percent) (Scientific Rationale for Implementing a Summer Program to Increase Juvenile Salmonid Survival in the Snake and Columbia Rivers, by: Columbia Inter-Tribal Fish Commission, ID Dept. of F&G, OR Dept. of F&W, USFWS, WA Dept. F&W).

[b] Spilling has been implemented at mainstem COE dams since 1989 under 1989 MOA (protection of juveniles until functional bypasses are installed) and at Mid-Columbia PUD dams since 1983 under the Mid-Columbia FERC Proceedings. Studies have shown mortality from turbine passage to be 8 to 32 percent compared to 0 to 4 percent for spillway passage.

[c] Some research has indicated that swimming stamina is affected at concentrations of 110 percent, growth is affected at 105 to 115 percent, and blood chemistry is affected at 115 percent.

SOURCE: Office of Technology Assessment, 1995.

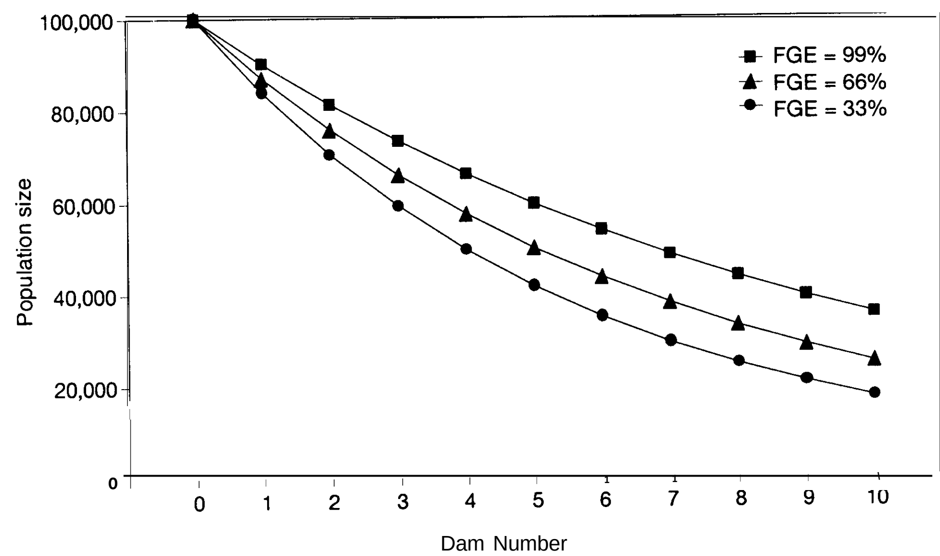
River Basin, recently recommended that spilling should be implemented on a broader scale to support juvenile downstream migration.

Turbine Passage

An explicit assumption behind the design of downstream bypass systems at hydropower facilities is that fish mortality associated with the bypass will be significantly less than turbine mortality (see figure 4-1; see chapter 2 for an in-depth discussion of turbine entrainment and mortality). This assumption is reasonable for many small-scale facilities, but is not always borne out at hydropower plants with large, efficient turbines (243). For example, studies at Bonneville Dam on the Columbia River indicate that subyearling Chinook salmon suffered more short-term mortality in screen/bypass systems than when passed through turbines, perhaps due to predation at outfalls (242). In a review of studies at 64 turbine installations, fish mortality ranged from zero to more than 50 percent (204). Turbine-induced fish mortality may be greatly overestimated or underestimated (206), and can vary considerably from site to site.

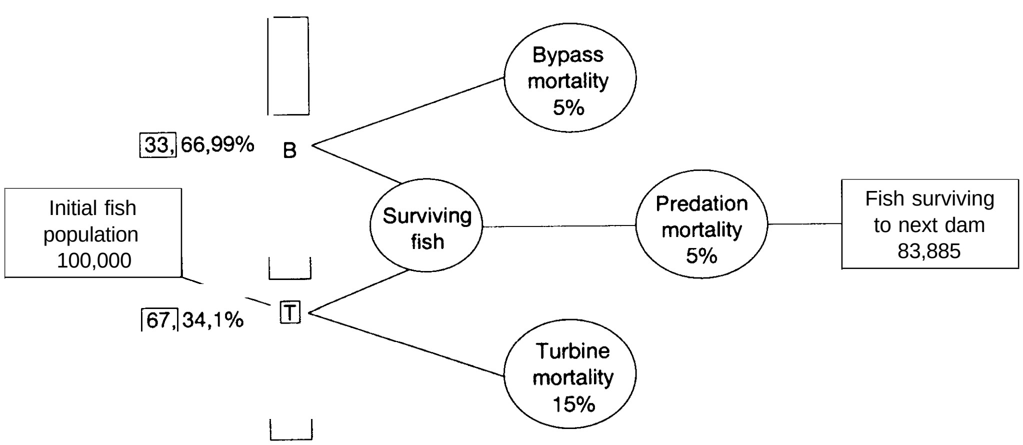
Turbine passage exposes outmigrating juveniles to blades, which can either de-scale or kill them, and distinct pressure changes, which can cause physical injury and/or death. Turbine mortality increases with fish size, suggesting that physical impact is also important (51,87). At the

FIGURE 4-1: Simulated Effects of Fish Guiding Efficiency (FGE) on a Group of Anadromous Fish Passing 10 Dams



Simulation Assumption: Initial population size = 100,000
Turbine Mortality = 15 percent
Bypass Mortality = 5 percent per dam
Predation Mortality = 5 percent per dam

Turbine mortality is only assessed to that part of the group that does not use the bypass. Bypass mortality is only assessed to that part of the group that uses the bypass. Predation mortality is assessed to all surviving individuals that pass through turbines and bypass.



SOURCE: Office of Technology Assessment, 1995.

edge of the turbine blade are areas of negative pressure that can be strong enough to pull molecules of metal from the turbine blades and likewise can cause damage to fish in the same vicinity.

Various turbine designs have been found to be linked to varying mortality rates for naturally and experimentally entrained fish.[12] Francis turbines are designed with "fixed" blades to accommodate a given head, flow, and speed. Kaplan turbines have "adjustable" blades which are better for low-head operations and seem to be better for fish survivability (i.e., are more "fish friendly"). To evaluate turbine mortality, fish must be tagged and released in the intake and then captured in the tailrace. The mark, release, and recapture technique has been found to be the most effective method of evaluating resultant turbine mortality for salmonid species; however, it has not been proven to be as useful for alosids (51) (see also chapter 2).

Operational factors can also affect turbine mortality rates. Running turbines at maximum overload during high power demands can result in higher losses of juveniles (23). In 1967, Milo Bell, a hydraulics engineer at the University of Washington, suggested that the best way to reduce mortality of smolts passing through the turbines was to operate the turbines at maximum efficiency. COE estimates that in most cases in the Columbia River Basin the expectation for turbine survival is 85 to 90 percent (230).

At Conowingo Dam (hydropower project) on the Susquehanna River, two old, damaged turbines were replaced with new Kaplan-type (mixed-flow) turbines.[13] This technology has been marked as more "fish friendly." The passage of American shad juveniles through the turbines was evaluated to determine survival rate. The new turbine design is based on a number of concepts: it allows for shallow intakes, and a smaller number of blades; it is capable of increasing dissolved oxygen in the tailwater; it has a wide flow range and is non-cavitating;[14] it also is greaseless and oil-free. These design considerations aim to increase survivability. Other factors are equally important to successful passage, such as where the fish exist in the turbine, what the blade strike range is, and what effect the pressure gradient that occurs in the vortexes between blades (gap flows) has on the juveniles. Principals in the turbine industry predict that technology is moving toward the use of these variable speed units.

Transportation

Transportation as a means of providing downstream passage of juvenile fish encompasses both trap and truck operations and barging. Transporting fish around hydropower facilities is used for a variety of reasons: to mitigate the loss of fish in long reservoirs behind dams; to avoid the impacts of nitrogen supersaturation that may be associated with spilling water; to decrease the possibility of turbine entrainment; and to help avoid predation problems associated with locating bypass entrances to downstream fish passageways and diversion systems.

The use of transportation to move juvenile salmonids downstream in the Columbia River Basin is to decrease the time it takes for outmigrants to move through the system.[15] However, transportation in the Basin is controversial. During high flow periods, the need for transport is diminished, while during low flows the need for

[12] Design changes to reduce turbine mortality include smoothing of conduit surfaces, increasing clearance spaces, decreasing speed of rotation of turbine blades, reducing the height of the turbine above the tailwater, increasing the depth of the entrance to the penstock, and decreasing turbine diameter (145).

[13] Entrainment survival increased from about 80 percent with the old turbines, to 95 to 98 percent with the new turbines. There are plans to replace the remaining turbines at some point in the future.

[14] Cavitation occurs when vapor masses collapse on or behind small localized areas of the turbine blade, creating intense negative pressure. This results in the loss of metal from the blade. This situation can result in injury to fish and/or oxygen depletion, nitrogen supersaturation, other physical stresses, and ultimately mortality.

[15] Trucking requires approximately six to eight hours and barging, from the Lower Granite Dam to below Bonneville Dam, about a day and a half (176).

transportation is favored, in part due to the length of time required for the juveniles to move through reservoirs (176). During high flows juveniles may be bypassed by spilling and may be able to pass relatively quickly through reservoirs. However, during times when flows range somewhere in the middle, the use of transportation becomes controversial.

In the Columbia River System, juvenile salmonids are screened from turbine intakes, then loaded onto trucks or barges. After being transported downstream, the fish are discharged below the lowest dam, thereby avoiding turbine entrainment and exposure to predators at intervening dams. However, juveniles may experience delay in their migration schedule as a result of transportation, depending on flow rates, points of collection, holding time, and points of release. Delay may have a negative impact on physiological development (i.e., smolting) critical to the survival of juvenile salmonids. Fish may also be exposed to diseases, stress, and disorientation. However, the effects of transportation on fish development and behavior are virtually unknown and little study has been done.

There is strong regional fish agency and tribal support for trap and truck operations to move juvenile fish in the Columbia River Basin, especially during low flow periods. Much work is needed to improve facilities and operations further to reduce stress and injury (7).

Barging juvenile fish downstream has drawn mixed reviews although it continues to be supported and promoted by the Army Corps of Engineers (230). More barges are scheduled for use during 1997 in the Columbia River Basin. Barging juveniles has generated support over the use of trucks by virtue of the fact that fish are left in the water when barges are utilized. However, some controversy remains.

In the Columbia River Basin the focus of the transportation effort is on increasing smolt survival and improving the numbers of returning adults in future years. Research results are not conclusive regarding the link between transportation and adult returns to spawning grounds (251). There is some evidence that transportation from rearing to release site does affect salmon homing, but the extent of the effect is dependent on the status of the salmon (smolt, hatchery resident, or in-river migrant), the method of transportation, and the physical distance between rearing and release sites (251). However, it has been shown that salmon trucked long distances do tend to return to their release site (i.e., below lowest obstruction on the river), as opposed to their rearing site (251). Juvenile salmon learn the odors of their home stream, or hatchery, prior to seaward migration and this olfactory memory is essential for the freshwater stages of homing (98). Salmon transplanted prior to smolt stage tend to return to their release site, not their natal (i.e., native) site. Smolts are more likely to return to the reach of river where they were released (251). Homing patterns may differ depending on whether fish are transported by truck or barge.

The COE supports the transportation of fish in the Columbia River Basin. However, due to the lifecycle of salmonids, the length of time spent at sea, and the various obstacles to survival any given fish encounters, it is difficult to pinpoint cause and effect relationships between the impacts of either of these methods on population. Although the desirability of transport is controversial, there is some agreement that barges are preferable to trucks; that the release site should not be an estuarine or marine one, but the river itself; and that fish should be captured after some period of migration rather than transported from the point of origin; and finally, transportation should be regarded as experimental (251).

EVOLVING DOWNSTREAM PASSAGE TECHNOLOGIES

A number of methods for providing downstream fish passage are currently under development or being experimented with.

■ Advanced Hydropower Turbine System (AHTS)

The heritage of current hydropower turbine designs dates from the late 19th and early 20th centuries, when little was known about environmental conditions and requirements. DOE has taken a new look at the "turbine system" in an effort to identify innovative solutions to problems associated with the operation of turbines at hydropower projects. DOE and the hydropower industry have co-funded the AHTS program. DOE has the lead role in developing and implementing the program (26). The hydropower industry created a non-profit organization, the Hydropower Research Foundation, Inc. (HRFI), which includes 10 utilities that have contributed funds for the conceptual design phase. HRFI will represent and administer industry funds for the program. Steering and technical committees consisting of representatives for industry, utilities, and other federal agencies are in place to provide program direction and technical evaluations.

The purpose of the program is to stimulate and challenge the hydropower industry to design, develop, build, and test one or more environmentally friendly advanced turbine(s). This would involve the development of new concepts, application of cutting-edge technology, and exploration of innovative solutions (26). Also, the AHTS program will function to develop, conduct, and coordinate research and development with industry and other federal agencies in order to improve the technical, societal, and environmental benefits of hydropower.

The first phase involves conceptual engineering designs submitted by the industry to a technical review committee. The second phase involves building and testing fully engineered models of the most promising designs. The third phase will consist of building and testing prototypes of the most promising models in actual operating hydropower plants. Each phase will be independent of the others and will follow in succession as the previous phase is completed. The program will be subject to ongoing evaluation by HRFI and DOE.

The AHTS Program completed Phase I during 1995. Two firms, Voith Hydro, Inc., and Alden Research Laboratory, Inc., have been selected for negotiations toward possible contracts. Phase II is scheduled to be initiated in the latter part of 1995.

The U.S. Army Corps of Engineers (COE) is also working to develop an advanced turbine design that would be more "fish-friendly" by determining the mechanisms which affected fish survival. Like the DOE effort, the COE is attempting to come up with new turbine designs to increase survival of downstream migrants (34). The COE program is more oriented toward relatively minor modifications of existing turbines in the Columbia River Basin; the DOE program is focused on developing new designs that would be applicable across the United States.

Eicher Screen

The Eicher Screen was developed in the late 1970s by biologist George Eicher in an effort to develop a better means of bypassing fish safely around a turbine. The elliptical screen design fits inside the penstock at an angle and can function in flow velocities up to 8 feet per second (fps) (262).[16] Non-penstock designs are also possible (54). The screen's ability to function at relatively high velocities is what distinguishes it from conventional screens, which tend to operate at channel velocities of about 1-2 fps (262).

Eicher Screens are relatively less expensive and have smaller space requirements than most barrier screens (175). The system is about 50 percent cheaper to install than conventional, low-velocity screening systems, and involves a screened area about one-tenth that of conventional systems. The other benefits of employing this screen are that it takes up no space in the forebay area, has low operating costs, no risk of icing, and is not dependent on forebay water levels. In addition, because the screen operates at high velocities, there is less chance that it will harbor predators (262)

The approach velocity into the screen violates most state and federal screening criteria. EPRI

[16] Both the Eicher Screen and the modular inclined screen are considered to be high-velocity screens. This type of screen is supposed to function (i.e., safely pass fish) at 8 to 10 feet per second or up to 3 feet per second perpendicular to the screen (59).

supported the University of Washington test of the screen's efficiency. The studies were performed under the assumption that the swimming ability and stamina of the fish were inconsequential to the functionality of the screen.[17] Tests performed in the laboratory as well as in two prototypes in the field have produced data to support this assumption. Prototype testing has been performed at two hydroprojects, the Elwha Hydropower Project near Port Angeles, Washington, and the Puntledge Project at B.C. Hydro on Vancouver Island.

EPRI tested a refined screen design at the Elwha Project with promising results. The Elwha tests evaluated screen performance under a range of velocity conditions. EPRI's tests used hatchery-raised smolts which were marked and then released into the forebay. After traveling into the penstock and being guided by the screen, the fish were bypassed to a collection tank where they were measured, counted, and classified by amount of de-scaling or injury they had suffered. According to EPRI, the screen had nearly perfect diversion efficiency (99 percent) for some species and life stages, indicating its potential for protecting downstream migrating fish (263).

Diversion efficiency was lower and mortality higher for fry of some species and the statistical validity of this non-peer reviewed study has been questioned (12). If the screen can pass different sizes and species of fish it could have wide application in the hydropower industry. Additionally, EPRI funded a series of hydraulic model tests during 1992 to evaluate the applicability of hydraulic data from Elwha to other sites and to evaluate potential for further improvement of the flow distribution via porosity control. To complete these tests, a model of the intake, penstock, and Eicher Screen was constructed at Alden Research Laboratory. The tests evaluated 1) the possibility that hydraulic conditions at Elwha were influenced by the bend in the penstock leading up to the screen; and 2) the potential for creating a more uniform velocity distribution over the length of the screen (263).

The hydraulic model studies indicated that the velocity distribution at Elwha was not significantly influenced by the upstream bend in the penstock (263). The other tests showed that passage survival rates exceeding 95 percent can be achieved for fish in the 1.5 to 2.0 inch range at velocities up to 7 fps, while smaller fish can be protected using lower design velocities and closer bar spacing (263). At the Puntledge, British Columbia project, evaluations indicate 99.2 percent successful guidance of coho yearlings through the new Eicher Screen (211).

In general, the Eicher Screen has multiple positive operating characteristics. For instance, it is biologically effective for target fish; the total costs of installation are usually less than for other types of screen; it is unaffected by changes in the forebay elevations; it takes up no critical space; operation and maintenance costs are negligible; the relatively high velocities at which it can be used make it adaptable to almost all penstock situations (53).

Research and evaluation of the Eicher Screen has led to approval at specific sites from agency personnel who were not otherwise convinced in the early stages. Agency approval of use at other sites will depend on documentation that the design performs well for target fish at velocities present at the site.

Modular Inclined Screen (MIS)

EPRI has developed and completed a biological (laboratory) evaluation of a type of high velocity fish diversion screen known as the Modular Inclined Screen (MIS). This screen is designed to operate at any type of water intake with water velocities up to 10 fps (221). The MIS consists of an entrance with trash rack, stop log slots, an inclined wedgewire screen set at a 10- to 20-

[17] These criteria are not applicable to this type of pressure screen, because the relative flat slope coupled with the high transportation velocity over the smooth surface funneling into the bypass means that the fish are involuntarily swept into the bypass seconds after passing over the screen (53).

degree angle to flow, and a bypass for directing diverted fish to a transport pipe.

This modular screening device is intended to provide flexibility of application at any type of water intake and under any type of flow conditions (221). Installation of multiple units at a specific site should provide fish protection at any flow rate (220) Currently, no fish protection technology has proven to be highly effective at all types of water intakes, for all species, and at all times (i.e., seasonal variability (65)).

To determine viability of the MIS, a testing program to evaluate biological effectiveness was undertaken by EPRI at the Alden Research Laboratory (ARL) in Holden, Massachusetts. Evaluations at ARL have focused on the design configuration which yields the best hydraulic conditions for safe passage and shows biologic effectiveness for diverting selected species to the bypass (58).

Mark, release, and recapture tests were undertaken with 11 species including walleye, trout, alosid, and salmon smolts. These species were chosen because they are representative of those fish that are of greatest concern at water intakes across the country, based on a review of turbine entrainment and mortality studies that have been conducted in recent years (62). The tests were conducted with two screen conditions: clean screen (i.e., no debris) and incremental levels of debris accumulation. Three replicates were conducted at each of the five test velocities and control groups were used to determine mortality and injury associated with testing procedures. Control fish were released directly into the net pen and recovered simultaneously with the test fish.

To assess effectiveness, four passage parameters were calculated for each combination of species, module water velocity, and test condition (i.e., clean screen and debris accumulation) that was tested. Success was measured by determining percent of fish diverted live, adjusted latent mortality, adjusted injury rate, and net passage survival (221).

According to the 1992 EPRI report, the results of the tests “clearly demonstrate that the MIS has excellent potential to effectively and safely divert a wide range of fish species at water intakes.” The results showed that nearly 100 percent of the test fish were diverted live and that the adjusted latent mortality was less than 1 percent, although this was variable depending on species and velocity (58). Fish were safely diverted over a range of velocities (e.g., 2 to 10 fps) with minimal impingement, injury, and latent mortality; and debris accumulation did not appear to affect fish passage up to certain levels of debris-induced head loss (221). Also, EPRI noted that it was possible that the testing procedures (i.e., transport, marking, fin clipping, netting from pen or bypass) may have contributed to the observed mortality.

ARL has developed a prototype of the MIS which will be field evaluated in the spillway sluicegate at Niagara Mohawk’s Green Island facility on the Hudson River in September of 1995. The prototype MIS test is important in the development and acceptance of the technology. However, resource agencies will be unlikely to approve full-scale applications of the MIS without additional testing (12). Resource agencies are particularly troubled by operational aspects of high-velocity turbine screening. These screens only collect fish when water is flowing over them. Hydropower operational changes may be necessary to ensure adequate flow to the screens, especially during periods when many hydropower projects are filling reservoirs and not producing much power (12).

Hydrocombine

A hydrocombine design of a hydropower facility is one where the spillway is situated over the turbine intakes. This design was employed at Douglas County PUD’s Wells Dam (hydropower project) on the Columbia River as a result of the wide success of ice and trash (debris) sluiceways in passing juvenile fish. Evaluations of the hydrocombine design showed that it too was effective in providing passage for juvenile salmonids. As a result, Wells Dam became the model for research on the “attraction flow” or “surface collection” concept of downstream fish passage and sparked investigation into the potential for use elsewhere.

The theory was that this combination system could improve salmon survival by taking advantage of natural behavior and accommodating the majority of juveniles that moved downstream in the upper portion of the water column. Providing a means of passage over a surface-level spillway as opposed to forcing juvenile fish to dive to turbine intakes is more in line with natural behavior of outmigrating juveniles. A bypass with vertical slot barrier is placed in the spill intakes, which creates an attraction flow for outmigrating juveniles. Once the fish are entrained in the flow, they enter the bypass and are diverted past the dam instead of passing through the turbines (242). The hydrocombine was shown to produce a 90 percent success rate for juvenile fish passing through the Wells project (42).

The success of such a system might decrease the need for spilling, as well as the possibility of electricity rate increases. However, the results at Wells Dam were not easily explained. As is the case for many evolving fish passage technologies, there is often a lack of information regarding *why* they work. As a result, a prototype was installed at Chelan County PUD's Rocky Reach Dam and Grant County's Wanapum Dam. The configurations of the Wells, Rocky Reach, and Wanapum projects are significantly different; however, the surface collection concept is the same. Results are not yet available on either of these evaluations, but this research has sparked the development of the COE's Surface Collection Program.

Surface Collector

Surface-oriented bypasses could prove to be effective in improving juvenile salmon survival in the Columbia River Basin (232).[18] There is a major effort underway in the Pacific Northwest spearheaded by the COE to develop a surface collector design (39,77). The thrust of the research is to better understand the biological and physical principles that are at work at the Wells Dam, where a hydrocombine design is in use, and apply them to the surface collector design to provide a safer means of passage for juveniles. This "attraction flow" concept may provide downstream-migrating juveniles with an alternate, more passive route through hydropower facilities than is possible with other methods (42).

Surface collector prototypes are being evaluated at The Dalles and Ice Harbor Dams by the Portland and Walla Walla Districts of the COE, respectively. Various configurations of the design are being tested. The attraction flow prototype consists of a 12-foot-wide by 60-foot-high steel channel attached to the forebay face of the powerhouse (42) perpendicular to flow in the forebay. The goal is to guide fish hydraulically directly into the collectors, and then pump them to a bypass which moves them around the dam.

Hydroacoustics will be used to monitor fish movement and behavior in and near the collector. An adaptation of the new surface collector design is in operation at Bangor Hydro's West Enfield project on the Penobscot River and Ellsworth project on the Union River, although debris blockage has been a problem at both sites. The results of the 1995 testing at Wanapum Dam could potentially add much to what is known about downstream fish passage and design at hydropower facilities. Also, results of the prototype tests would hopefully be transferable to other powerhouses at projects on the Columbia and Snake Rivers (42).

Barrier Nets

Most technologies proven to be effective in downstream mitigation at hydropower intakes rely on large screening structures designed to provide a very low approach velocity. For many projects, such technologies are not financially feasible. For others, screens are inappropriate for other reasons. In these cases, the use of barrier nets may provide a cost-effective means of protecting fish from entrainment. In general, barrier nets have not been utilized in situations where

[18] For a more indepth discussion of the surface collector see appendix A.

both downstream passage and protection from entrainment are desirable.

Barrier nets of nylon mesh can provide fish protection at various types of water intake, including hydropower facilities and pumped storage projects. Nets generally provide protection at a tenth the cost of most alternatives; however, they are not suitable for many sites. Their success in excluding fish from water intakes depends on local hydraulic conditions, fish size and the type of mesh used. Barrier nets are not considered to be appropriate at sites where the concern is for entrainment of very small fish, where passage is considered necessary, and/or where there are problems with keeping the net clear of ice and debris (213). It may not be practical to operate nets in winter due to icing and other maintenance problems. Thus nets may not offer entrainment protection in winter at some sites.

Nets tend to be most effective in areas with low approach velocities, minimal wave action and light debris loads. Biofouling can reduce performance, but manual brushing and special coatings can help alleviate this problem. An evaluation was underway during the spring of 1995 at the Northfield Pump Storage Project on the Connecticut River in Massachusetts. The study has yet to be completed. There have been problems with debris loading and net inversion when flow in the river is reversed due to pumpback at the project.

The Ludington Pumped Storage Plant, one of the world's largest pumped storage facilities, located on the eastern shore of Lake Michigan, has had a 13,000-foot-long barrier net installed around the intake since 1989. Barrier net effectiveness, described as the percentage of fish prohibited from entering the barrier net enclosure, was estimated at about 35 percent in 1989, but substantially increased to about 84 percent in 1994 after significant improvements were made (90). This seasonal barrier appears to be effective for target fish (90).

ALTERNATIVE BEHAVIORAL GUIDANCE DEVICES[19]

Behavioral guidance technologies include any of the various methods that employ sensory stimuli to elicit behaviors that will result in down-migrating fish avoiding, or moving away from, areas that potentially impair fish survival. In all cases, the purpose is to get fish to leave a particular area (e.g., a turbine intake) and move somewhere else. The nature of the response may be long-term swimming in response to a continuous stimulus where the fish has to move some distance (e.g., a sound that is detected for an extended period of time and from which the fish continues to swim), or it may be a "startle response" that gets a fish to turn away and then continue in a different direction without further stimulation. Any stimulus that produces a startle response or frightens a fish from a particular place (essentially exclusion) is not a suitable deterrent unless there is a component to the response that moves the fish in a specific direction that leads to safety as opposed to swimming away from the stimulus in a random direction (202).

Fishes, as well as other vertebrates, are capable of detecting a wide range of stimuli in the external environment (76). The modalities most often detected include sound, light, chemicals, temperature, and pressure. Some fishes can detect electric currents and possibly other stimuli that fall outside of human detection capabilities.

For the most part, behavioral barriers have not been approved of and accepted for use by the resource agencies because they have not been shown to achieve a high enough level of protection (220). In some cases, progress has been made in developing technologies that can guide fish, possibly at a lower cost than physical barriers. Some in the industry would like to see sub-

[19] This section is drawn largely from A.N. Popper, "Fish Sensory Responses: Prospects for Developing Behavioral Guidance Technologies," an unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, June 1995.

stantial investment in developing these technologies for use at sites where complete protection is not required, or as a means of improving the effectiveness of an existing physical protection device (220).

Behavior-based technologies are touted as being less expensive than physical screening devices and easier to install than more conventional methods. Another presumed benefit is that these technologies can be used with little disturbance to the physical plant or project operation. Lastly, developers of these technologies claim that although they have not yet achieved 100 percent effectiveness, they have shown that various behavioral methods do guide fish, and that guidance can be improved upon with research and experimental application.

Lights

Many species of fish have well-developed visual systems. Light has a high rate of transmission in water and is not masked by noise. At the same time, the usefulness of light depends upon the clarity of the water as well as upon the contrast between the artificial and ambient light.

The visual system of fishes is highly adapted to enable different species to see in environments that range from shallow waters of streams to great ocean depths (142). These adaptations include, for example, the shape of the lens, the distance between lens and the photoreceptor layer, the ability to adjust the eye to see objects at different distances ("accommodate"), and other aspects of the optics of the eye. As one example, diurnal fish living in shallow waters often have yellow corneas (and sometimes yellow lenses). This serves as an optical filter to screen out some of the shortwave light which is found in such waters, and which can scatter around the eye and decrease visual acuity. Special adaptations may also be found in the setup of the photoreceptors.

While most fish see reasonably well, problems with use of light include transmission characteristics being very dependent on water turbidity, and variable attenuation of different wavelengths. Also, the effectiveness of light is likely to vary between day and night when the ratio between the stimulus light (e.g., strobe) and background illumination (e.g., daylight) differs (152).

Two types of lighting are the most widely used in experiments—mercury and strobe. Of the two, experimental results suggest that strobe lights (pulsing light) are the more successful in affecting fish movements, although mercury illumination was useful in a number of instances (61,101,163), including attracting and holding blueback herring at the Richard B. Russell Dam to keep them from entering undesirable areas (165,178). At the same time, light may attract some species and repel others living in the same habitat (25,76).

One of the earliest studies on use of lights (sealed beams) was by Brett and MacKinnon who provided data on a limited number of animals moving down a canal away from a light source (25). The fish were restrained in a particular region of the canal with nets. The results were not extensive, but two findings are of interest. First, some species swam away from the light while others did not, suggesting different behaviors by different species. Second, flashing lights were more effective at eliciting a response than continuous light, a harbinger for the use of strobe lights. Response differences to the same light source between species have been documented by others and are not surprising. These differences raise the issue, germane to all stimuli and not just light, that the stimulus has to be closely fit to the species being studied.

Strobe light has been extensively evaluated as a fish deterrent in both laboratory and field situations (59). Deterrence has been shown with a number of species, but the lights have worked most extensively and effectively with American shad juveniles (220). Successful fish deterrence with strobe lights has often been site specific, which indicates that hydraulic and environmental conditions and project design and operation have influence on the effect the lights have on species (59). The lack of conclusive results may also be attributed to inadequate sampling methodology and design.

Field tests conducted at the York Haven project on the Susquehanna River demonstrated a strong avoidance response to strobe lights by juvenile American shad (62,63). The system was designed to repel fish away from the turbine intakes and through the sluiceway. The system proved to be effective (94 percent). However, the study pointed out the need for establishing relationships between behavioral fish bypass systems and site-specific hydraulics in an effort to maximize bypass efficiency (59). Hydraulic and environmental factors had primary influence over the occurrence, distribution, and behavior of shad (152). The influence of these factors has definite bearing on the success of the system. As a result, it was concluded that the proper combination of physical and hydraulic conditions must exist in the area of the lights and the bypass system in order to achieve the desired level of effectiveness (152). Additional work is underway to verify response of various species.

The use of mercury lights to attract or repel various species including salmonids and clupeids is reviewed by EPRI (57). The results suggest that such illumination can be used with a number of species to move fish away from intakes, although the results are quite variable between sites and species. Such illumination may be more effective at night than during the day (not an unreasonable situation considering the contrast between the stimulus and ambient illumination differs greatly at night). Incandescent illumination has been tried as a method to modify behavior (57), but with no clear success.

Studies conducted at the York Haven project on the Susquehanna River indicate that mercury lights can be highly effective in attracting gizzard shad, and several studies have successfully improved bypass rates of salmonid species using mercury or incandescent lighting (57). The relatively inexpensive nature of mercury lights is a driving force of research. However, additional research is necessary to determine the feasibility of using sound as part of a directional bypass system (57).

Acoustics (Sound)

Sound has many characteristics that make it suitable for use in the possible modification of fish movement, especially over longer distances or when visibility is marginal. Sound travels at a high rate of speed in water, attenuates slowly, is highly directional, and is not impeded by low light levels or water turbidity (201). Moreover, many species of fish are able to detect sounds (69). From the standpoint of directionality, attenuation characteristics (especially with depth), the lack of effect of turbidity, and suitability during the day and night, other potential signals are not as versatile as sound. At the same time, high noise levels, such as at turbine intakes, may prevent fish from hearing artificially generated sounds in such environments, while high-intensity sounds (produced by any source) might have deleterious effects on fish.

Many fish species are known to use sound as part of their behavioral repertoire for intra-specific communication. Sounds produced by fish for communication are generally low-frequency (usually below 500 Hz) and broad-band (159,181). More recently, it has become apparent that fish are also likely to use sound to get a general "sense" of their environment, much as do humans. These sounds may include those produced by surf, water moving against objects in the environment, or wind action on the surface of the water (207). In addition, there is some evidence that fishes may respond to sounds that are produced in association with human-made structures, such as bypass screens and other signals produced as a byproduct of hydropower projects (6,164), although little is known about the actual behavioral responses to these sounds.

It is important to understand that detection of vibrational signals (which includes sounds) by fishes involves two sensory systems, the ear and the lateral line. Together, these are often referred to as the octavolateralis system (182). Both systems use similar sensory hair cells as the transducing structure for signal detection and both respond to similar types of signals. However, from the perspective of modifying the behavior of fish with sound, it is probably unimportant which sensory system per se is involved with the response; however, the distance over which stimuli can affect each sensory system differs.

A variety of different studies have been conducted using sound in attempts to affect movement patterns of fish. For the most part, these studies have concentrated on various species of salmonids and clupeids, although work has been done with regard to a variety of other species. The range of techniques used has also varied quite widely, as have the sound sources and the frequencies employed. Results are also quite variable and range from totally unsuccessful in controlling behavior to demonstrating potential usefulness for a few species under certain conditions.

Various species of clupeids (herrings and their relatives) have been studied by a number of investigators. A major thrust of this work has been to modify the swimming behavior of alewives and American shad so that they are kept from entering turbine intakes at dams. Some investigations have proven unsuccessful, while others have achieved some success.

The most compelling studies to date on clupeids in the United States involve the use of ultrasound to modify the swimming behavior of American shad and other species at a variety of sites. These transducers produce high-frequency (approximately 120 kHz) signals that appear to produce an avoidance response in juvenile American shad, causing them to move away from the sound source. Field studies have demonstrated that the effectiveness of sound can be altered by environmental conditions such as water temperature or site hydrology. Moreover, sound may be more effective at certain times in the life cycle of clupeids than at other times, and at certain times of the day or night, possibly depending upon the particular species being studied.[20]

Early studies on controlling the migration of salmonids with sound across a range of frequencies generated mixed and somewhat unclear results (33,156,254). One study showed that animals in a lab setting would respond to certain wavelengths, but there was no apparent response in a river (254). In another study, attempting to guide trout into a channel using plates set into vibration at 270 Hz, there was some evidence of success. However, there was no statistical analysis, and the limited amount of data does not suggest that results were replicated or that other compounding factors were taken into consideration (254).

Hawkins and Johnstone found that Atlantic salmon would respond to sounds from 32 to 270 Hz with best sensitivity from about 100 to 200 Hz (99).[21] More recently, studies on Atlantic salmon by Knudsen et al. (128) support the findings of Hawkins and Johnstone (99) that this species only detects very low-frequency sounds. Using a behavioral paradigm, Knudsen and his colleagues (126,128) measured the responses of salmon to tones from 5-150 Hz. The best responses were in the 5-10 Hz range. They also determined that the juvenile salmon would show an avoidance response (in a pool of water) to 10 Hz signals but not to 150 Hz signals, although avoidance to the 10 Hz signal would only occur if the fish were within 2 m of the sound source.[22,23]

Knudsen et al. tested this hypothesis and demonstrated that low-frequency sounds could be used to modify salmonid movements in a field

[20] Blaxter and Batty (1987) show that the responses to sounds of clupeids changes in the light and in the dark (22).

[21] Hawkins and Johnstone (1978) trained fish using classical conditioning so that they would show a decrease in heart rate whenever a sound was presented (99).

[22] Unconditioned startle responses were also investigated by Stober (217) on the cutthroat trout (*Salmo clarki*). Stober found that a number of specimens (but not all) would show an unconditioned startle response to sounds up to 443 Hz, although no response was found below 50 Hz. He also showed rapid habituation, as reported by Knudsen et al. (128).

[23] While exact distances are different from those reported by VanDerwalker (254), the order of magnitude of the distance from the source at which salmonids will respond to sound is the same. These results strongly support the suggestion that the response of salmonids to signals is when they are close to the sound source and very far into the acoustic nearfield.

experiment (126). They were successful in getting salmon to change direction and swim away from a sound source. The stimulus was only effective when the fish were within a few meters of the source (within the acoustic nearfield). For such a system to be fully effective in rivers or by a dam, a large number of projectors would be needed to insure that fish were properly ensonified.

A similar study reported effective, statistically significant guidance (80-100 percent diversion from the entrance to an intake canal for downmigrating steelhead trout smolts and Pacific Chinook salmon smolts) for a patented sound system now available from the Energy Engineering Services Company (EESCO). Natural sounds of various salmonids were recorded, and modified forms of the recorded sounds were played back to affect fish movements (141). Results suggested that the fish could be as much as 70 feet from the projector and the sound would still elicit a response. These results have yet to be replicated and the study only provided minimal information as to the nature of the specific sounds used to modify fish movements.

Results from preliminary tests of the EESCO system on the Sacramento River in 1993 were inconclusive (46,94a), largely due to the preliminary nature of the study and problems in experimental design. Studies are continuing at the Georgiana Slough on the Sacramento (171). The results of testing that took place during the spring of 1994 at Georgiana Slough were encouraging (50 percent overall) and statistically significant (95 percent level) (100).

Infrasound testing is currently underway within the Columbia River Basin as part of the Columbia River Acoustic Program.[24] Two types of sources are being tested, both of which generate infrasound. They differ in one component of the sound field they generate. The infrasound source, patterned after that used in Norway, is referred to as an “acoustic cannon” because it generates a sound field with large particle motion. The acoustic cannon has a 19-cm-diameter piston with a displacement of 4 cm (39). Startle followed by avoidance has been shown under controlled laboratory and field conditions for Chinook and steelhead juveniles and smolt. The other sound source, EESCO technology, generates a sound field with little particle motion. This source has a moving coil with a diameter of approximately 8 cm with a displacement of approximately 0.08 cm (39). The Acoustic Program has not conducted nor do they know of any controlled laboratory behavioral tests of fish response to the EESCO technology source. Experience to date indicates that large particle motion is required to elicit avoidance responses by salmonids.

Few other fish groups have been tested in a systematic way to determine if they would avoid low-frequency sounds (69,181). There are, however, remarks in the literature regarding avoidance responses of a number of species, and lack of avoidance or any sort of responses by other species. The Empire State Energy Electric Research Corporation (ESEERCO) (65a) reported laboratory studies of behavioral responses to low frequencies by striped bass, white perch, Atlantic tomcod, golden shiner, and spottail shiner (51a, 201a, 201b). Despite some limitations, the studies demonstrate that white perch and striped bass would show an avoidance response to broad-band sounds of below 1,000 Hz at sound levels of 148 and 160 dB (re: 1 µPa) during the day, but they showed only a weak response at night to sounds as high as 191 dB (re: 1 µPa). The other species only showed a weak avoidance response during the day.

Considerable study and data are needed to elucidate the mechanisms through which certain fish receive sound. No matter what the actual stimulus, it is of considerable interest that sound can affect the behavior of certain species either by causing a startle response or actually causing

[24] Information on the Columbia River Acoustic Program taken from Tom Carlson, Pacific National Laboratory, comments to the Office of Technology Assessment, August 1995 (39).

fish to swim away from the source of the sound. It must be kept in mind that a startle response alone is not sufficient for controlling movement of a fish. Instead, whatever the stimulus, it must elicit sustained movement of the fish in a specific direction so the fish avoids the area of danger.

Electric Fields

There are several recent reports in the gray literature that describe the use of electric fields to guide fish behavior. To date, the results from these experiments are equivocal as to their success in controlling downstream migration of several different species (20,106).[25] A couple of significant points, however, arise from consideration of these studies. First, electric fields are potentially dangerous to other species that may enter the water in the area of electric field. Second, the electric fields are restricted to regions between electrodes. Thus, they are most effective in shallow streams and relatively narrow regions where sufficient field strength can be set up between opposing electrodes.[26]

In general, evidence supporting the effectiveness of electrical barriers at supporting the downstream passage of fish is not available (220). Effectiveness will vary depending on site-specific parameters and species/size-specific responses. Several problems have been identified with their application, including fish fatigue and the relationship between fish size and susceptibility to electrical fields (59).

A combination electric screen and infrasound system has been extensively tested by Simrad in Scotland over the last two years (39). It is novel in the sense that the electric portion of the behavioral barrier is used primarily to reinforce the response to infrasound by migrating salmonids. The infrasound sources used are large particle motion sources.

Bubble Curtains

Bubble barriers were used by Brett and MacKinnon in an attempt to guide fish, with no apparent success (25). Other researchers suggested that success with air bubbles may have been associated with the sound that they produce and not necessarily with the bubbles (107,131). Ruggles points out that air bubbles are effective for some saltwater species and possibly for some species in streams, but not in rivers. Patrick et al. report that air bubbles were effective in producing avoidance behavior in laboratory experiments with gizzard shad, alewife, and smelt (172). They also reported that avoidance increased when air bubbles were combined with strobes. However, these studies have apparently not been followed up with field experiments. Patrick et al. found that air bubbles were most effective when there was some illumination. They also pointed out that the basis for fish response was not known, but may have been visual or sound-associated, as suggested by Kuznetsov (131).

Air-bubble curtains have not proven to be effective in blocking or diverting fish in a variety of field applications, nor is there data available to indicate potential effectiveness (220). There are small-scale studies of water jet curtains in various field applications; however, mechanical and reliability questions have prevented further study. Hanging-chain curtains have shown some success in preventing fish passage under laboratory conditions. Lab results have not been duplicated in the field and research has ceased (220).

Hybrid Barriers

Some study has been done to evaluate the effectiveness of using behavioral barriers in various combinations to increase overall effectiveness, yet the results have been equivocal (220). Many of the field evaluations have been conducted for

[25] The results of testing done during the spring of 1995, of an electrical barrier, at RD 108 (Wilkens Slough) on the Sacramento River were inconclusive (100).

[26] There is literature from the manufacturer of electrical guidance systems, Smith-Root, Inc., that their devices can also be used to protect turbine intakes and in other environments than streams. However, this reviewer has seen no analysis, peer-reviewed or “gray” literature, that evaluates the success of these systems beyond those described in the cited references.

application at hydropower projects, including a test combining strobe lights and ultrasonics to guide down-migrating juvenile American shad at the York Haven Dam hydropower project on the Susquehanna River.

PERSPECTIVES ON TECHNOLOGIES

In an effort to minimize expenditures while still meeting protection goals, the hydropower industry is looking to implement low-cost fish protection. New behavioral guidance technologies may be less expensive than conventional fish protection methods (for downstream passage); however, the agencies approach application of behavioral technologies with caution and consider them to be "experimental." Therefore, the industry is reluctant to invest in these technologies for fear that they will simply have to replace them with more conventional technologies. This leads to frustration for the technology vendors.

Resource Agencies

National Marine Fisheries Service

The NMFS national office seeks a high level of effectiveness for new technologies before the agency will approve application in the field, and in some cases regional offices have released position statements regarding fishery protection and hydropower. These statements do not apply on a national level, but they do have the potential to be precedent-setting. The Northwest and Southwest offices have specific guidelines for developing, testing, and applying alternative fish protection technologies (see appendix B). NMFS regional offices in the Northwest and California strongly prefer physical barrier screens, which can completely exclude fish, for use at hydropower projects over other structural or behavioral guidance devices. In addition, the agency requires that experiments evaluating a new technology should parallel the development of a conventional (technology) solution.

NMFS maintains that it is critical to require technology developers and the hydropower industry to abide by this high standard in order to uphold the agency's primary charge to protect fish and because so many fish populations have reached a "crisis" status (257). It is this argument that forms the basis of NMFS support of the use of physical barrier screens for fish protection from turbine entrainment. The agency may be more comfortable with the use of these barriers because they physically block or physically divert fish, but also because the technologies have evolved over a fairly long period during which much was learned about how to optimize performance and make adjustments based on site criteria and biological considerations. In addition to NMFS's Southwest and Northwest regional offices, Washington State's Department of Fisheries and Wildlife and the California Department of Fish and Game have released statements regarding screening criteria for salmonids (237,238,239).

U.S. Fish and Wildlife Service

In the northeastern United States, FWS may be willing to consider the application of "experimental" devices as an interim or complementary measure, depending on the situation and the species. However, FWS has no formal policy or position statement regarding the acceptability of experimental fish passage technologies. The agency accepted the use of these technologies in certain limited circumstances, but these were site-specific decisions based on professional judgment, project specific characteristics, and the significance of the resource at risk (150).

Determinations are a reflection of expert opinion and best professional judgment about what might work best at a given site. The possibility of achieving 100 percent efficiency with a passage technology, or reducing entrainment to zero percent, is unlikely. However, given the status of an increasing number of threatened and endangered species, the agency may be willing to approve the application of a technology that fails to reach a 100 percent performance goal, but provides a good level of protection, in situations where the development of a physical barrier screen or structural guidance device may take years to achieve.

In the West, FWS is generally inactive on screening, but is involved to a degree in experimenting with alternative guidance devices. The agency has developed interim screen criteria for one species, and supports the use of technologies that provide the highest degree of protection possible for target fish at all intakes.

The agency prefers the use of physical barrier and structural guidance devices over alternative experimental guidance devices. However, there is some concern within the agency that constant pressure from vendors to utilize alternative devices has led to concession in certain cases. The agency is especially concerned that once an experimental measure is in place at a site it will remain as the long-term protection measure regardless of whether performance is less than what would be expected from a conventional technology. Many agencies view experimentation as a delaying tactic. Although experimentation can be very costly over time (possibly matching the cost of a conventional approach), yearly expenditures are often much lower than the capital outlay to install a conventional technology.

Hydropower Industry

The industry's goal is to provide effective fish protection and to minimize costs, which can be a challenge especially at large hydropower projects. The industry claims to be facing difficult economic times, which may be exacerbated by the possibility of deregulation. This mood has forced the industry to come out against expenditures for what they refer to as seemingly "unnecessary" items such as fish passage and protection mitigation technologies.

The possibility of deregulation has also caused the industry to reassess its role in the alternative energy market. NHA views hydropower to be the cleanest, most efficient, and most developed renewable energy source. As a result, some industry representatives balk at the federal research and development investment to advance and perpetuate other renewable energy sources (i.e., wind, geothermal, solar, etc.), as opposed to investing in the further improvement and efficiency of hydropower on a broad scale. The industry claims that it cannot afford to bear the costs associated with research and development of fish passage technologies and that this support should come from the federal government.

Technology Vendors

Vendors of new behavioral and guidance technologies are frustrated by the reluctance of resource agencies to approve their use despite what some consider convincing results in the field (27,50). Technology developers claim that these alternatives to conventional fish protection technologies will work for a fraction of the cost of conventional screening mechanisms. The agencies continue to question "how well" the technologies work, and NMFS requires that hydropower operators also pursue a parallel track with an accepted technology (e.g., design a physical barrier or other interim measure technology or method) while an alternative is being developed or tested at a site (174).

Though there is some discussion of allowing the use of behavioral technologies to enhance physical barriers or as interim protection devices, the agencies are unwilling to allow these technologies to be utilized as the sole line of defense in fish passage mitigation in the absence of scientifically rigorous demonstrations of effectiveness. This frustrates the vendors who argue that no such evaluation exists for physical barriers and that behavioral and alternative guidance devices are being held to a standard that other conventional technologies were not during previous years.

CONCLUSIONS

Physical structures, including barrier screens, angled bar racks, and louvers, that are designed to suit fish swimming ability and behavior, as well as site conditions, remain the primary downstream mitigation technologies at hydropower facilities. There is general consensus among practitioners that the conventional technologies effectively protect downmigrating fish. Barrier screens have an appeal in that they are perceived to be absolute in their operation. According to some resource agencies, under certain conditions they may be the only viable technology. However, the high costs associated with these technologies are often barriers to their use. As a result, much of the fish passage research presently being done is focused on further developing behavioral guidance devices. Some of this effort might be directed toward the installation of physical structures because the resource agencies have identified the need to provide protection *now* while research on behavioral and alternative guidance devices is taking place.

Extensive descriptions of downstream fish passage mitigation measures are available (16,59,65). Numerous and varied measures have been used to reduce turbine entrainment, including fixed and traveling screens, bar rack and louver arrays, spill flows, and barrier nets, and alternative behavioral devices. However no single fish protection system or device is universally effective, practical to install and operate, and widely acceptable to regulatory agencies (37).

With a few interesting exceptions, there is no behaviorally-based technology that is operationally successful in guiding fish. There is potential for use of strobe illumination with a number of species, as well as use of infrasound with salmonids (and possibly other species) and use of ultrasound with clupeids and cod. These investigations need to be continued and include both basic biology and investigation of field applications of these signals. Very little work is being done with electrical stimuli and bubble barriers, and these do not appear to have been broadly successful in earlier studies. There is some evidence (165,178) that combinations of sensory stimuli (e.g., light and sound) might be a productive possibility that needs further exploration.

There are major discrepancies in the views of resource agencies and technology vendors about the potential value and performance of alternative behavioral guidance devices. Part of the discrepancy in interpreting performance data has arisen from lack of a standard approach to testing and evaluation of the technologies. Vendors will work closely with clients and consultants but rarely involve the agencies in the early stages and the decisionmaking process. In addition, though some behavioral guidance devices have been shown to elicit an avoidance response in fish at certain sites, there are inconsistencies in subsequent years of testing. This type of result has caused the resource agencies to question the validity of the assumptions and criteria on which the studies, and the evaluation, are based. It is critical to keep in mind that results and methods developed for large western hydropower facilities may not be applicable to much smaller facilities in the Northeast and Midwest. At the same time, methods that do not work at the larger facility may be very useful and appropriate for much smaller facilities. In effect, it may be important to have research programs directed at different "classes" of sites—such as large hydropower projects, small hydropower projects, bypasses, etc.

Most of the research on fish exclusion systems has not been reported in the peer-reviewed scientific literature, but appears in progress reports for funded installations, and may be overly optimistic. Often research is not described in sufficient detail to allow thorough analysis of the results. Thus, it becomes difficult, if not impossible, to assess the effectiveness of many of the techniques described or the results reported. Some experimental results seem at odds with others, and care must be taken in interpreting this information (204). Conclusions reached should be viewed as tentative.

Many of the earlier studies are weak with regard to behavioral analysis. Methods of analyzing the behavioral responses of fish (e.g., methods of observation of fish in experimental pens) have often been poorly described. Also, inappropriate methods have been used in some cases. This has led some to believe that experimenters did not use appropriate observational techniques (e.g., "double-blind" experiments where the observers were unaware of the presence of a sound stimulus when reporting the behavior of a fish). Moreover, the applicability of techniques across species, or to the same species under different environmental or physical conditions (age and size), is not well understood. Researchers for the most part have failed to ask very basic questions about the general behavior of fishes under a variety of conditions and information which could be useful in developing bypass systems.

Statistical analyses of behavioral responses are often inadequate and thus it is hard to assess the effectiveness of a technique. An issue that often arises appears to be differences in ways that various investigators have used statistics to interpret data. What may appear to be a positive response in one statistical analysis may appear to be nonsignificant in another.

Additional studies, with very specific directions, are needed to advance behavioral guidance technologies. A key need is to develop a basic understanding of the mechanism(s) by which stimuli elicit responses. In particular, it is not known how very high-frequency sounds are detected by clupeids, and basic information to answer that (and other) questions could help markedly in the design of more suitable control systems. Knowledge of the mechanisms of signals detection, the normal behavioral responses to signals, and the range of signals to which a fish will respond are critically important in helping design appropriate control mechanisms.[27]

Even basic information on the general behavior of fish is often lacking. Thus, it becomes impossible to predict how a fish might alter its behavior when it encounters a hydropower facility or water bypass, how it might respond to various sensory stimuli (e.g., light or sound), including noxious stimuli, and whether certain sensory stimuli are within the reception capabilities of a particular species. Without such basic data it is very difficult to design a truly effective means for controlling fish behavior.

An interdisciplinary approach to investigating the potential for improving fish passage is needed. Studies should be designed with close collaboration between fisheries biologists having interest and expertise in the needs for fish passage and basic scientists knowledgeable in the behavior and sensory biology of fishes. Other important specialists would likely include hydraulic engineers and hydrologists, who would bring special knowledge of currents and other aspects of the problem to the discussion, and engineers involved in designing and maintaining barriers to fish movement. To date, there has been little interaction along these lines.

[27] An example of this is found in the work controlling the movement of Atlantic Salmon by Knudsen et al. (126,128). Their experimental design for their field work was clearly based upon their first studies on hearing capabilities (128), as well as the earlier studies of Hawkins and Johnstone (99).