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Equipment Design

Computational Tools to Assess Turbine Biological Performance

To help ensure the safety of fish passing through the new turbines at 912-MW Priest Rapids, Public Utility District No. 2 of Grant County is employing the BioPA method to analyze the biological performance of proposed designs — and to choose an improved one for this facility.

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Public Utility District No. 2 of Grant County in Washington operates the 912-MW Priest Rapids facility on the Columbia River. The powerhouse contains 10 Kaplan-type turbines that are more than 50 years old. Plans are under way to install new runners. The Columbia River is a migratory pathway for several species of threatened and endangered juvenile and adult salmonids, thus safe fish passage is a major consideration when upgrading the turbines.

To ensure biological impact is considered during design of the replacement turbines, the PUD has included specific criteria in the contract with prospective manufacturers for addressing fish passage risk. Pacific Northwest National Laboratory (PNNL) has developed a method for estimating this risk, called the biological performance assessment (BioPA). BioPA computes a suite of biological performance indicators based on data from a computational fluid dynamics (CFD) model of a proposed turbine design.[1]

This article presents the strategy Grant County PUD used to incorporate fish passage criteria into the design phase of the Priest Rapids turbine upgrade project.

Priest Rapids turbine upgrade project

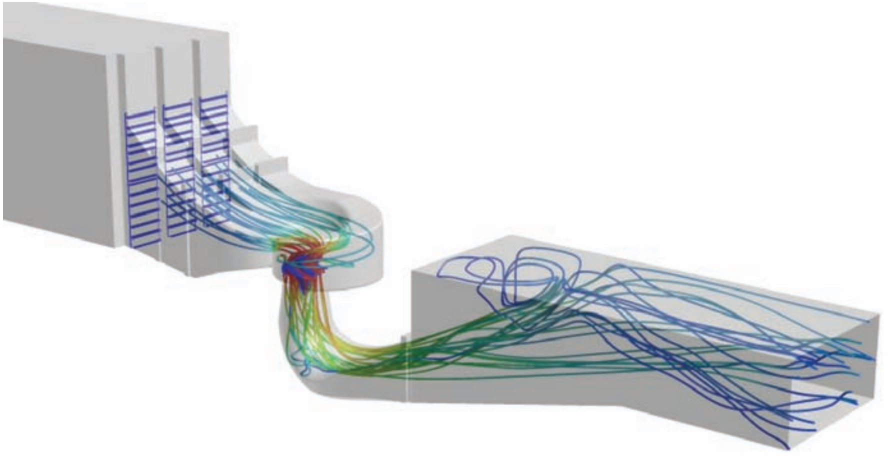
Priest Rapids Dam impounds water for a powerhouse that contains 10 six-bladed Kaplan-type turbines and features a spillway with 22 tainter gates, two fish ladders for upstream migrant salmon, and dam embankments on each flank. The turbine units are rated at 114,000 hp each at the rated head of 78 feet, and the average river flow is about 120,000 cubic feet per second.

The units began operation in 1961, and the PUD has determined major upgrades are necessary to extend equipment life and increase turbine efficiency. The Priest Rapids turbine upgrade project — which involves installing new Kaplan turbines and rebuilding the generators — was designed to address this issue. The goal is to extend the life of the units by 50 years but also increase power production and efficiency while maintaining or improving fish passage conditions. This article addresses only the turbine design phase of the work, focusing on the biological considerations.

Grant County PUD will select the new turbine design by means of a competition. The contract specifies the criteria used to evaluate the new designs, including such standard measures as turbine power, efficiency, capacity, cavitation potential and runaway speed. Additionally, this contract required that each design meet specific biological performance criteria. This was done to ensure that concepts known to improve fish passage survival were incorporated into the designs. Each design was required to pass a biological baseline, defined as the biological performance of the current turbines, to be considered for further evaluation. Use of biological design criteria is not new to modern turbine design,[2,3] but this is the first case, to the authors' knowledge, where it has been explicitly included in a competitive procurement process.

The Columbia River is home to several migrating salmonid species — including chinook, coho, and sockeye salmon and steelhead — as well as numerous hydropower facilities. Concerns about diminishing fish populations have resulted in extensive efforts to improve the survival of juvenile downstream migrants. Actions taken include modified turbine operations, fish barging, construction of bypass facilities and increased spillway discharge during periods of downstream migration. Nevertheless, many fish (e.g., about 75% of subyearling chinook salmon) pass through the existing turbines, where injury and mortality

Figure 1 — Stream Traces from the CFD Model



These stream traces originate from several thousand "seeds," located in the turbine intake and distributed so that each represents an equally likely entry point for a fish into a turbine.

can occur. Recent studies at the nearby 1,038-MW Wanapum facility, which was originally equipped with turbines of a vintage and design similar to those at Priest Rapids, indicate that turbine passage mortality was 1% to 5%.[4]

Implementation of biological criteria in a contract for design and procurement of turbines is a relatively new idea. Recognizing the importance of fish passage to the success of the turbine upgrade project, the PUD worked with PNNL to implement the BioPA technique for assessing risk to fish passing through Kaplan turbines. BioPA provides a quantitative measure, or score, of the estimated fish survival performance of a new design. After determining a baseline score for the existing Priest Rapids turbines, PNNL computed scores for each competitor's final design. Because of the uncertainties involved in the technique, the actual amount by which a new design exceeded the baseline score was not considered in the evaluation.

Due to the novelty of the BioPA method, Grant County PUD fully engaged with the three competing turbine manufacturers (Alstom, Andritz and Voith), regulators and stakeholders throughout the design phase of the project. Committees and workshops provide the mechanisms for exchange of ideas and making decisions. Obtaining early buy-in from all involved parties was critical to the success of this venture.

Biological performance assessment tool

Past attempts to predict the risk to fish passing through turbines have focused on identifying the locations and sizes of potentially hazardous regions.[5,6,7] Improving passage survival was a matter of reducing the volume and number of these regions. However, the presence of dangerous zones within the turbine may be biologically inconsequential if few fish experience them. The undersides of runner blades generally have low pressures, which may be detrimental to fish, but only a small fraction of the population may pass through these locations. The BioPA method estimates the probabilities that fish will encounter specific conditions during passage. This is done with a proportional sampling scheme that uses stream traces in a numerical flow simulation to model potential pathways through the turbine environment.

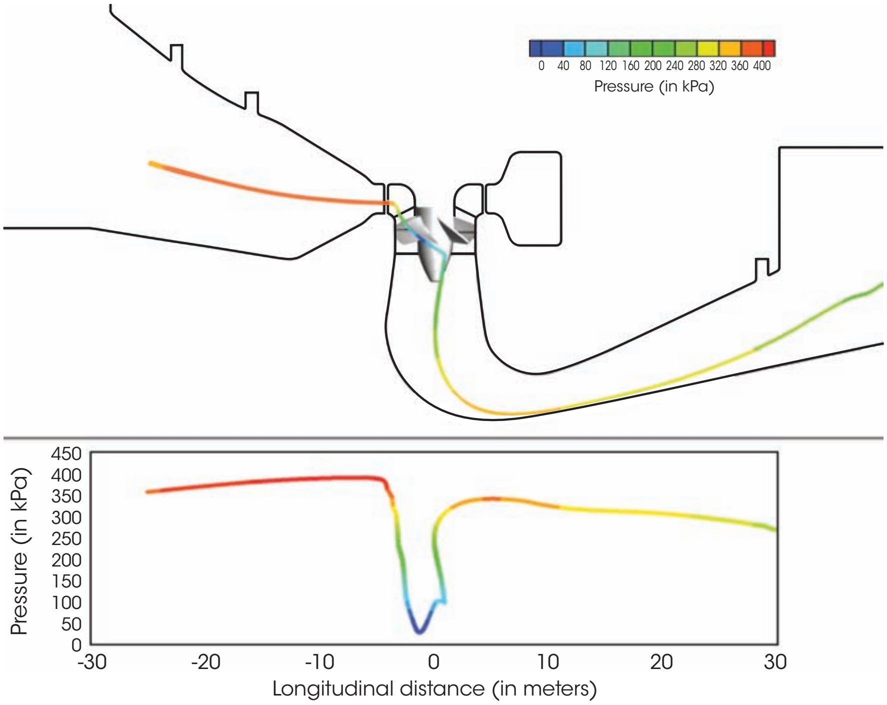
Fish biologists have conducted numerous field and laboratory studies in an attempt to quantify the response of various fish species to the hydraulic stressors in the turbine environment. The object of this work is to establish dose-response relationships between species of fish and known injury mechanisms. Dose-response relationships are determined by subjecting a suitable number of fish to various magnitudes of a stressor and computing the probability of injury or mortality at each magnitude. An empirical curve is produced from which predications can be made for any doses within the range of the data. Field investigations using live fish have identified types and rates of injuries at hydroelectric facilities under multiple operating conditions.[8,9] In the laboratory, researchers have subjected live fish to pressure regimes that simulate passage through a turbine.[10,11] Researchers also have observed the tolerance of juvenile salmon to various levels of shear,[12] exposed several species to turbulence,[13] and looked at the effects of runner blade thickness and velocity on fish strike injury.[14] Based on the availability of sufficient quantitative data, PNNL selected four injury mechanisms for use in BioPA: nadir pressure, shear, turbulence and blade strike.

If each of these injury mechanisms can be associated with a measurable variable, the probability of injury can be predicted from the distribution of this variable. However, biological studies often relate injury rates to variables that do not correspond to values that are readily available to the turbine blade designer. Therefore, a conversion is made to a stressor variable that is computable from information obtained from the turbine design or results of a numerical model. While geometrical and operational variables are defined in the design, flow characterization information is obtained using three-dimensional CFD models. These models provide a suite of flow quantities at all locations throughout the turbine domain.

The turbulent nature of the flow and the random location of entry into this environment suggest that fish have many potential pathways through a turbine. Moreover, each of these pathways can be reasonably expected to result in a unique exposure experience. Some paths will traverse regions that could be more harmful to fish than others. BioPA accounts for this variation by sampling the domain in a way that gives more weight to regions that receive more frequent visits from fish.

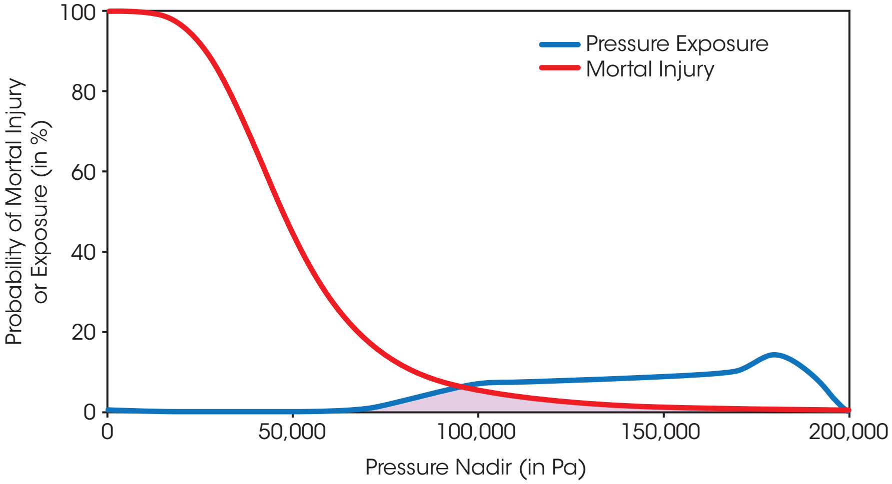
BioPA uses stream traces to model the trajectories of fish through the turbine. A stream trace is the path of a massless,

Figure 2 — Nadir-Pressure Value and Location



The computed pressure-nadir stressor variable computed using BioPA helps estimate fish exposure to passage stressors.

Figure 3 — Risk of Injury



The hatched area represents non-zero products of stressor-exposure probability and mortal-injury probability. Risk to fish grows as the size of this region increases.

neutrally buoyant particle through a velocity field. The velocity field from the CFD model result is used to generate the stream traces (see Figure 1). Stream traces originate from several thousand "seeds," located in the turbine intake and distributed so that each represents an equally likely entry point for a fish into the turbine. A uniform distribution is normally assumed, unless site- and species-specific distribution data are available. When each seed is "released," it samples modeled variables along its path through the turbine unit. Stream traces follow the velocity field, so they will sample the turbine environment in proportion to the volume of flow. Regions through which little flow occurs will contain few stream traces and thus carry less weight in the analysis.

To estimate exposure to passage stressors, BioPA computes stressor variable values for each stream trace. For example, the pressure-nadir stressor variable is computed by determining the lowest value of absolute pressure sampled along the stream trace (see Figure 2). Assuming a fish has an equal probability of taking any generated path, the frequency distribution of stressor values computed for all stream traces is equivalent to the probability distribution for the stressor variable. So, if 20% of the stream traces have nadir pressures of 60,000 to 70,000 Pa, the probability that a fish will experience a nadir in this pressure range is 20%. The calculations for blade strike follow a specific probabilistic method,[3] with modifications to include the effect of blade thickness. Although the effect of fish length is accounted for, the mass of the fish is not explicitly included in the current version of BioPA.

BioPA combines information about fish response to turbine passage stressors with estimates of exposure to those stressors in order to obtain a measure of injury risk, known as a BioPA score. The BioPA score is high when the risk of passage injury is low. For a given value range of a stressor variable, the risk of injury is the probability of injury at that level of stress, obtained from the dose-response relationship, multiplied by the probability of exposure to that level of stress, obtained from the exposure estimate (see Figure 3). Integrating these risks over all values of the stressor variable yields the BioPA score.

BioPA scores are first computed for each individual stressor. Next, the four stressor scores are combined into a single operating condition score using a weighting algorithm. Finally, an overall design score is computed by weighting the condition scores for a suite of expected operating conditions. Several factors determine the weighting of the BioPA scores, including the relative contribution of the injury mechanisms to overall passage risk and the reliability of quantitative information about dose-response. Turbines may be operated at a variety of discharges depending on power demand and other factors, some discharges being more hazardous to fish passage than others. BioPA scores for each likely discharge are weighted by the expected frequency of plant operation at that level.

Except for the CFD modeling, which may require specialized hardware and software, BioPA can be performed on a desktop workstation using commercial software packages.

Assumptions

The BioPA process relies on confidence in data sets and assumptions regarding how they may be used. BioPA depends heavily on the reliability of biological data relating fish response to stress. However, confidence in the linkage between dose-response data and stressor variables varies. Pressure studies provide the most well-defined dose-response relationship that can be tied directly to a model variable with good confidence. For the other injury mechanisms, the relationships are either qualitative in nature or the experimental dose variables do not correspond completely with the stressor variables. For example, the magnitude of turbulence a fish experiences is difficult to measure quantitatively in an experimental setting, so experimental results are presented using general descriptors, such as "low, "medium, and "high."[13] While this lack of data is certainly a limitation, qualitative relationships are still of value when comparing the baseline score to new design scores.

Laboratory experiments also tend to evaluate specific situations, which in some cases do not represent a duplication of exposure conditions within the turbine. Extrapolation of these data to more general situations is a challenge. Moreover, injury studies that yield dose-responses generally do not account for the synergistic effects of multiple mechanisms because each injury mechanism is evaluated in isolation. A fish stressed by one mechanism could be more susceptible to injury by another mechanism or repeated instances of the same mechanism, even if the dose of the latter exposure would not ordinarily harm an unstressed individual.

The behavior of fish before and during turbine passage is also the subject of uncertainty. Of possible significance to turbine passage is the observation that juvenile salmon tend to orient with their heads upstream in the turbine intake.[15] However, observation of fish beyond the intake has not been possible,[16] so their behavior and paths have never been measured. This knowledge gap has led many researchers to assume that fish basically follow the flow when confronted with the high velocities of the turbine environment. This is supported by the observation that burst speed of juvenile salmon does not exceed about nine body lengths per second,[17] or about 1 meter/sec, which is significantly lower than the 5 to 20 meter/sec velocities typical of the turbine runner environment.

Another consideration is the depth to which fish are acclimated when entering the turbine, which is a significant factor in pressure-related injuries.[11] The depth at which fish enter the intake does not necessarily represent the depth to which they are acclimated, nor is there an effective way to measure depth acclimation in the field. BioPA assumes a conservative value of 5 meters for salmonid acclimation depth, which lies approximately midway between the water surface and this species' maximum acclimation capacity.[18]

Finally, BioPA relies on data generated through numerical modeling of the turbine environment. With CFD modeling, the general lack of prototype-scale validation data is a limitation. Direct measurement of many flow variables in an operating turbine is difficult,[16,19] thus model validation is often limited to confirmation of bulk performance measures, such as power and discharge, and comparison to data from reduced-scale laboratory physical models. Even in physical models, comprehensive velocity measurements are not typically performed.

Baseline assessment

Prior to the start of the design competition, PNNL computed a BioPA score for the existing Priest Rapids turbines that would be used as a baseline for evaluation of new designs. After review by the oversight committee, the set of operating conditions and weighting factors for computing the BioPA score was established. The score would be based on three flow conditions (see Table 1), weighted according to the frequency of occurrence during the periods associated with fish migrations. The four stressors used in BioPA were weighted as pressure 50%, shear 20%, turbulence 10% and strike 20%. This weighting scheme represents the level of confidence given to the dose-response data for each of these four mechanisms.

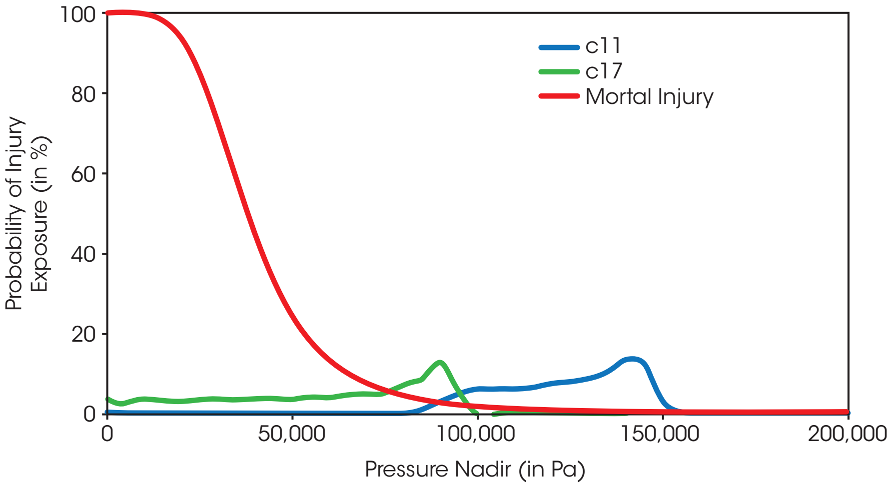
Based on a sensitivity analysis, 7,560 seeds spaced uniformly at 0.2 meter in the turbine intake were chosen as starting points for the stream traces. The sensitivity analysis was performed by progressively increasing the number of seeds, from about 100 to 100,000, until there was no longer a significant variation in the BioPA score. Although juvenile salmonids are more concentrated in the upper part of the water column, a uniform seed distribution was selected because measured vertical distributions varied by season, species and time of day and because this resulted in a more conservative BioPA score.

A CFD model was created in STAR-CCM+ v8 for the three baseline cases, as well as two cases that match available physical model results. Steady-state simulations were run at prototype scale. In every case, a computational mesh was created based on geometry, with the appropriate wicket gate angles and blade angles. Prototype computational meshes had 30 million to 50 million cells.

As a check on the performance of the CFD model, net head and power were compared to physical model data obtained at the Laboratory for Hydraulic Machines at Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. Good agreement between physical model and numerical model results for power and net head gave confidence in the numerical modeling procedures and that results were representative of the hydraulic environment fish would likely encounter during passage.

Table 1 is the BioPA scoring matrix for the baseline analysis. The overall

Figure 4 — Exposure Distribution



Exposure distribution of nadir pressures for two modeled conditions. Note how the high-discharge c17 condition potentially exposes some fish to very low pressures. The mortal injury curve is based on laboratory dose-response studies.[11]

Table 1: Baseline BioPA Scoring Matrix

Condition and Nominal Discharge		Pressure	Strain	Turbulence	Strike	Total
c11	**11,000 cfs**	98.6	94.9	99.9	94.7	**97.2**
c15	**15,000 cfs**	87.2	94.7	99.9	95.8	**91.7**
c17	**17,000 cfs**	66.6	94.1	99.9	96.0	**81.3**
Total		**81.2**	**94.5**	**99.9**	**95.7**	**88.6**

score of 88.6 represents the weighted averages of the individual condition and stressor scores. Several trends are noteworthy. The pressure score decreases significantly with increasing discharge, reflecting the larger pressure drop, and lower pressures, across the runner blades associated with higher flows (see Figure 4). Blade strike scores increase slightly with discharge. This likely results from higher velocities through the runner region, which reduces the exposure to strike as fish pass faster across the leading edge plane of the runner blade.

Summary and future plans

New techniques for predicting the biological impact of hydro turbines make it possible to include fish safety criteria in turbine design contracts. Using these tools in a collaborative process with regulators and stakeholders provides confidence that new designs balance economic performance with environmental responsibility. At Priest Rapids Dam, Grant County PUD is using the BioPA method of risk analysis to guide the design of its replacement turbines. With early involvement from regulators and stakeholders, the license modification process is facilitated and reduces the need for expensive live fish testing after installation of the new turbine units.

Meanwhile, interest in the BioPA tool has prompted PNNL to pursue a licensing arrangement that will allow interested parties to obtain the toolset for their own use. Furthermore, PNNL plans to continue improving the BioPA software in collaboration with industry.[20] In addition to aiding in the design process, BioPA can assist operators of existing hydro turbines in determining optimum fish passage operations for their units during the critical times of salmonid-smolt migration. By computing BioPA scores over a range of discharge scenarios, the operator can develop a "fish-passage efficiency curve" for a facility.

Further development of the BioPA tools is continuing at PNNL. Key refinements of the tools will include:

— Spherical and non-spherical particles with mass;

— Options to include turbulence effects and unsteady flow (e.g., detached eddy simulation) on particle trajectories; and

— Inclusion of new biological dose-response criteria for a wider range of fish species as they become available from laboratory test studies.

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