bioengineering **feature**

The Development of Advanced Hydroelectric Turbines to Improve Fish Passage Survival

ABSTRACT

Recent efforts to improve the survival of hydroelectric turbine-passed juvenile fish have explored modifications to both operation and design of the turbines. Much of this research is being carried out by power producers in the Columbia River basin (U.S. Army Corps of Engineers and the public utility districts), while the development of low-impact turbines is being pursued on a national scale by the U.S. Department of Energy. Fisheries managers are involved in all aspects of these efforts. Advanced versions of conventional Kaplan turbines are being installed and tested in the Columbia River basin, and a pilot scale version of a novel turbine concept is undergoing laboratory testing. Field studies in the last few years have shown that improvements in the design of conventional turbines have increased the survival of juvenile fish. There is still much to be learned about the causes and extent of injuries in the turbine system (including the draft tube and tailrace), as well as the significance of indirect mortality and the effects of turbine passage on adult fish. However, improvements in turbine design and operation, as well as new field, laboratory, and modeling techniques to assess turbine-passage survival, are contributing toward resolution of the downstream fish passage issue at hydroelectric power plants.

Glenn F. Čada

Glenn F. Čada can be reached at the Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6036, cadagf@ornl.gov.

One of the major environmental issues for hydroelectric power production is mortality of turbine-passed fish. This source of mortality can have serious consequences for fish populations, especially among anadromous species (such as Pacific salmon and steelhead [*Oncorhynchus* spp.], Atlantic salmon [*Salmo salar*], American shad [*Alosa sapidissima*]), and catadromous eels [*Anguilla rostrata*]) that must travel from rivers to the sea in order to complete their life cycles. Turbine-passage losses can be mitigated by reducing the numbers of entrained fish (e.g., by improved fish screens or other measures to divert fish from the intake, collection and transport, and/or spillway passage). Alternatively, mortality may be lessened by improving passage conditions within the turbine.

Increasing the survival of downstream-migrating fish at hydroelectric dams is a major environmental goal throughout the United States, and particularly in the Pacific Northwest. Downstream passage research performed at Columbia River Basin hydropower projects up to the mid-1990s is summarized in Whitney et al. (1997). The purpose of this article is to describe the progress of recent research and development activities related to improving the survival of fish passing through hydroelectric turbines. This article does not consider the widespread efforts to reduce the numbers of fish that are entrained, for example, through the application of intake screens, surface bypass collectors, or behavioral barriers. Rather, it focuses on the effects on fish of physical or operational modifications to turbines, and applications of new modeling, experimental, and technological approaches to develop a greater understanding of the injury mechanisms associated with turbine passage.

Research and Development Related to Advanced Turbines

Injuries and mortality among fish that pass through hydroelectric turbines can result from several mechanisms (Čada 1990; USACE 1995; Čada et al. 1997), including

- rapid and extreme pressure changes (water pressures within the turbine may increase to several times atmospheric pressure, then drop to subatmospheric pressure, all in a matter of seconds),
- cavitation (extremely low water pressures cause the formation of vapor bubbles which subsequently collapse violently),
- shear stress (forces applied parallel to the fish's surface resulting from the incidence of two bodies of water of different velocities),
- turbulence (irregular motions of the water, which can cause localized injuries or, at larger scales, disorientation),
- strike (collision with structures including runner blades, stay vanes, wicket gates, and draft tube piers), and
- grinding (squeezing through narrow gaps between fixed and moving structures).

The locations within a turbine at which these injury mechanisms tend to be most severe are shown in Figure 1, although fish experience varying levels of all the mechanisms throughout passage. Each of the injury mechanisms can be severe enough to kill fish directly, either singly or in combination with other stresses (direct mortality). If the turbine-passage injury mechanisms are not immediately lethal, fish may nonetheless be disoriented so that they are subsequently more susceptible to predation in the tailwaters below the dam, or disabled so that they later succumb to disease (indirect mortality). The concern about disorientation and increased susceptibility to predators is particularly relevant for passage through the lowermost portion of the turbine system (i.e., draft tube and tailrace) because of the high levels of large-scale turbulence found there (Carlson 2001).

Hydropower project operators have sought to reduce the direct and indirect mortality of turbine-passed fish by altering the operation or design of the turbines (see Gulliver and Arndt [1991] for descriptions and diagrams of hydroelectric turbine types). For example, turbines on the Columbia and Snake River systems are operated within 1% of peak efficiency during the juvenile and adult salmonid migration season. This constraint is based on the expectation that when turbines are operating most efficiently, potential fish injury mechanisms (e.g., turbulence, pressure changes, probabilities of strike and cavitation) will have their lowest values and fish survival will be the highest (NMFS 1995). Beyond the Columbia River basin, there are numerous aging hydroelectric turbines in the United States that will be replaced, and replacement with advanced, low-impact (often called "fish-friendly") turbines could reduce environmental impacts while maintaining electrical generating capacity. Within the last decade, efforts have been made to redesign conventional turbines to reduce obstructions and to narrow the gaps between moveable elements of the turbine that are thought to be injurious to fish. The effects of changes in the number, size, orientation, or shape of the blades that make up the runner (the rotating element of a turbine which converts hydraulic energy into mechanical energy) are being investigated. This paper summarizes the recent efforts of several organizations to increase the survival of turbine-passed juvenile fish.

Public Utility District No. 2 of Grant County

The survival probabilities of coho salmon (*O. kisutch*) entrained at two depths and at four turbine discharge rates were compared at the Wanapum Dam on the Columbia River (Normandeau et al. 1996). Among the objectives was an evaluation of the effects on fish survival of entrainment depth and turbine operation efficiency (i.e., a measure of the effectiveness of the transfer to the runner of the available power in the water that flows through it). All tests were run at Unit 9, a conventional Kaplan turbine.

Balloon-tagged fish were released at two depths (10 feet and 30 feet below the intake ceiling) and four turbine discharges (9,000 cfs, 11,000 cfs, 15,000 cfs, and 17,000 cfs). From lowest to highest, the four turbine discharges were equivalent to turbine operating efficiencies of 93.51%, 94.23% (peak efficiency), 92.75%, and 88.57% (an inefficient range of opera-

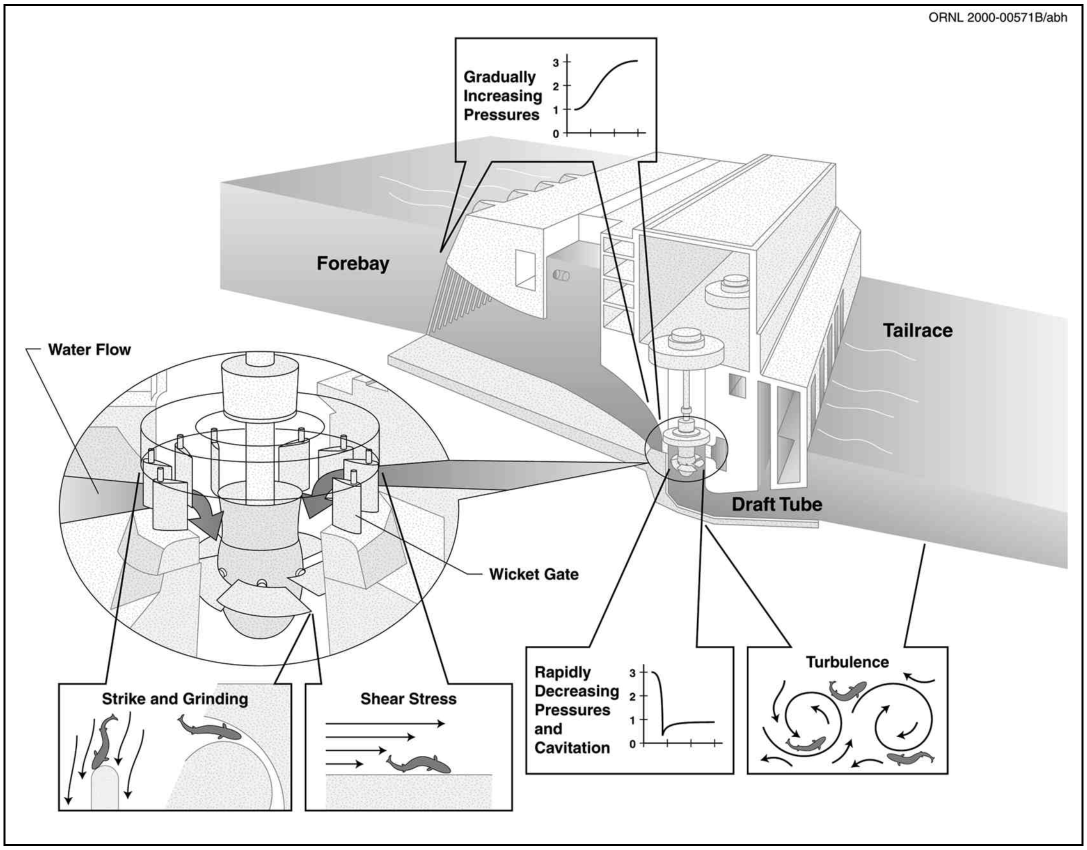

Figure 1. Locations within a hydroelectric turbine at which particular injury mechanisms to turbine-passed fish tend to be most severe.

tion that causes extremely low water pressures and cavitation downstream from the runner).

At the two highest discharges, survival probabilities were significantly lower among fish introduced at the 10-ft depth than among those released at the 30-ft depth. Average 48-h survival probabilities were 0.914 and 0.971 for smolts at the 10-ft and 30-ft release depths, respectively. Because the actual paths of the turbine-passed coho salmon could not be observed, computational fluid dynamics (CFD) modeling was used to predict the paths of fish introduced at the different depths and discharges. The CFD model suggested that fish introduced at the 10-ft depth passed near the hub, whereas those introduced at the 30-ft depth passed near mid-blade. The authors speculated that, compared to mid-blade-passed fish, fish passing near the hub may have been subjected to greater turbulence, exposure to a cavitation zone, swirling flows, and sharp-edged gaps between the runner blades and the hub. With regard to operating conditions, the highest probabilities of fish survival occurred at a turbine discharge of 15,000 cfs (turbine operating efficiency of 92.75%). The highest turbine operating efficiency tested (94.23% at 11,000 cfs) did not coincide with the highest estimated fish survival. However, the differences in survival probabilities at different discharges (efficiencies) were not statistically significant.

Public Utility District No. 1 of Chelan County

Rocky Reach Dam. Based on a preliminary study in 1994, the Public Utility District No. 1 of Chelan County (Chelan County PUD) replaced an old Kaplan turbine in Unit 6 with a Kaplan turbine with a new runner blade design. In the new design, the gaps between the blade and the hub were essentially closed by means of a recessed pocket in the hub. The benefits of this new runner design were examined by estimating the survival probabilities of balloon-tagged chinook salmon (*O. tshawytscha*) passed through the new turbine in Unit 6 at three power loads and two release depths (Normandeau and Skalski 1996). Survival probabilities were compared to those in Unit 5, an adjacent conventional Kaplan.

Overall survival probabilities were not significantly different between the two turbines: 0.958 for old Unit 5 and 0.950 for new Unit 6. Consistent, statistically significant patterns in survival related to power level (60 MW, 80 MW, and 100 MW) and release depth were not apparent for either turbine. Although turbine efficiency values were not reported, the absence of differences in estimated survival probabilities among the three power levels did not suggest that fish passage survival is only highest at the highest operating efficiencies. Surprisingly, the survival of fish that were expected to pass near the hub (10-ft release depth) was significantly lower in new Unit 6 than in old Unit 5. It was proposed that this unexpected result was due to the gap between the hub and the trailing edge of the blade in Unit 6. A temporary steel wedge was used in later tests to close that gap, which reduced injury rates (Normandeau and Skalski 1996). There appeared to be an improvement in survival following closure of the hub gap, but because controls were not used the significance of this benefit could not be determined.

Rock Island Dam Chelan County PUD compared the probability of survival of chinook salmon smolts that passed through three different types of turbines at the Rock Island Dam (Normandeau and Skalski 1997). Survival probabilities were estimated for passage through a fixed blade propeller turbine, a Kaplan (adjustable blade) turbine, and a bulb turbine. The turbines were operated at constant discharges throughout the tests (each turbine at its normal peak efficiency), and fish were passed through the turbines at two depths: near the ceiling and near mid-depth.

The estimated 48-h survival probabilities were 0.932, 0.961, and 0.957 for the fixed blade, Kaplan, and bulb turbines respectively. The survival probability estimates were not significantly different among either turbine type or entrainment depth. The authors attributed most injuries from the fixed blade and Kaplan turbines to strike and grinding. On the other hand, injuries from passage through the bulb turbine were believed to be pressure-related (Normandeau and Skalski 1997).

U.S. Army Corps of Engineers

The U.S. Army Corps of Engineers (USACE) operates eight large, multipurpose dams on the lower Columbia and Snake rivers. The USACE's Columbia River Fish Mitigation program focuses on improving the passage of adult and juvenile salmon at these dams. The USACE has put considerable effort into improving turbine passage survival in response to the Northwest Power Planning Council's request to enhance the survival of migrating adult and juvenile salmonids passing the Columbia and Snake River projects, as well as the National Marine Fisheries Service's Biological Opinions on the operation of the federal Columbia River power system (NMFS 1995; 2000). The NMFS Biological Opinions recommended that the USACE develop a comprehensive program to study engineering and biological aspects of juvenile fish passage through turbines, develop biologically based turbine design criteria, and evaluate how well various prototype designs and modifications improve juvenile fish survival through Kaplan turbines. Further, Reasonable and Prudent Alternatives mandated by NMFS (1995; 2000) to improve the operation and configuration of the federal hydropower system include operating turbines within 1% of peak efficiency during the juvenile and adult migration season and attaining 95% fish passage survival at each dam.

The USACE Turbine Passage Survival Program (TSP) was developed to investigate means to improve the survival of juvenile salmon as they pass through Kaplan turbines located at Columbia and Snake River dams (USACE 1998). The TSP is organized along three functional elements that are integrated to achieve the objectives: biological studies of turbine passage at field sites, hydraulic model investigations, and engineering studies in support of the other two elements and to optimize turbine operations. Biological studies that have been conducted or are planned at three of the USACE dams are summarized below; the other two elements of the TSP are described in USACE (1998).

Lower Granite Dam Mathur et al. (2000) examined the effects of different operating conditions (turbine discharges) on survival of turbine-passed spring chinook salmon smolts at the Lower Granite Dam Unit 4 (conventional Kaplan turbine). Three operating conditions were tested: 18,000 cfs (normal efficiency range), 13,500 cfs (normal efficiency range), and 19,000 cfs (moderate cavitation mode). Also, test fish were released near the top and at mid-elevation in the intake bays in order to assess the effects of different paths through the turbine (fish released near the top of the intake tend to pass through the runner near the hub, whereas fish entering the intake at greater depths tend to pass through the runner near the blade tip).

Overall short-term (1-h) probability of survival among the juvenile spring chinook salmon averaged 0.961; at 120 h after passage, pooled probability of survival averaged 0.948 (Normandeau et al. 1995; Mathur et al. 2000). No statistically significant differences were observed in the survival probabilities of turbine-passed spring chinook salmon smolts among the six test scenarios (combinations of turbine discharge and release location). The hypothesis that survival of turbine-passed fish may be greatest at discharges within 1% of peak turbine efficiency could not be supported by this study. In fact, survival rates of turbine-passed fish under moderate cavitating conditions were not significantly different from survival rates at highest efficiency.

McNary Dam. In 1999, the USACE supported a study of the survival and injury rates of chinook salmon smolts that passed through a conventional Kaplan turbine, Unit 9 at McNary Dam (Normandeau et al. 1999). Their goal was to determine the relative survival rates of salmon smolts that followed different routes through the turbine. There were no control releases, so test results were expressed as ratios which describe the relative survival rates among the four passage routes. Fish were released at four locations in the turbine: 1) near the runner hub; 2) at mid-blade; 3) near the blade tip; and 4) at the wicket gates/stay

Figure 2. Comparison of (a) a conventional Kaplan turbine runner and (b) a Minimum Gap Runner (MGR) at two tilt angles. Unlike fixed blade, propeller-type runners, blades on Kaplan and MGR runners are pivoted on the hub to maintain efficiency under different flow rates. Gaps on a conventional Kaplan turbine between the blade tip and discharge ring and between the blade and the hub are reduced in the MGR by changing the shape to a more spherical profile. Modified from Odeh (1999).

vanes. These locations were chosen to test the idea that fish that passed through the runner in the mid-blade region would experience fewer injuries and higher survival than fish that passed near the runner hub or the blade tip. Fish were introduced at the hub, mid-blade, and tip locations in a way that they would not encounter the wicket gates and stay vanes.

All tests were conducted with the unit operating within 1% of maximum efficiency. A total of 1,264 fish were released; of the 1,209 fish recovered, 35 were dead (2.9%), and other fish died over the 48-h post-recovery holding period. Normandeau et al. (1999) found that (1) there were no significant differences among the passage routes in terms of fish survival after 1 h (the best data). That is, in terms of short-term survival, it did not matter whether the fish passed through the mid-blade region or through a route that was expected to be more dangerous (along the hub or blade tip); (2) injury rates appeared to be slightly higher among fish that passed near the blade tip (5.1%) than over other routes (3.0% for wicket gate group and 3.8% for hub and mid-blade groups); and (3) the types of injuries appeared to be different among different routes. This was considered a pilot test to better delineate fish injury mechanisms, and to evaluate the experimental protocols and fish release systems for future experiments.

Bonneville Dam First Powerhouse. The USACE plans to install minimum gap runners (MGR) on all 10 turbines at the Bonneville I powerhouse. As the name implies, compared to a conventional Kaplan runner, the MGR incorporates some "fish-friendly" features by reducing the gaps between the adjustable blade and the hub, and between the blade tip and the discharge ring (Figure 2). It has been suggested that these modifications would reduce the fish injury caused by grinding, cavitation, shear stress, and turbulence associated with the gaps found on conventional Kaplan runners (Odeh 1999). The first units to be replaced were Unit 6 (put into commercial operation in July 1999) and Unit 4 (September 1999).

Between November 1999 and January 2000, USACE tested the ability of Unit 6 to pass juvenile salmon safely. The survival of turbine-passed fish through Unit 6 was compared to the survival of fish passed through Unit 5, an adjacent, conventional Kaplan turbine. The objective of the biological testing was to determine if the MGR is equivalent to or better than the existing Kaplan turbine in terms of fish passage survival. Using releases of a total of 7,200 juvenile chinook salmon, the study produced 24 probability of survival estimates, one for each of the two turbines at four operating conditions with three release points. Although considerable effort was devoted to releasing fish in areas that would cause them to pass near the hub, at the mid-blade region, or near the blade tip, subsequent computational analyses suggested that hub-released fish may have actually passed along the blade.

Fish passage survival through the MGR Unit 6 was equal to or better than through the conventional Kaplan unit (Normandeau et al. 2000). Probabilities of survival for fish passed near the hub were high (0.97 or greater) for both units. Survival probabilities among fish passed through the mid-blade region were similar in both units and ranged from 0.95 to 0.97. Depending on the power level, fish that passed near the blade tip of the MGR had as much as 3% greater survival than fish that passed through that region of a conventional Kaplan turbine. Overall injury rates among turbine-passed fish were low for both units: 1.4% and 2.5% for the MGR and Kaplan unit, respectively.

U.S. Department of Energy (DOE)

The U.S. Department of Energy (DOE) supports the development of low impact (fish-friendly) turbines under the Advanced Hydropower Turbine System (AHTS) Program. The AHTS program is exploring innovative concepts for the design of turbines that will have environmental benefits while maintaining efficient electrical generation. The new designs will be installed and demonstrated in operating power plants. The AHTS program awarded contracts for the conceptual designs of advanced turbines to Alden Research Laboratory, Inc./Northern Research and Engineering Corporation (ARL/NREC) and Voith Hydro, Inc. (Voith) in October 1995. The design reports that were completed by the two engineering firms (Cook et al. 1997; Franke et al. 1997) were summarized by Odeh (1999).

The ARL/NREC conceptual design focused on the development of a new turbine runner to minimize fish injury and mortality. The new runner (Figure 3), based on the shape of a pump impeller, minimizes the number of blade leading edges, reduces the pressure versus time and the velocity versus distance gradients within the runner, minimizes clearance between the runner and runner housing, and maximizes the size of flow passages, all with minimal penalty on turbine efficiency. The flow characteristics of the new runner were analyzed using two-dimensional and three-dimensional CFD models (Hecker et al. 1997). With DOE support, ARL/NREC is installing a 4-foot diameter (pilot scale), three-bladed runner in a test loop. The subsequent test program will quantify the effects on fish passing through the runner and verify the basic hydraulic characteristics of the turbine runner.

The Voith team examined how existing turbine designs can be modified to improve efficiency and reduce environmental effects. Design concepts for improved fish passage survival in Kaplan and Francis turbines (as well as designs for boosting dissolved oxygen levels in discharges from Francis turbines) were developed. These concepts can be readily incorporated into rehabilitation/upgrade of existing projects, or into new installations. Some of the ideas developed under this effort were incorporated into the design of the MGR (Figure 2).

Early in the development of conceptual designs, it became clear that there were significant gaps in the knowledge of fish responses to physical stresses (injury mechanisms) experienced during turbine passage (Čada et al. 1997). Whereas instrumentation of turbines and the increasing use of CFD modeling can provide considerable information about the levels of each of these potential injury mechanisms that can be expected within the turbine (Ventikos et al. 1997), data on the responses of fish to these injury mechanisms are frequently missing. Consequently, the activities of the AHTS program were expanded to include studies to develop biological criteria for turbines.

The biological research is being conducted under controlled laboratory conditions and coupled with physical and numerical modeling that will relate test conditions to levels of shear stress, turbulence, water pressure, and dissolved gas encountered during passage through a hydropower turbine. DOE supported laboratory tests needed to develop the biological criteria for shear stresses and turbulence (Neitzel et al. 2000). In these studies, fish were exposed to a submerged jet in an experimental flume, and the consequent injury and mortality rates were related to the forces created in the jet's mixing zone. Presently, studies are underway of the complicating effects of nitrogen gas supersaturation (a common water quality problem in the Columbia River basin) on fish's responses to pressure changes associated with turbine passage (Abernethy et al. 2001).

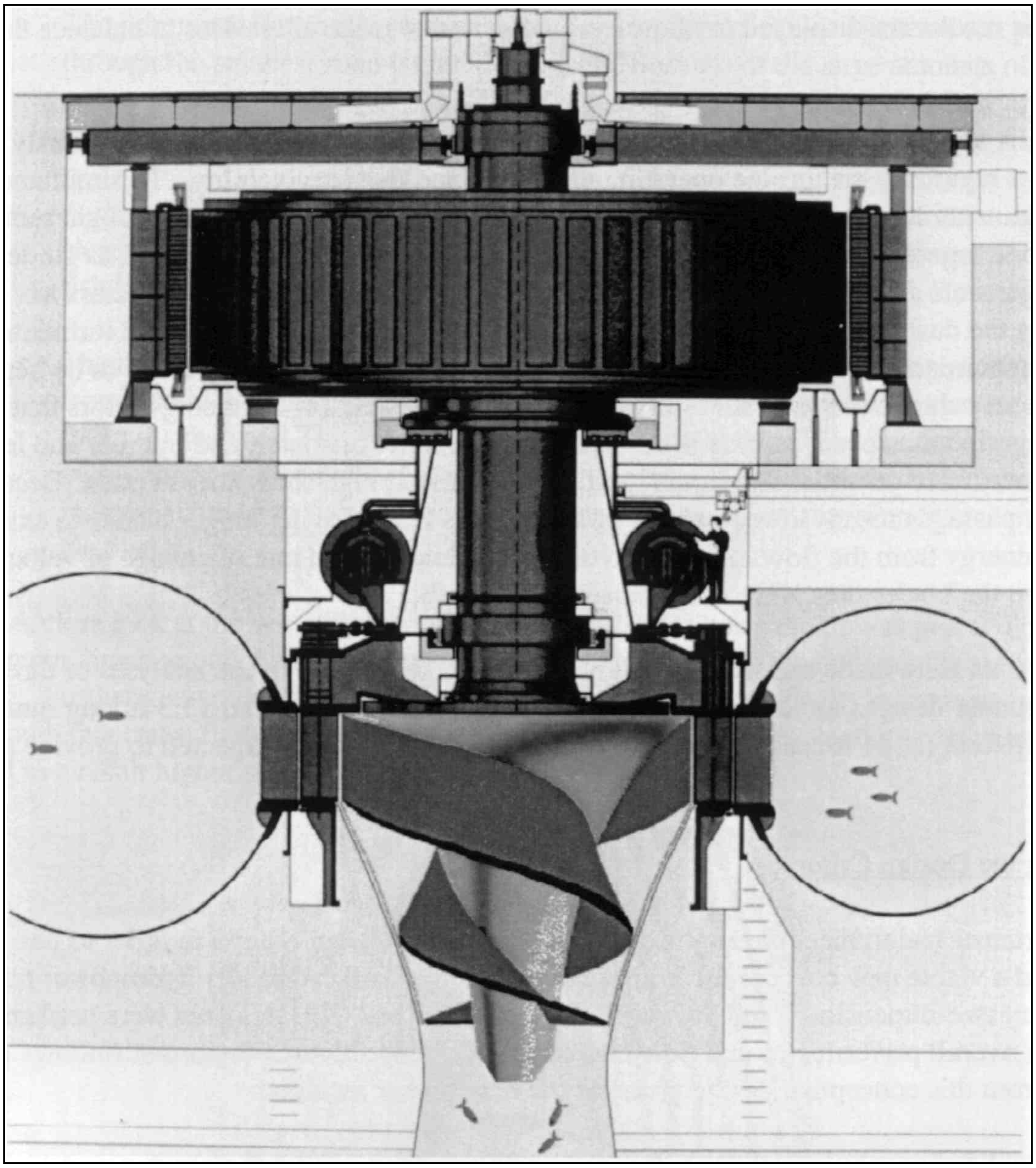

Figure 3. Conceptual installation of the ARL/NREC turbine runner at a hydroelectric plant.

Conclusions

Research on downstream fish passage at hydroelectric dams accelerated in the last decade, largely in response to the need to explore all possible means of protecting declining salmon and steelhead stocks. This research has included investigations into operational and structural measures to improve the survival of turbine-passed fish. The field, laboratory, and modeling studies outlined in this article are greatly adding to our understanding of the downstream fish passage issue at hydroelectric power plants. Answers to the following questions reflect conclusions that can be drawn from the completed studies, identify important gaps and contradictions, and suggest future research and development to resolve the turbine-passage issue.

What is the range of survival among turbine-passed fish?

The survival of turbine-passed fish depends greatly on characteristics of both the hydropower plant (e.g., the type and size of the turbine, environmental setting, and the mode of operation) and the entrained fish (species, size, physiological condition). Almost all of our information comes from studies of juvenile fish, especially salmon smolts; very little is known about the turbine-passage survival of post-spawned adults (e.g., steelhead, American shad, and other clupeids) or upstream-migrating adults that fall back through the turbines. Some small turbines designed for high-head installations (e.g., Pelton turbines) most likely cause complete mortality. On the other hand, survival of small fish for turbine types with larger water passages (e.g., Kaplan, Francis, and bulb turbines) is commonly 70% or greater. Among the most "fish-friendly" conventional turbines, e.g., large Kaplan turbines that are used at the mainstem Columbia and Snake river dams, average survival (including both direct and indirect effects) has been about 88% (Bickford and Skalski 2000). Testing of new designs with "fish-friendly" features (e.g., MGR) may demonstrate even higher survival probabilities. A goal of the DOE AHTS program is to develop turbines that achieve 98% survival of turbine-passed fish (including both direct and indirect effects). Achieving this goal will necessitate not only improvements in the design and operation of turbines, but also an increased understanding of the magnitude of indirect mortality associated with all passage routes.

> Turbine-passage survival is a complicated function of gap sizes, runner blade angles, wicket gate openings and overhang, and water passageway flow patterns.

A recent workshop (Carlson 2001) highlighted the issue of passage of adult salmonids through turbines. Participants concluded that while large numbers of kelts (post-spawning adult steelhead) may pass through Columbia River turbines on the way back to the ocean, few data were available to estimate the numbers of upstream-migrating spawners that reach the top of fish ladders and "fall back" through the turbines. Similarly, there is little information to confirm the belief that turbine-passage injury and mortality rates may be higher for adult fish than for juveniles.

Does turbine efficiency have an effect on fish survival?

Within a broad range, yes. At the ends of the turbine operating range, the pressure changes, shear stresses, and turbulence become very severe, and cavitation can occur. Because these are all sources of injury to fish, it is expected that survival will be reduced under conditions of very low operating efficiency. However, within a narrower range, but perhaps broader than the "within 1% of peak efficiency" target that is employed in the Columbia River basin, there may not be a direct relationship between turbine operating efficiency and survival. Turbine-passage survival is a complicated function of gap sizes, runner blade angles, wicket gate openings and overhang, and water passageway flow patterns. Many of these factors constitute a source of mechanical injury to fish (from strike and grinding), and they also produce localized fluid forces (shear stress, turbulence, vortices) that may cause injury. Fisher et al. (1997) proposed that large-scale turbulent energy caused by flow incidence on structures may be a significant source of injury to fish within the turbine. These investigators suggested that the optimum configuration of factors that minimizes the chances of strike, grinding, and the magnitude of fluid stresses may not necessarily coincide with highest operating efficiency.

A number of studies have been performed to ascertain whether modifications to the way that existing Kaplan turbines are operated would improve fish passage survival. The fish-passage studies of conventional Kaplan turbines at Lower Granite, Rocky Reach, and Wanapum dams have all failed to detect a direct relationship between peak turbine efficiency and probability of highest survival (see analysis by J. Skalski, in Carlson 2001). In fact, survival of spring chinook salmon at Lower Granite under a moderately cavitating condition was not significantly different from survival at highest efficiency. Preliminary analyses of the recently completed Bonneville I tests suggest that for the MGR turbine, high fish survival can also be achieved outside of the 1% range.

Does passage route through the turbine have an influence on the types of injuries and probability of survival?

To date, results of research on this question are mixed. Because different routes of passage through the turbine impose different combinations of fluid stresses and strike potential on fish, it is reasonable to suppose that injury rates and survival would also be affected. We have not yet been able to watch a fish passing through the turbine runner and out the draft tube, so we can only predict the path that each fish takes, based on where it was introduced into the intake and assuming that its path generally follows flow lines described by hydraulic models. Coutant and Whitney (2000) note that salmonid smolts often (but not always) enter hydropower intakes with their heads oriented upstream, but caution that fish may subsequently change orientation in the flow fields within the turbine. We know nothing about a fish's volitional movements within a turbine (e.g., its ability to sense and avoid obstacles or to compensate for increasing density due to increasing pressure), and for now must assume that they behave passively.

Juvenile salmonids that enter hydropower intakes are surface oriented, which in many turbine installations tends to take them along the ceiling of the intake and through the runner near the hub. It has been generally believed that a fish passing the runner near the mid-blade will suffer less injury than one passing near the hub or blade tip. This is because the hub and blade tip zones pose a greater risk of mechanical damage (striking walls as well as the blade; grinding in the blade-tip and hub gaps) and probably fluid damage (high-energy shear stress and turbulent vortices associated with blade-tip and hub gaps). Consistent with this idea, it appears that different passage routes result in different frequencies of injury types. The McNary Dam study suggested that injury rates were slightly higher among chinook salmon smolts that passed near the blade tip than over other routes, and that types of injuries differed as well; however, the study was not designed to test the statistical significance of the differences.

In terms of survival, studies of turbine passage routes yielded mixed results. For example, the study at Wanapum Dam indicated that the release location (and presumed path of the fish through the turbine) had a significant effect. Fish believed to have passed near the runner hub had lower probabilities of survival than fish that passed through the runner in the mid-blade region. On the other hand, introducing fish in different locations had no significant effect on survival at McNary, Lower Granite, and Rock Island dams. The recently completed Bonneville I tests suggest that mid-blade passage resulted in high fish survival for both conventional Kaplan and MGR turbines, whereas blade-tip passage was the route with lowest and most variable survival. It is worth reiterating that passage of test fish along particular routes is not guaranteed, owing to inaccuracies in the fish introduction system and volitional movements of the fish once they are released.

Do the modifications associated with minimum gap runners (reduced gaps at the hub and blade tips) result in higher survival of turbine-passed fish?

The survival of fish that passed through an MGR and conventional Kaplan turbine have most recently been compared at the Bonneville I powerhouse (Normandeau et al. 2000). Preliminary analyses suggest that the MGR yielded higher survival than the adjacent conventional Kaplan overall, and was particularly beneficial for improving survival of fish that passed near the runner blade tips. There is good reason to expect that reducing gaps will improve survival. Modifications characteristic of MGRs should reduce the chance of grinding, cavitation, shear stress, and turbulence associated with the hub and blade-tip gaps on conventional Kaplan runners. However, the fish-passage tests at Rocky Reach Dam did not support this idea. Although the new runner tested at Rocky Reach Unit 6 was not an MGR, it closed the gap between the hub and the leading edge of the blade with a recessed pocket. Contrary to expectations, this modification seemed to lower survival among test fish that passed near the hub. Subsequent modifications to also reduce the gap between the hub and the trailing edge of the blade seemed to reduce injuries.

In addition to modifications to the runners represented by the MGR design, additional changes have been suggested in the design of stay vanes, wicket gates, and the draft tube to reduce gaps and overhangs that may cause strike, grinding, and hydraulic stresses (Franke et al. 1997). Resulting reductions in these injury mechanisms would almost certainly improve fish survival.

Is indirect mortality significant for turbine-passed fish?

Indirect mortality is the term used to describe mortality among fish that experience low (sublethal) levels of physical stress during dam passage, but subsequently die because of increased susceptibility to disease or predation. Predation in the tailrace is the most immediate source of indirect mortality to downstream-migrating fish. Fish that pass through turbines and spillways are exposed to shear stress and turbulence, pressure changes, and potentially abrasion and collision with structures. These injury mechanisms cause loss of equilibrium and disorientation which may make the fish at least temporarily more susceptible to predators. It is suspected that the disorienting effect of large-scale turbulence may be particularly acute in the draft tubes and tailraces of some hydropower plants, so that survival benefits might be gained by redesigning these components of the turbine system. While fish that pass through properly functioning screening and bypass systems probably experience lower levels of these physical stresses, they may be concentrated at the bypass release site below the dam and be more vulnerable to waiting predators.

Indirect mortality has not been rigorously studied in the field, and as a consequence we do not know whether indirect mortality is a significant factor for turbine-passed fish. Bickford and Skalski (2000) suggested that the difference between their independent estimates of immediate turbine passage survival (average = 0.933) and longer term survival (average = 0.873) in a number of Columbia River basin studies may be due to subacute or chronic (i.e., indirect) mortality. Recent laboratory experiments demonstrated that rainbow trout (*O. mykiss*) exposed to levels of shear stress and turbulence that do not cause obvious physical damage may nonetheless suffer significantly greater predation than controls (Neitzel et al. 2000). Because fish using any of the downstream passage routes may experience some level of sublethal injury or increased vulnerability to predators, the short-term survival probabilities estimated by existing studies focused on turbine or spillway passage are likely to be too high by an unknown amount. Although the direct mortality studies indicate that probability of survival is often higher among spillway-passed fish than among turbine-passed fish, subsequent losses to predation and disease could potentially reduce these differences.

> Quantification of fish injury mechanisms in a turbine has often been based more on model predictions than actual measurements because it is difficult to install instruments in the areas where these mechanisms are likely to be most severe.

How can the injury mechanisms experienced by fish passing through turbines be quantified?

Although pressure changes, shear stresses, and turbulence that occur in different areas of a turbine can be estimated with models, actual measurements must be made to calibrate and validate the models. Available instruments can be used to make these measurements in some parts of the turbine (e.g., along the walls of the forebay, intake, or draft tube), but the magnitudes of fluid forces in the center of the water passages or near the runner have not been measured. It is likely that shear stress and turbulence are most extreme in localized areas near the hub, blade tips, wicket gates, and stay vanes, and these areas are the most difficult to instrument. Fish injury mechanisms can be quantified with devices such as the sensor fish, a fish-sized package of instruments that has been sent through turbines to record pressure and acceleration (Carlson 2001). Actual measurements can be correlated with CFD analyses to estimate the magnitudes of physical stresses throughout the turbine passage.

How can the physical stress mechanisms experienced by turbine-passed fish be reduced?

Generally, reduction of turbine-passage mortality could be accomplished by the following sequence: (1) quantify the injury mechanisms that impact turbine-passed fish; (2) determine at what levels these physical stresses are injurious by means of controlled, laboratory bioassays; and (3) redesign the turbine or modify its operation to reduce the physical stresses to safe levels.

Quantification of fish injury mechanisms in a turbine has often been based more on model predictions than actual measurements because it is difficult to install instruments in the areas where these mechanisms are likely to be most severe. Once quantified, the values could be put into perspective by performing controlled laboratory studies of the response of fish to the injury mechanisms. Ideally, such studies would examine each of the injury mechanisms in isolation, i.e., the bioassay would not be complicated by combinations of different sources of injury as occurs in field studies. The bioassays would apply the physical stresses in relevant ways (similar to the way the stress impinges on turbine-passed fish) and would encompass the full range of values that are encountered in a turbine (or other downstream passage route). The fish responses (disorientation, injury, and mortality) can be expressed as a function of the magnitude of the physical stress, and different stresses can be compared to determine which should receive greatest consideration in the redesign of turbines.

When safe levels for each turbine-passage stress have been established, measurements and model studies can be reexamined to ascertain the locations within the turbine where the level of the stress is too high. Further modeling can be used to redesign the turbine or to suggest changes in operation to reduce these areas. Ultimately, field studies will be needed to determine whether the new designs and operational modifications increase turbine-passage survival.

A longstanding goal of both power producers and regulators has been the employment of environmentally improved hydroelectric turbines that permit the efficient generation of electricity while minimizing damage to fish and their habitats. Although there are many unanswered questions, recent advances in our understanding of the turbine-passage issue and the ongoing development of new turbine designs show promise for achieving that goal.

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References

Abernethy, C. S., B. G. Amidan, and G. F. Čada. 2001. Laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish. U.S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho.

Bickford, S. A., and J. R. Skalski. 2000. Reanalysis and interpretation of 25 years of Snake–Columbia River juvenile salmonid survival studies. North American Journal of Fisheries Management 20:53-68.

Čada, G. F. 1990. A review of studies relating to the effects of propeller-type turbine passage on fish early life stages. North American Journal of Fisheries Management 10(4):418-426.

Čada, G. F., C. C. Coutant, and R. R. Whitney. 1997. Development of biological criteria for the design of advanced hydropower turbines. DOE/ID-10578. Prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Carlson, T. 2001. Proceedings of the turbine passage survival workshop. June 14-15, 2000. PNNL-SA-33996. U.S. Army Corps of Engineers Portland District, Portland, Oregon.

Cook, T. C., G. E. Hecker, H. B. Faulkner, and W. Jansen. 1997. Development of a more fish tolerant turbine runner—advanced hydropower turbine project. DOE/ID-10571. Prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Coutant, C. C., and R. R. Whitney. 2000. Fish behavior in relation to passage through hydropower turbines: a review. Transactions of the American Fisheries Society 129:351-380.

Fisher, R. K., S. Brown, and D. Mathur. 1997. The importance of the point of operation of a Kaplan turbine on fish survivability. Pages 392-401 *in* D .J. Mahoney, ed. Waterpower '97. Proceedings of the international conference on hydropower. American Society of Civil Engineers, New York.

Franke, G. F., D. R. Webb, R. K. Fisher, D. Mathur, P. N. Hopping, P. A. March, M. R. Headrick, I. T. Laczo, Y. Ventikos, and F. Sotiropoulos. 1997. Development of environmentally advanced hydropower turbine system design concepts. Voith Hydro, Inc. Report No. 2677-0141. Prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Gulliver, J. S., and R. E. A. Arndt (eds.). 1991. Hydropower engineering handbook. McGraw Hill, Inc., New York.

Hecker, G. E., T. C. Cook, and W. Jansen. 1997. A new fish friendly turbine runner. Pages 383-391 *in* D. J. Mahoney, ed. Waterpower '97. Proceedings of the international conference on hydropower. American Society of Civil Engineers, New York.

Mathur, D., P. G. Heisey, J. R. Skalski, and D. R. Kenney. 2000. Salmonid smolt survival relative to turbine efficiency and entrainment depth in hydroelectric power generation. Journal of the American Water Resources Association 36:737-747.

Neitzel, D. A., M. C. Richmond, D. D. Dauble, R. P. Mueller, R. A. Moursund, C. S. Abernethy, G. R. Guensch, and G. F. Čada. 2000. Laboratory studies on the effects of shear on fish: final report. DOE/ID-10822. U.S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho.

NMFS (National Marine Fisheries Service). 1995. Biological Opinion—Reinitiation of consultation on 1994-1998 operation of the federal Columbia River power system and juvenile transportation program in 1995 and future years. Endangered Species Act Section 7 consultation. Northwest Region, Seattle, Washington.

_____. 2000. Biological Opinion—Reinitiation of consultation on operation of the federal Columbia River power system, including the juvenile transportation program, and 19 Bureau of Reclamation projects in the Columbia Basin. Endangered Species Act Section 7 consultation. Northwest Region, Seattle, Washington.

Normandeau Associates, Inc. and J. R. Skalski. 1996. Relative survival of juvenile chinook salmon (*Oncorhynchus tshawytscha*) in passage through a modified Kaplan turbine at Rocky Reach Dam, Columbia River, Washington. Prepared for Public Utility District No. 1 of Chelan County, Wenatchee, Washington.

_____. 1997. Turbine passage survival of chinook salmon smolts at the Rock Island Dam Powerhouse I and II, Columbia River, Washington. Prepared for Public Utility District No. 1 of Chelan County, Wenatchee, Washington.

Normandeau Associates, Inc., J. R. Skalski, and Mid Columbia Consulting, Inc. 1995. Turbine passage survival of juvenile spring chinook salmon (*Oncorhynchus tshawytscha*) at Lower Granite Dam, Snake River, Washington. Prepared for Walla Walla District, U.S. Army Corps of Engineers, Walla Walla, Washington.

_____. 1996. Fish survival investigation relative to turbine rehabilitation at Wanapum Dam, Columbia River, Washington. Prepared for Grant County Public Utility District No. 2, Ephrata, Washington.

_____. 1999. Relative passage survival and injury mechanisms for chinook salmon smolts within the turbine environment at McNary Dam, Columbia River. Prepared for Walla Walla District, U.S. Army Corps of Engineers, Walla Walla, Washington.

_____. 2000. Direct survival and condition of juvenile chinook salmon passed through an existing and new minimum gap runner turbines at Bonneville Dam First Powerhouse, Columbia River. Prepared for Portland District, U.S. Army Corps of Engineers, Portland, Oregon.

Odeh, M. 1999. A summary of environmentally friendly turbine design concepts. DOE/ID/13741. Prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

USACE (U.S. Army Corps of Engineers). 1995. Proceedings: 1995 turbine passage survival workshop. U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

_____. 1998. Turbine passage survival program. Annual Report FY97. Northwest Division, U.S. Army Corps of Engineers, Portland, Oregon.

Ventikos, Y., F. Sotiropoulos, and R. K. Fisher, Jr. 1997. Predicting fish passage through hydropower installations. Pages 1729-1736 *in* D. J. Mahoney, ed. Waterpower '97. Proceedings of the international conference on hydropower. American Society of Civil Engineers, New York.

Whitney, R. R., L. D. Calvin, M. W. Erho, Jr., and C. C. Coutant. 1997. Downstream passage for salmon at hydroelectric projects in the Columbia River Basin: Development, installation, and evaluation. Report No. 97-15 for the Northwest Power Planning Council, Portland, Oregon.