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Efforts to Reduce Mortality to Hydroelectric Turbine-Passed Fish: Locating and Quantifying Damaging Shear Stresses

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ABSTRACT / Severe fluid forces are believed to be a source of injury and mortality to fish that pass through hydroelectric turbines. A process is described by which laboratory bioassays, computational fluid dynamics models, and field studies can be integrated to evaluate the significance of fluid shear stresses that occur in a turbine. Areas containing potentially lethal shear stresses were identified near the stay vanes and wicket gates, runner, and in the draft tube of a large Kaplan turbine. However, under typical operating conditions, computational models estimated that these dangerous areas comprise less than 2% of the flow path through the modeled turbine. The predicted volumes of the damaging shear stress zones did not correlate well with observed fish mortality at a field installation of this turbine, which ranged from less than 1% to nearly 12%. Possible reasons for the poor correlation are discussed. Computational modeling is necessary to develop an understanding of the role of particular fish injury mechanisms, to compare their effects with those of other sources of injury, and to minimize the trial and error previously needed to mitigate those effects. The process we describe is being used to modify the design of hydroelectric turbines to improve fish passage survival.

A major environmental issue for hydroelectric power production is injury and mortality to fish that pass through the turbines. Anadromous fishes, such as Pacific salmon (*Oncorhynchus* spp.), steelhead trout *(Oncorhynchus mykiss)*, American shad *(Alosa sapidissima)*, and catadromous fishes, such as eels *(Anguilla rostrata* and *A. anguilla)*, must pass from freshwater rivers to the sea as part of their life cycle, and they often encounter hydroelectric dams and turbines along the way. Other, nonmigratory fish in the hydroelectric reservoir may incidentally be drawn into the turbine intake and suffer turbine-passage mortality. Even nonanadromous fish often make long-distance migrations within fresh water systems and pass hydroelectric facilities. As few as 5% of turbine-passed fish may be killed in the best conventional turbines, but mortality associated with other common turbine designs may exceed 30% (Čada 2001) Turbine-passage morality has long been recognized as a significant issue in North America, and concern about it is increasing all over the world, especially as new, large hydropower dams are being constructed in previously unimpounded rivers (Jungwirth and others 1998; WCD 2000; Pavlov and others 2002). If the survival of turbine-passed fish can be improved, there is a potential to preserve or restore fish stocks while maintaining an important source of renewable electricity.

Injuries and mortalities among turbine-passed fish can result from several mechanisms, including rapid and extreme pressure changes, cavitation, strike, grinding, turbulence, and shear stress (Turnpenny and others 1992; USACE 1995; Čada and others 1997; Turnpenny 1998). Although the potential injury mechanisms have been identified, until recently little was known about the location and magnitude of these phenomena within turbines. For the last decade, the U.S. Department of Energy (DOE), through its Hydro-

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*Author to whom correspondence should be addressed; *email:* cadagf@ornl.gov power Program, has supported the development of ''environmentally friendly'' turbines, i.e., turbine systems in which environmental attributes such as fish passage survival are emphasized (Brookshier and others 1995). Advanced turbines would be suitable for installation at new hydropower facilities and to replace aging turbines at existing plants. It is expected that these turbines could permit the efficient generation of electricity while minimizing the damage to fish and restriction of their migratory habits. Advanced turbine research sponsored by the DOE Hydropower Program has encompassed 1) development and testing of instrumentation (to measure conditions inside of turbines); 2) bioassays (to ascertain fish responses to those conditions); and 3) computational modeling (to aid in the design of advanced turbines by extending the results of measurements and bioassays to unstudied conditions).

For effective environmental management, in this case provision of less damaging turbines, the three elements above must be wedded into an analytical framework that will provide useable turbine designs. Biological data on response thresholds by fish (levels of exposure that cause damaging effects) must be compared to quantitative measures of the actual or predicted occurrence of these conditions in the turbines. If these damaging conditions are indicated to occur, then field tests are needed to determine whether the damages actually occur (and to what extent). The objectives of this article are to show how we are integrating these three disciplines and to provide some preliminary results of the ongoing process.

Of the potential turbine-passage injury mechanisms listed above, effects of the related phenomena of shear stress and turbulence have been the most difficult to gauge. Briefly, fluid stresses result from forces acting on an area such as a fish body. The components of the force that are parallel to the surface area create shear stress. These fluid forces are normally a result of changing velocity within a flow field and/or turbulence. Shear stress is most obvious where two masses of water moving in different directions intersect, or where moving water slows near a solid structure. In most natural environments, shear stresses are small and nondamaging. Aquatic organisms have developed numerous adaptations to the levels of shear stresses found in normal river flows (Vogel 1994). However, high and potentially lethal values of shear stress can occur where rapidly flowing water passes near structures such as ship hulls, pipelines, canals, spillways of hydroelectric dams, and internal structures of hydroelectric turbines (Čada and others 1997). The effects of shear stress can be similar to those of friction forces between solid surfaces. The effects of shear stress on turbine-passed fish are poorly known because of the difficulties in determining its magnitude and distribution within hydroelectric turbine systems, and then recreating it in a controlled laboratory environment. Field observations (Normandeau and others 1996) suggest that these fluid forces can be severe enough to cause descaling, tearing or bruising of tissues, and even decapitation. In order to maximize the survival of turbine-passed fish, it is important to understand the relationship between shear stresses in the environment and fish survival and, if necessary, reduce these fluid forces through operational changes or physical modifications.

Recently developed biological criteria for shear and new computational fluid dynamics (CFD) models allow the identification of areas where injurious shear stress may occur inside turbines. We describe an effort to couple the findings of shear stress bioassays with computational modeling in order to determine the locations and extent of potentially damaging shear stresses within a common type of turbine. The resulting model predictions are compared to estimates of injury and mortality in the field to illustrate an approach for systematically evaluating and mitigating the effects of particular turbine-passage stresses.

Methods

Bioassay

In order to assay the biological effects of shear, Neitzel and others (2004) exposed juvenile fish to a high-velocity, submerged jet in a large laboratory test flume. Water entered the flume through a 25.4-cm-diameter circular nozzle, 0.6 m below the water surface. The exit velocities from the nozzle ranged from 0 to 23 m/s, and contact with the boundary of the expanding jet exposed the fish to average rates of strain (shear) up to 1185 s^{-1}. After exposure, fish were held for 48 h to monitor delayed mortality and other effects indicative of shear stress injuries. Logistic regressions of the injury and mortality data were used to estimate the values of shear that caused minor injuries, major injuries, or mortalities.

Computational Fluid Dynamics

CFD models were used to estimate the shear stresses within a Kaplan turbine (a common, adjustable blade, propeller-type turbine) at the Wanapum Dam on the Columbia River, Washington. The entire flow passage through the Wanapum turbine was divided into three sections for CFD analysis: 1) the intake region (including the semispiral case, stay vanes, and wicket gates); 2) the runner (hub and blades); and 3) the draft tube region (Figure 1). A separate calculation for the stay vane–wicket gate region was used to generate

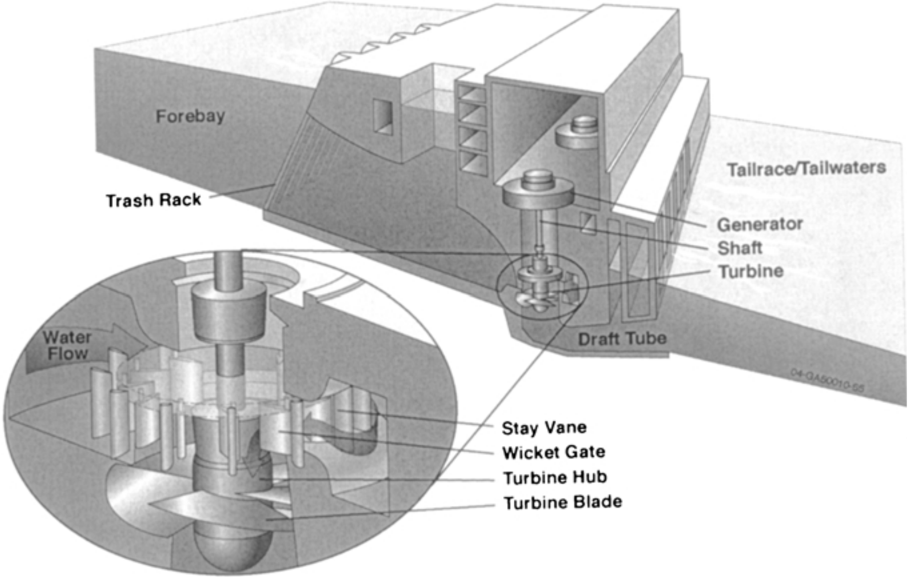

Figure 1. Diagram of a Kaplan hydroelectric turbine. Turbine-passed fish are transported from the forebay to the tailwaters and are exposed to several potential injury mechanisms, including shear stresses.

inflow boundary conditions for the runner region. Similarly, results of the runner calculations were used to provide inflow conditions for the draft tube region (Garrison and others 2002). Velocity, pressure, and turbulence values in each of the regions were estimated using a 3-D viscous flow solver, TASCflow, with Reynolds-Averaged Navier-Stokes (RANS) equations and a Kato-Launder k-epsilon turbulence generation model (AEA 2000). The solver is fully coupled and uses an Algebraic Multigrid discretization method with blocking based on the nodal formations (AEA 2000). The semispiral case calculation that included stay vanes and wicket gates utilized over 1.4 million nodes. A single runner blade had approximately 450,000 nodes, and the draft tube almost 900,000 nodes. The RANS equations are time-averaged, and yield average values of shear stresses in all three dimensions; random fluctuations in velocity (and consequently shear stress) were estimated using the k-epsilon turbulence model. Postprocessing was completed using Ensight software version 7.4.0. Shear stresses in each region were calculated by using a maximum shear stress variable available in Ensight. This calculation approximates the maximum shear stress in any direction at each node within the computational domain (CEI 2000).

Shear stress values within an existing Kaplan turbine at Wanapum Dam were calculated for four operating conditions (flow rates): 255, 311, 425, and 481 m^3s^{-1}, all at a net hydraulic head of 23 m. These turbine flow conditions were chosen to correspond to those used during field tests of fish passage survival at the Wanapum Dam in 1996 (Normandeau and others 1996).

No water velocity data from field studies or physical models were available to validate these calculations directly for the Wanapum turbine. Instead, the computational model was used to make predictions of shear stresses associated with the submerged jet in the Neitzel and others (2004) test flume; the predictions were then compared to estimates based on velocity measurements in the jet made with a laser Doppler velocimeter. The comparisons between CFD predictions and measured jet velocities were relatively good. The CFD calculations somewhat overpredicted turbulent shear stresses in the far field (where shear stresses are lower), but predicted well the maximum values near the edge of the jet (Garrison and others 2002).

Field Study

Injuries and mortalities to turbine-passed juvenile coho salmon, *Oncorhynchus kisutch*, were estimated at the Wanapum Dam (Normandeau and others 1996). A total of 1,278 fish were passed through one of the Kaplan turbines at that site at the same four flow rates used in the CFD modeling effort. In addition, fish were introduced into the intake at two depths from the turbine ceiling, 3 m and 9.1 m, in order to ascertain whether different paths through the turbine resulted in different survivals. Fish introduced closer to the ceiling were believed to pass through the runner near the hub, whereas those introduced at the mid-depth of 9.1 m were expected to pass through the runner in the mid-blade area. Turbine-passed fish were recaptured below the dam, examined for injuries, and held for 48 h to determine delayed mortality.

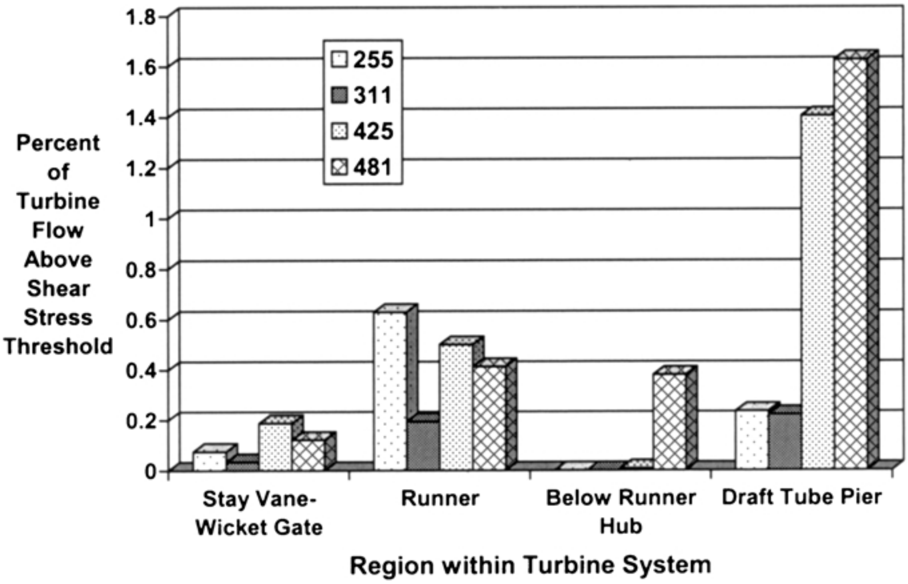

Figure 2. Estimated percentages of flow through the Kaplan turbine at Wanapum Dam that exhibit shear stress values in excess of the fish injury threshold of 1600 Pa. Predictions are provided for different regions of the turbine system and at four different turbine flow rates (255, 311, 425, and 481 m^3s^{-1}).

Results

The fluid environment created in the laboratory flume by the submerged jet was damaging to test fish at certain levels of strain (Neitzel and others 2004). For example, jet velocities of 9.1 ms^{-1} (which created a strain rate of 517 s^{-1}) caused minor injuries to fall Chinook salmon (*O. tshawytscha),* and higher velocities (e.g., 18.3 ms^{-1}; 1008 s^{-1}) were lethal to some individuals. Not surprisingly, no single value for jet velocity or strain rate could be used as an overall threshold for damage; injuries and mortalities were species specific and affected by the fish's orientation when struck by the jet. The most sensitive species, American shad, suffered injuries at a strain rate of 400 s^{-1}, and complete mortality at 1008 s^{-1}.

Strain rates estimated in the laboratory experiments were converted to shear stress values (Garrison and others 2002). The conditions under which minor injuries to fall Chinook salmon were first observed (jet velocity of 9.1 ms^{-1} and strain rate of 517 s^{-1}) were used as a single threshold value for CFD calculations under all Wanapum turbine flow conditions. The resultant shear stress value of 1600 Pa, the maximum shear stress corresponding to a strain rate of 517 s^{-1}, was taken as a threshold for fish injury due to shear stress inside the turbine system. That is, areas within the turbine that had estimated shear stress values greater than 1600 Pa were assumed to cause injury or mortality to fish that passed through them.

The CFD analyses revealed no large areas of damaging shear stress in the intake region upstream of the stay vanes at any of the four turbine flow conditions (Garrison and others 2002). Small areas of shear stress above the 1600 Pa threshold value were found in the wakes of the wicket gates under all conditions, and at higher flows at the entrance edge of stay vanes.

The Kaplan runner at the Wanapum Dam is predicted to have damaging shear stress in four areas: 1) near the surface (boundary layer) of the runner blades; 2) at or near the gap between the blade tips and the discharge ring that encases the runner; 3) at or near the gaps where the moveable blades are attached to the hub; and 4) in the wakes downstream from the blades. Shear stresses in the first three (runner) areas vary with flow; in the draft tube downstream from the runner the shear stresses are largest at the highest flow rate of 481 m^3s^{-1}. High shear stresses in the boundary layer are expected, because water velocities drop from more than 10 ms^{-1} in the main flow to zero at the blade surface over a small lineal distance. The high shear stresses near the blade tips and hub are caused by some of the turbine flow being ''squeezed'' through the small gaps and creating high-energy vortices in the wake. Finally, the spinning runner imparts a rotational motion on the bulk of the flow. CFD analyses predict that this rotation results in a vortex with high angular velocities (and thus high values of shear stress) directly downstream from the hub. Damaging shear stress also occurs where the rotating flow below the runner strikes the draft tube piers at a sharp angle (piers are wall-like structures that support the draft tube and divide the passage into three sections).

The sizes of the turbine regions with shear stress values greater than 1600 Pa were quantified, and nor-

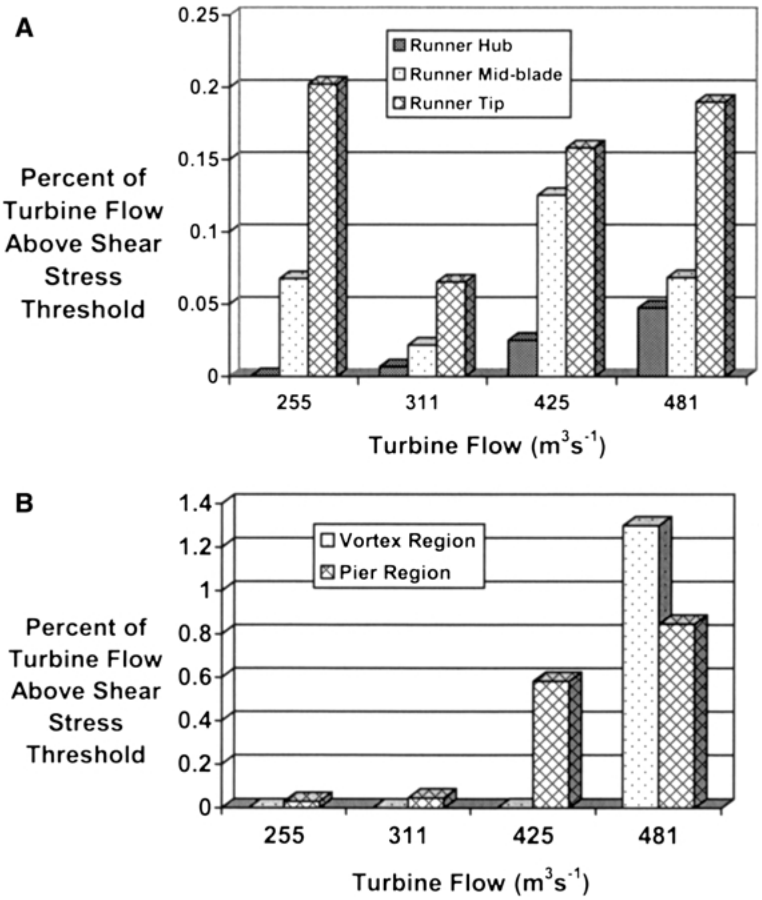

Figure 3. Estimated percentages of flow through the Kaplan turbine at Wanapum Dam that exhibit shear stress values in excess of the fish injury threshold of 1600 Pa. (**a**) Partitions the shear stress within the runner into three regions from the hub to the tip. (**b**) Displays predicted shear stress in the draft tube associated with the vortex (below the hub) and the draft tube piers.

malized by the amount of water passing that point. Adjustment for localized flow rates is necessary because velocities are not uniform across a cross section of the turbine passage; presumably, regions of the turbine with higher flow rates will expose more fish than those with lower flow rates. The sizes of areas with potentially damaging shear stress were predicted to vary not only with location but also with total turbine flow rate (Figure 2). Shear stresses in excess of the threshold value comprised relatively small percentages of the flow in the regions upstream from the runner (intake and stay vane–wicket gate region). The largest predicted volumes of water exposed to damaging shear stresses in the stay vane–wicket gate region were less than 0.2% of the overall flow volume.

Shear stress volumes were moderate in the runner area, and were predicted to decline with increasing turbine flows. This is likely due to changes in the angle at which water approaches the adjustable blades in a Kaplan turbine. At low water flow rates into a turbine, the blades are flatter, i.e., tilted at a low angle so that they are more perpendicular to the flow lines (as in Figure 1). Water passing through the runner must change direction and velocity more than at higher flows. At the highest flow tested, 481 m^3s^{-1}, the blades are tilted at a 43° angle and are better aligned with the overall water-flow streamlines. At all turbine flows, there was a larger volume of damaging shear stresses at the blade tips than in the region where the adjustable blade attaches to the hub (Figure 3a).

Downstream from the runner, the predicted volumes of flow containing potentially damaging shear stresses increased greatly with increasing turbine flow rates (Figures 2 and 3b), Even so, the volume of damaging shear stresses accounted for no more than 1.6% of the total turbine flow. Turbulent shear stresses in this area occur especially in the vortex immediately below the hub and near the draft tube piers, where the water spreads out and slows down as it is discharged to the tailwaters, in some cases impacting the draft tube support piers.

The numbers of injured fish in the Wanapum field tests were low; 30 of 1202 (2.5%) treatment fish recaptured after turbine passage exhibited visible injuries (Normandeau and others 1996). Because only 3 of the 30 injured fish were thought to result from

Table 1. Percent survival (and standard error of the estimate) of juvenile coho salmon at 1 h after passage through a Kaplan turbine at Wanapum Dam[a]

	Fish release depth	
Turbine flow (m^3s^{-1})	Hub passage (3 m)	Mid-blade passage (9.1 m)
255	0.897 (0.027)	0.949 (0.020)
311	0.924 (0.023)	0.968 (0.017)
425	0.948 (0.022)[b]	1.000 (0.013)[b]
481	0.885 (0.026)[b]	0.968 (0.014)[b]
Mean survival	0.914 (0.016)	0.971 (0.012)

[a] From Normandeau and others (1996).

[b] Survival was significantly higher at the 9.1-m release depth than the 3-m release depth ($P < 0.05$).

exposure to shear stresses (based on incidence of torn or flared operculum or inverted gill arches, which are the signs found by Neitzel and others 2004), it is not possible to quantitatively associate rate of injuries with the predicted sizes of damaging shear stress in this study.

Of 1278 coho salmon that were passed through the Wanapum turbine in the Normandeau and others (1996) tests, 21 were recovered dead and 33 were not recovered (and assumed dead) or were preyed upon before recovery. Estimated survival probabilities ranged from 0.885 to 1.000, depending on turbine flow rate and travel route. Because a fish passes through all three sections of the turbine (intake, runner, and draft tube), it is impossible to assign mortalities among fish collected in the Wanapum tailwaters to shear stresses experienced in, for example, the intake region. However, fish were introduced at two depths in the 1996 field study—3 m and 9.1 m. If it is assumed that fish simply follow the streamlines and do not actively change their position as they travel through the turbine, the CFD model indicates that fish released at 3 m will pass through the turbine runner near the hub. On the other hand, fish introduced lower in the intake (9.1 m) are expected to pass through the runner near the mid-blade (Normandeau and others 1996). The mortalities of fish that traveled through these areas (Table 1) can be compared to the predicted volumes of damaging shear stresses in these runner locations (Figure 3a).

The 1-h postpassage survival of juvenile coho salmon appeared to be inversely related to CFD predictions of the volume of flow with shear stresses greater than the threshold value. That is, a larger volume of high shear stress seemed to be associated with better survival. In most cases, however, the differences in survival were not statistically significant. Significant differences in survival between hub-passed and mid blade-passed fish were detected only at the two highest turbine flows (Table 1). The lowest survival observed in this study, 0.885 at 481 m^3s^{-1}, occurred among fish that are believed to have passed through areas of the turbine that are predicted to have relatively small volumes of high shear stresses along the hub (Figure 3a) but large volumes in the draft tube region below the hub (Figure 3b). The runner mid-blade was predicted to have larger flow-weighted volumes of damaging shear than the hub region under all flows (Figure 3a). Contrary to expectations, mid-blade-passed coho salmon had higher survivals than hub-passed fish under all flows, although these differences were statistically significant only for the two highest flows.

Discussion

It has been speculated that severe fluid forces (e.g., shear stress) are a source of injury and mortality to hydroelectric turbine-passed fish (Turnpenny and others 1992; USACE 1995; Čada and others 1997). Laboratory studies by Neitzel and others (2004) indicated that rates of strain of as low as 517 s^{-1} could injure juvenile fall Chinook salmon. Converting that threshold to a shear stress value, our steady-state CFD model predicted that volumes of damaging shear stress were small percentages of the overall flow passage. Highest values were estimated to occur in the runner and draft tube areas, and even these areas did not exceed about 1.6% of the volume of passage, weighted by localized flow rate. This suggests that very large portions of the passage through large Kaplan turbines (as at the Wanapum Dam modeled in this exercise) will not create shear stresses that are damaging to fish. If it is assumed that mortality resulting from this particular injury mechanism is proportional to the flow-weighted volumes estimated by CFD, then less than 0.6% of the fish passing through the Wanapum turbine would be killed by shear stresses under most of the flows tested.

Predicted mortalities from shear stresses were smaller than observed mortalities in the Wanapum field tests because turbine passage injury and mortality can result from several possible mechanisms, including shear stress and turbulence, strike, grinding, pressure changes, and cavitation. The magnitude of each of these mechanisms is related to the geometry of the adjustable blade turbine and turbine flow rates (Franke and others 1997). For example, the potential for hub grinding (fish squeezed through gaps between the blade and hub) is smallest at high flows, whereas the opposite is true from fish passing through gaps between the blade tip and turbine housing. Generally, pressure drops across the runner and the related potential for cavitation are greatest at the highest flows. Predicted shear stresses often, but not always, increased with turbine flow rate. Turbine passage mortality is a function of all these injury mechanisms, each of which has a unique relationship to flow rate and blade tilt, and some of which show opposing trends. In such a case, it may not be possible to precisely delineate the role in overall mortality played by any single mechanism, especially when the incidences of injuries and mortalities are low. However, it is possible (and desirable) to develop a good understanding of that mechanism, compare its effects to those of other injury mechanisms, and minimize it by modifications in turbine design or operations. The techniques described here can be usefully applied to other turbine designs that exhibit greater injuries and mortalities among turbine-passed fish.

When compared to the results of field tests of turbine-passage injury and mortality conducted in 1996, there were few correlations between salmon mortality and shear stress volumes. In fact, the differences in survival among the test conditions were contrary to expectations—turbine flows and passage routes that led to higher probability of shear stress exposure often appeared to coincide with higher survival. These comparisons are constrained by the relatively narrow range of turbine flows that were tested. A wider range of flows would have created more severe hydraulic conditions and presumably greater mortalities, making the identification of trends in injury and mortality data more likely. Because of the geometric configuration of the Kaplan turbine at Wanapum, the highest turbine flow rates tested (481 m^3s^{-1}) cause the most extreme hydraulic conditions. This would include the development of a turbulent vortex below the hub and extreme decrease in pressure leading to cavitation below the hub and trailing edges of the blades. In the field tests, fish that passed through the runner near the hub under the highest flows suffered the highest mortality, significantly greater than experienced by mid-blade-passed fish. Because of the interactions of different injury mechanisms, it may be that coho salmon survival in the Wanapum turbine was more related to strike or grinding at the lower flows, until hydraulic conditions become so severe in the draft tube region at high flows (e.g., 481 m^3s^{-1}) that the mechanisms of fluid stress and cavitation came to dominate the mortality.

Downstream-migrating juvenile salmon tend to be surface-oriented, especially during daylight hours. For example, Olson (1984) found that 90% of coho salmon smolts entered the top 5.5 m of the Wanapum intake in the daytime (vs. 70% at night). These surface-oriented fish would be more likely to pass through the runner near the hub. Under the lower flow rates at which the Wanapum turbines are typically operated, hub-passed fish would be exposed to small volumes of damaging shear stress. In addition, lower turbine flow rates would result in smaller pressure changes across the runner and small or no areas of cavitation, which would contribute to good fish passage survival Conversely, if the Kaplan turbines at Wanapum are operated at high (cavitating) flow rates, a large proportion of the surface-oriented, downstream migrating salmon in the river will be exposed to large areas of damaging shear stress, cavitation, and extreme pressure changes along the hub and in the vortex region below the hub. The fish-survival advantages of lower shear at low turbine flow rates are countered somewhat by an increased probability of grinding in the blade-hub gaps (Franke and others 1997).

There are other reasons why the relationship between predicted shear stresses and observed injuries/mortalities were not as good as hoped. As mentioned, laboratory bioassays demonstrated that there are numerous threshold values for effects of shear stress on a fish, depending on the species and life stage as well as its orientation relative to the shearing flow. The particular shear threshold we chose for fish injury affected the predicted volumes of damaging shear stress; choice of a different threshold may have revealed different patterns. Second, at present it must be assumed that fish follow flow streamlines as they pass through the turbines and are exposed to the predicted large or small areas of damaging shear stress. However, recent field and laboratory studies suggest that fish may follow different pathways, either because of volitional swimming or because their shape and density makes them drift differently than neutrally buoyant particles. As a consequence, their exposures to different injury mechanisms may be different than supposed. We do not yet know whether movements of fish depart from streamlines and, if so, in a predictable way. Finally, the CFD model used in this analysis essentially describes a steady-state situation, in which shear stresses are time-averaged. In a turbulent system, instantaneous pulses of flow can cause higher values of shear stress that are not adequately reflected in mean values. That is, a particular volume within the flow passage may have momentarily damaging shear stresses, but on the average appears to be an area of safe passage. The ongoing development of computational models of time-varying, turbulent flow fields (e.g., Jones and others 2002) will produce more representative assessments of damaging shear stresses inside turbines. The correlation of damaging shear stress volumes to mortality observed in the field might improve with refined information on movements of individual fish and effects of unsteady flows (turbulence) on the shear stresses experienced by fish.

Mortality and directly visible injury to fish may not be the most important indicators of an ''environmentally friendly'' turbine. Injuries that are sublethal and not visible in the time frame of the field study observations may also be important for ultimate survival. For example, decreased reaction times (Čada and others 2003) or impaired swimming performance (EPRI 2000) associated with nonvisible injuries can logically affect vulnerability of migrating salmon smolts to predation, as has been shown for sublethal exposures to high temperatures (Coutant 1973). Such studies are rare, but needed to explain the full consequences of turbine passage (Ryon and others 2004). Attempts to correlate CFD model predictions with these additional biological indicators could be fruitful for quantitatively relating exposures to survival.

Conclusion

A process is described by which laboratory bioassays, computational fluid dynamics models, and field studies can be integrated to evaluate the significance of one of the potential fish injury mechanisms associated with hydroelectric turbine passage. Areas of potentially lethal shear stresses were identified in the regions of the stay vanes and wicket gates, runner, and draft tube. Under typical turbine operating conditions, time-averaged computational models estimated that these dangerous areas comprise less than 2% of the flow path through the turbine. However, the estimated volumes of damaging shear stress in the turbine did not correlate well with observed fish mortality at the Wanapum Dam, which ranged from less than 1% to nearly 12%. Possible reasons for the poor correlation include 1) the influence of other, potentially more important injury mechanisms; 2) uncertainty about the path that fish follow through the turbine; 3) narrow range of hydraulic conditions (shear stress exposures) in the field tests; 4) uncertainty about the appropriate threshold for effects on fish; and 5) the use of a steady-state, time-averaged CFD model, which may underestimate the damaging effects of instantaneous, turbulent flows. Each of these possibilities indicates a direction for further research.

At this stage of development, CFD models are not yet reliable for precisely predicting mortality at particular turbine systems. However, the models are still very useful for comparing alternative turbine designs, if not for determining absolute values of fish mortality. Knowledge of the locations, causes, and general magnitudes of shear stresses inside a conventional Kaplan turbine, as described here, has led to major refinements in turbine design. For example, a new minimum gap runner has been installed at the Wanapum Dam that corrects many of the features of conventional Kaplan turbines now known to create severe hydraulic conditions (Brown and others 2004). Similarly, CFD models have been used extensively to evaluate different configurations of another turbine design, the Alden/Concepts NREC turbine, in order to maximize safe fish passage (Lin and others 2004).

Computational models will continue to be essential means to minimize the amount of trial and error associated with developing new designs, where new prototypes are constructed and tested in the field with large numbers of fish. As estimates are refined and new information is developed about fish responses to all injury mechanisms, turbine manufacturers will be able to focus on correcting those aspects of turbine design and operation that are damaging. These improvements will help promote the environmentally sound development of a globally important source of renewable energy.

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