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Shaken, Not Stirred: The Recipe for a Fish-Friendly Turbine

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MASTER

Abstract

It is generally agreed that injuries and mortalities among turbine-passed fish can result from several mechanisms, including rapid and extreme water pressure changes, cavitation, shear, turbulence, and mechanical injuries (strike and grinding). Advances in the instrumentation available for monitoring hydraulic conditions and Computational Fluid Dynamics (CFD) techniques now make it possible both to estimate accurately the levels of these potential injury mechanisms in operating turbines and to predict the levels in new turbine designs. This knowledge can be used to "design-out" the most significant injury mechanisms in the next generation of turbines. However, further improvements in turbine design are limited by a poor understanding of the levels of mechanical and hydraulic stresses that can be tolerated by turbine-passed fish. The turbine designers need numbers (biological criteria) that define a safety zone for fish within which pressures, shear forces, cavitation, and chance of mechanical strike are all at acceptable levels for survival.

This paper presents the results of a literature review of fish responses to the types of biological stresses associated with turbine passage, as studied separately under controlled conditions in the laboratory rather than in combination at field sites. Some of the controlled laboratory and field studies reviewed here were bioassays carried out for reasons unrelated to hydropower production. Analysis of this literature was used to develop provisional biological criteria for hydroelectric turbine designers. These biological criteria have been utilized in the U.S. Department of Energy's Advanced Hydropower Turbine System (AHTS) Program to evaluate the results of conceptual engineering designs and the potential value of future turbine models and prototypes.

Introduction

The U.S. Department of Energy's Advanced Hydropower Turbine System (AHTS) Program supports the development of "environmentally friendly" turbines, i.e., turbine systems in which environmental attributes such as entrainment survival are

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emphasized. Advanced turbines would be suitable for installation at new hydropower facilities and potentially 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 their habitats.

Development of advanced, environmentally friendly hydroelectric turbines requires knowledge of the physical stresses (injury mechanisms) that impact entrained fish and the fish's tolerance to these stresses. Instrumentation of turbines and the increasing use of Computational Fluid Dynamics (CFD) modeling can provide considerable information about the levels of each of these potential injury mechanisms that can be expected within the turbine. Frequently missing, however, are data on the responses of fish to these levels of stress. In an attempt to address this gap, a review and analysis of literature was conducted (Čada et al. 1997) and is summarized here. In the report we examined each of the injury/mortality mechanisms associated with turbine entrainment and derived preliminary, biologically based performance criteria for advanced turbine designs.

Injury/Mortality Mechanisms

Injuries and mortalities among fish passing through a hydroelectric turbine can result from several mechanisms, including rapid and extreme water pressure changes, cavitation, shear, turbulence, and mechanical injuries (Čada 1990; USACE 1995). The locations within a turbine at which these mechanisms tend to be most severe is shown in Figure 1, although entrained fish experience varying levels of all of these mechanisms throughout passage. Each of the mechanisms can be severe enough to kill the fish directly. If the entrainment stresses are not immediately lethal, the fish may nonetheless be disoriented so that they are subsequently more susceptible to predation in the tailwaters or disabled so that they later succumb to disease (indirect mortality). A review of the literature related to these mechanisms suggests the following biological criteria:

Pressure - Water pressure changes are experienced by the fish throughout its passage through the turbine system. The severity of pressure changes experienced depend on characteristics of the turbine (e.g., design and flow rate) and on the location of the fish in the water column when it was entrained.

Pressure **increases** of the magnitude found in most hydroelectric turbines do not appear to cause direct damage to entrained fish. Rapid pressure increases much higher than those found within a turbine did not result in mortality in a variety of laboratory experiments. Pressure **decreases** within the turbine are a greater concern. Effects of pressure decreases relate not only to the absolute low pressure experienced by fish in the turbine but also to the magnitude and rate of change from the fish's acclimation pressure. For example, a fish acclimated to surface water (101 kPa) may be unaffected by brief passage through a region of low pressure (say 60 kPa) in the turbine. On the other hand,

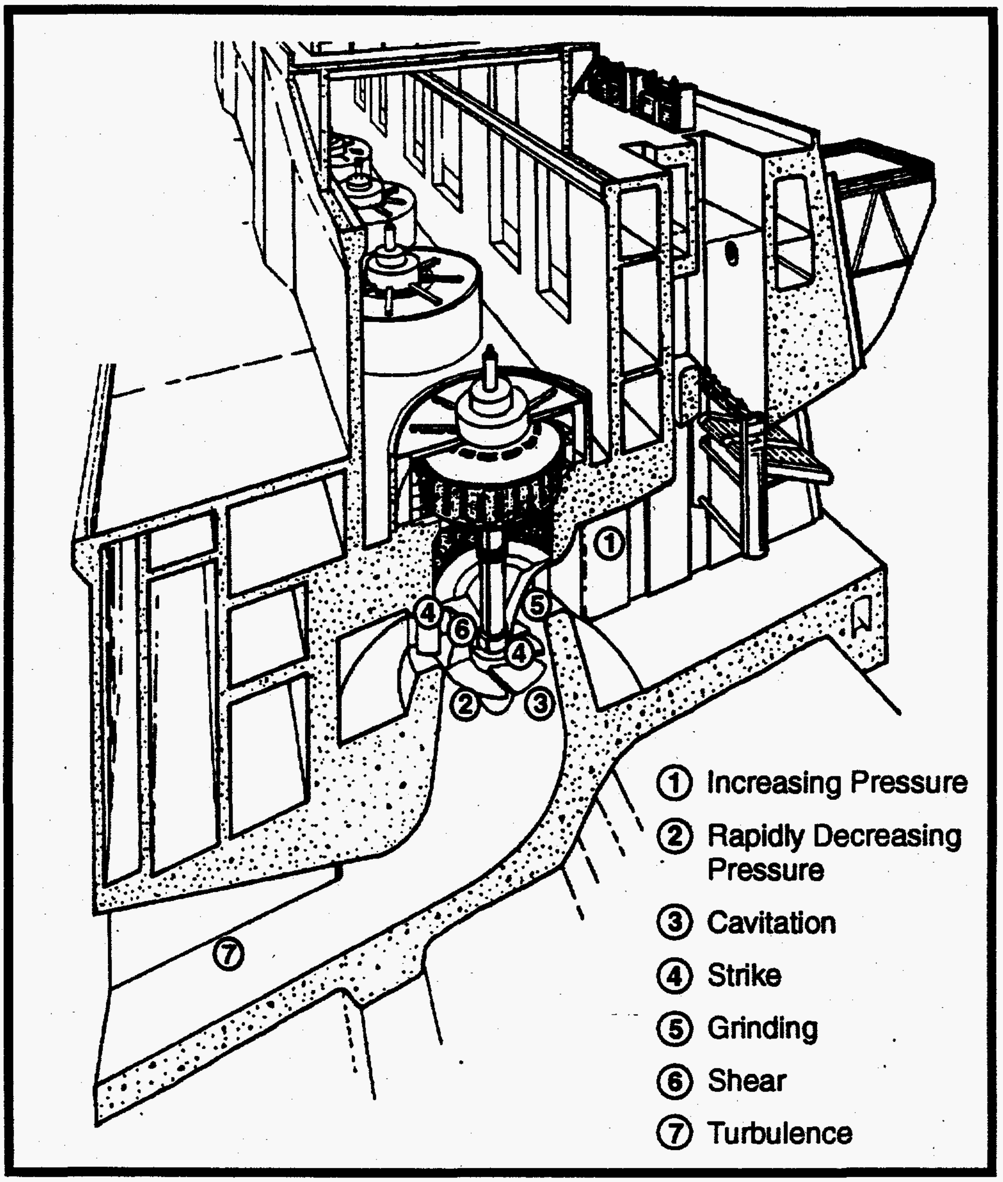

Figure 1. Locations within a turbine at which particular injury mechanisms to entrained fish tend to be most severe.

a fish acclimated to deep water (300 kPa) will experience a large relative pressure decrease passing through the same region of the turbine. Because the decrease is virtually instantaneous, a fish will be unable to vent gas from the rapidly expanding swim bladder. The swim bladder may distend or rupture, causing mortality or reduced ability to escape predators in the tailrace. Studies of swim bladder rupture and fish mortality following rapid decompression indicate that allowing minimum pressures within the turbine to fall to no less than 60 percent of the value to which fish are acclimated should protect most fish from direct mortality.

Cavitation - Cavitation is the process of formation of gas bubbles in a liquid caused by a localized reduction in pressure to a point at or below the vapor pressure (Turnpenny et al. 1992). In a turbine, cavitation can occur in areas of low pressure (e.g., downstream of the turbine blades), increasing local velocities, abrupt changes in the direction of flow, roughness or surface irregularities, and under certain conditions of water temperature and air content (USACE 1995). Once formed, cavitation bubbles stream from the area of formation (e.g., the blade surface) and travel with the flow to regions of higher pressure, where they collapse. The violent collapse of cavitation bubbles creates shock waves, the intensity of which depends on many factors, including bubble size, water pressure in the collapse region, dissolved gas content, and the presence of air (not water vapor) bubbles. Forces generated by cavitation bubble collapse may reach tens of thousands of kilopascals at the instant and point of collapse (Hamilton 1983; Rodrigue 1986). These pressure waves decrease rapidly from the center of collapse, but nearby fish could be injured.

Turbine designs that minimize pressure reductions to no greater than 60 percent of ambient will not cavitate, and cavitation-related injury to fish will not occur. If cavitation cannot be entirely prevented, introduction of air or oxygen bubbles may serve to mitigate adverse effects by cushioning the shock waves created by the collapsing water vapor bubble. This measure would have the additional advantage of aerating water that is discharged from the turbines.

If cavitation does occur, the consequences could be predicted in a similar way to those of mechanical strike. The probability of injury from cavitation could be calculated from information about the magnitude of cavitation and the likelihood that fish will pass near enough to be affected by the pressure waves and/or high-velocity microjet that emanates from a collapsing bubble. Presently, there is insufficient information in the literature to predict how close to areas of cavitation bubble collapse fish can pass without injury.

Shear and Turbulence - A fish passing through hydraulic machinery at high and varying velocities will be influenced not only by pressure changes but also by accelerative and shear forces. Accelerative forces include changes in the speed of the overall bulk flow, small-scale velocity changes associated with turbulence, and collisions with solid surfaces. Shear forces occur when two bodies of water moving at different velocities are incident with each other. Shear forces are greatest along the walls, other fixed structures, and the leading edges of runner blades (Figure 2); these forces can spin or deform the entrained fish (Čada 1990). Shear stress, like pressure, is expressed as force per unit area. The difference between pressure and shear stress is the direction in which the force is applied. In pressure the force acts *perpendicular* to the surface, whereas a shear force acts *parallel* to it (Gordon et al. 1992).

The effects of shear within the turbine and draft tube environment have not been adequately studied. The best available information comes from laboratory studies in which the fish is exposed to a high-velocity water jet in a static water tank. These tests examine the injury and mortality rates of fish in which high shear values are applied to only a portion of the fish. Shear effects are both species and life-stage specific:

- 3,410 N/m^2 (34,100 $dynes/cm^2$; 3.4 kPa) caused no apparent injury and no mortality among eels.
- 1,920 N/m^2 (19,200 $dynes/cm^2$; 1.9 kPa) caused low levels (~ 10%) of injury and mortality to juvenile salmonids.
- 206 N/m^2 (2,060 $dynes/cm^2$; 0.2 kPa) can cause complete mortality in clupeids, apparently due to loss of scales, epithelium, and mucous layers.
- 35 N/m^2 (350 $dynes/cm^2$; 0.035 kPa) caused an average of 38 percent mortality among white perch larvae exposed for 1 minute, 52 percent for 2 minutes, and 75 percent for 4 minutes. Striped bass larvae were nearly as sensitive.

Other, larger-scale effects of shear and turbulence on entrained fish, including elongation, compression, torsion, rotation, and deformation, have only been studied for fish eggs and larvae. At high levels, these forces could cause injury and mortality among larger fish. At lower, non-injurious levels, fish would be disoriented and may suffer greater indirect mortality (predation) below the turbine discharge.

Strike and Grinding - Damage to turbine-passed fish can occur if they collide with structures within the turbine systems, including fixed guide and stay vanes, moving runner blades, and flow-straightening walls in the draft tube (Figure 2). This mechanism is called strike. The probability of a fish being injured or killed by strike is a complicated function of characteristics of the fish (species, age, length, mass, condition), the turbine (number of runner blades, size of the openings between vanes and blades, sharpness of the blade edges, blade velocity), and the relationship between the fish and the turbine (e.g., the region of fish passage relative to the runner hub, orientation of the fish's longitudinal axis relative to the blade edge, and the fish's velocity relative to the blade velocity)(USACE 1995). Mechanical injury can also be caused by grinding, in which the fish is drawn through narrow openings or clearances

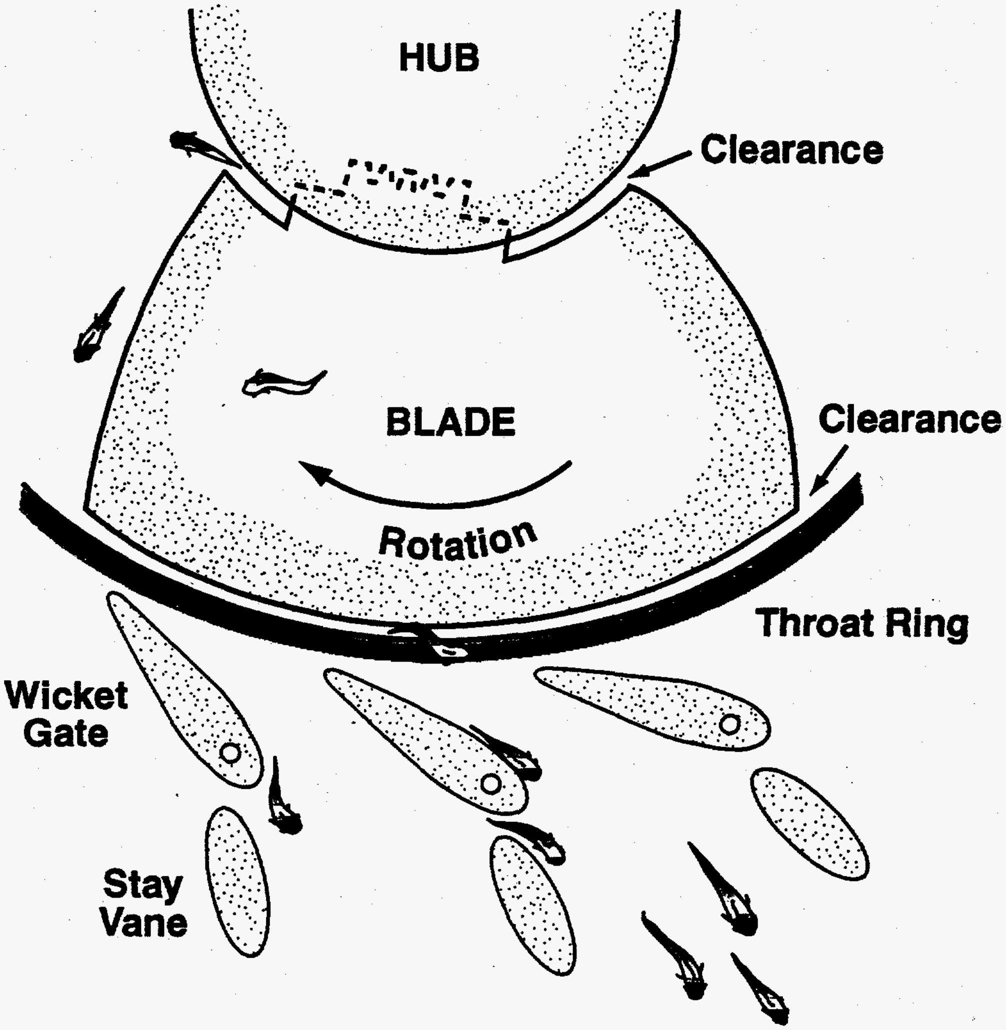

Figure 2. Locations within a turbine at which fish are exposed to injuries from shear, mechanical strike, and grinding.

(gaps) between structures in the turbine passageway (Figure 2). Grinding injury is most often evidenced as localized bruises that result from the fish being squeezed through the narrow gaps. However, grinding may also cause deep cuts and decapitation.

Because of the numerous variables that may influence strike and grinding, the probability of injury cannot be precisely estimated for any turbine. Some strictly biological factors, such as the species, length, and mass of entrained fish, influence the injury/mortality rate but cannot be altered by the turbine designer. Other biological factors may be influenced by turbine design (fish swimming behavior and orientation during turbine passage), but we do not know how design changes could be made to accommodate these factors. All else being equal, qualities of the turbine system that could be considered in order to minimize strike injury include:

- reducing the number of blades or amount of blade leading edge will reduce the probability of contact;
- maximizing the open space between blades and other structures will provide the largest routes of safe passage for entrained fish;
- blunt leading edges will cause less injury than sharp leading edges;
- lower runner speeds (blade rotational speeds) result in lower collision velocities and lower injury rates;
- fish struck by the blade near the hub will experience fewer injuries than fish struck near the blade tip because of reduced collision velocities. Consequently, turbine designs that direct entrained fish away from the runner periphery and towards the hub may cause lower injury rates;
- minimize gaps between fixed and moving parts of the turbine.

Research Needs

Among the potential injury mechanisms to which turbine-passed fish are exposed, the effects of water pressure on fish seem to be the best understood (Čada et al. 1997). The influence of pressure increases and decreases have been studied for a variety of species, so that reasonable biological criteria that will protect turbine-passed fish can be determined. Strike and cavitation appear to be similar in that the effects are probabilistic; it is generally accepted that collision with the blade at sufficient velocity or proximity to a collapsing cavitation bubble will cause injury and death. Expanding this database with new information collected under controlled laboratory conditions would not be difficult. The greatest uncertainties associated with strike and cavitation are understanding how fish behavior can alter the risk of injury. We do not know whether behavioral responses to stimuli (changes in illumination, sounds, and flow fields) lead fish into areas within the turbine of lesser or greater risk and, if so, whether the behavioral response is reliable enough to point toward turbine design changes.

Least understood are the effects of shear forces on fish. Several experiments have investigated the effects of localized shear by causing the fish to be struck on a portion of its body by a high-velocity water jet. These experimental conditions can be used to develop biological criteria. Of perhaps greater relevance to turbine passage, however, are the rotational and deformational forces experienced by the entire fish as is passes through highly turbulent areas of the turbine, draft tube, and tailrace. These effects have been shown to be damaging to fish eggs and larvae, but have not been adequately studied in larger fish. Even if these aspects of shear and turbulence cause little direct mortality, they disorient the fish and make them more susceptible to predators.

There is an obvious need to perform controlled studies of the individual injury mechanisms in order to make informed decisions and, if necessary, tradeoffs in design changes. These studies will define a "safety zone" for fish within which all the injury/mortality mechanisms are believed to be at acceptable levels for survival. However, it should be remembered that other factors beyond these specific mechanisms influence the entrainment mortality that will occur at a hydropower plant. For example, adverse water quality may alter the effects of the physical injury mechanisms considered in this review. The mortality ultimately resulting from physical stresses such as pressure changes or strike may be increased by suboptimal water temperatures (either high or low), low dissolved oxygen concentrations, supersaturated nitrogen gas, and high levels of debris and other suspended materials. These water quality factors are usually optimized in laboratory studies. At actual operating turbines water quality problems may add to the overall level of stress and may contribute to greater-than-expected turbine passage mortality.

One of the drawbacks of examining individual injury mechanisms in the laboratory under controlled, optimal water quality conditions is that no information is developed about possible synergistic or antagonistic effects of multiple stresses. Synergistic effects occur when the mortality resulting from several stresses applied simultaneously is greater than would be expected from summing the expected mortalities from each of the separate stresses. Synergistic effects might occur, for example, when a fish that is already stressed by high water temperatures dies after exposure to levels of shear that are considered to be sublethal from laboratory studies. Conversely, antagonistic effects occur when the combined effect of multiple stresses is lower than would be expected from summing the separate effects (you can't kill a fish twice, so a fish that is killed by blade strike will not be killed subsequently by lethal levels of cavitation). Examples of both synergistic and antagonistic effects of multiple contaminants are known in the toxicology field, but they have not been widely studied for turbine-passage stresses.

Finally, most of the studies of turbine-related injury mechanisms have examined only direct mortality (USACE 1995). Much less is known about indirect mortality, i.e., the influence of sublethal turbine-passage stresses on later mortality due to predation or disease. Further investigations are needed to ensure that reductions in direct mortality due to turbine design changes are not nullified by high levels of indirect mortality.

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