Conf 910778 - 2

CONF-910778--2

DE91 007848

Effects of Hydroelectric Turbine Passage on Fish Early Life Stages

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Abstract

Turbine-passage mortality has been studied extensively for juveniles and adults of migratory fish species, but few studies have directly quantified mortality of fish eggs and larvae. An analysis of literature relating to component stresses of turbine passage (i.e., pressure changes, blade contact, and shear) indicates that mortality of early life stages of fish would be relatively low at low-head, bulb turbine installations. The shear forces and pressure regimes normally experienced are insufficient to cause high mortality rates. The probability of contact with turbine blades is related to the size of the fish; less than 5% of entrained ichthyoplankton would be killed by the blades in a bulb turbine. Other sources of mortality (e.g., cavitation and entrainment of fish acclimated to deep water) are controlled by operation of the facility and thus are mitigable. Because turbine-passage mortality among fish early life stages can be very difficult to estimate directly, it may be more fruitful to base the need for mitigation at any given site on detailed knowledge of turbine characteristics and the susceptibility of the fish community to entrainment.

Introduction

One of the major environmental issues facing hydroelectric development is fish mortality resulting from turbine passage. Whether the action involves licensing a proposed installation or relicensing an existing facility, the potential for turbine operation to kill downstream-moving fishes must often be considered. Turbine-passage mortality has been studied extensively for migratory fishes, but little is known about corresponding

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impacts to resident fisheries resources of inland waters, the location of many existing and planned facilities. Studies of the susceptibility of fish eggs and larvae (i.e., ichthyoplankton) to turbine-passage mortality have been especially rare, probably because of the extreme difficulty of obtaining reliable estimates.

Although few studies have directly examined the issue of turbine-caused ichthyoplankton mortality, the same types of stresses experienced by turbine-passed fishes have been considered in other contexts, notably entrainment studies at steam-electric power plants and pumped storage projects. Cada (1990) reviewed and synthesized these studies to assess the level of ichthyoplankton mortality that could be expected at hydroelectric power plants. This paper summarizes that study and suggests an approach for assessing the level of turbine-passage mortality in lieu of direct measurements. Emphasis is placed on propeller-type turbines (e.g., bulb or STRAFLO turbines), which are commonly installed at low-head hydroelectric plants.

Influence of Turbine Characteristics on Mortality

An entrained fish egg or larva may experience three general types of stress during turbine passage: (1) rapid pressure changes and cavitation, (2) contact with the turbine blades, and (3) shear forces and turbulence. Pressure changes, shear, and turbulence occur throughout the system, whereas blade contact and cavitation are restricted to relatively small areas. The expected magnitudes of each of these sources of stress for bulb turbines, as well as studies that relate to the effects of these stresses on early life stages of fish, have been reviewed in Cada (1990) and are summarized here.

Pressure and Cavitation - The pressures experienced by a turbine-passed fish will depend on characteristics of the turbine (design and flow rate) and on the location of the fish in the water column when it is entrained in the intake flow. A fish inhabiting the surface waters will be adapted to an absolute pressure of approximately 100 kPa (i.e, 1 atm). When entrained in the turbine intake flow, the fish may experience pressure increases caused by the change in depth before reaching the gatewell, and, if the penstock leads downward from the gatewell, a pressure increase between the gatewell and the turbine blades. On the other hand, a fish entrained from greater depths is already adapted to higher pressures and may experience little or no change in pressure upstream of the turbine.

Immediately downstream of the turbine blades, the fish may be briefly exposed to subatmospheric pressures (as low as 80 kPa) before returning to normal hydrostatic pressures in the draft tube and tailwaters. This negative pressure will be only a little less than that to which a surface-dwelling fish is adapted, but it represents a substantial, short-term pressure decrease for a bottom-adapted fish.

Depending on factors such as flow rate and penstock length, passage through the turbine (and the sequence of associated pressure changes) may occur in as little as 15 seconds; subatmospheric pressures would be experienced for less than 1 second. A fish drawn from surface waters would experience a doubling of pressure upstream of the turbine blades followed by a momentary pressure decrease to approximately 80% of the pressure to which it is adapted. Fish drawn from deep waters would be exposed to continuous pressure decreases; for example, the hydrostatic pressures experienced by a fish drawn from a depth of 20 m would decline from 300 kPa to 80 kPa, then return to around 100 kPa at the tailwater surface. Other turbine types or higher-head installations could cause more severe hydrostatic pressure changes.

Several laboratory studies have examined mortality of fish early life stages under more severe pressure conditions. These pressure regimes, depicted in Figure 1, were applied to a wide variety of freshwater fish species (e.g., whitefish, carp, rainbow trout, white bass, bluegill, and channel catfish). In all cases, mortality was very low or not significantly different from controls. It appears from these studies that the range of pressures experienced by most young fish during hydroelectric turbine passage will not result in significant mortality. Most entrained ichthyoplankton would be drawn from depths at or above the turbine and consequently would be exposed to relatively minor, nonlethal pressure increases before returning to natural pressures in the tailwaters.

Fish are more sensitive to pressure decreases than to increases, so the most stressful period of turbine passage may be the momentary decompression immediately behind the turbine blades. The fish that are exposed to the greatest decompression are those that are acclimated to deep waters upstream from the dam. For example, a fish rapidly drawn from a depth of 20 m and exposed to the turbine pressures depicted by the bold line in Figure 1 would experience a gradual initial pressure decrease of about 30% in front of the turbine, followed by a rapid, momentary decrease of as much as 75% from that to which it was originally acclimated. Fish eggs and newly hatched larvae have not developed swim bladders and therefore are unlikely to be damaged by this brief exposure. However, if juveniles are drawn into the intake so rapidly that they cannot adjust the pressure within their swim bladders, they may suffer mortality from burst swim bladders (Cada 1990).

Cavitation, an extreme case of subatmospheric pressures within a turbine, can cause pitting damage to the machinery and have concomitantly severe effects on fish. The mortality that can be expected from cavitation at hydroelectric facilities is difficult to predict. It is certain that implosive forces sufficient to tear metal fragments from the turbine will kill fish. However, model tests and damage evidence indicate that the zone of

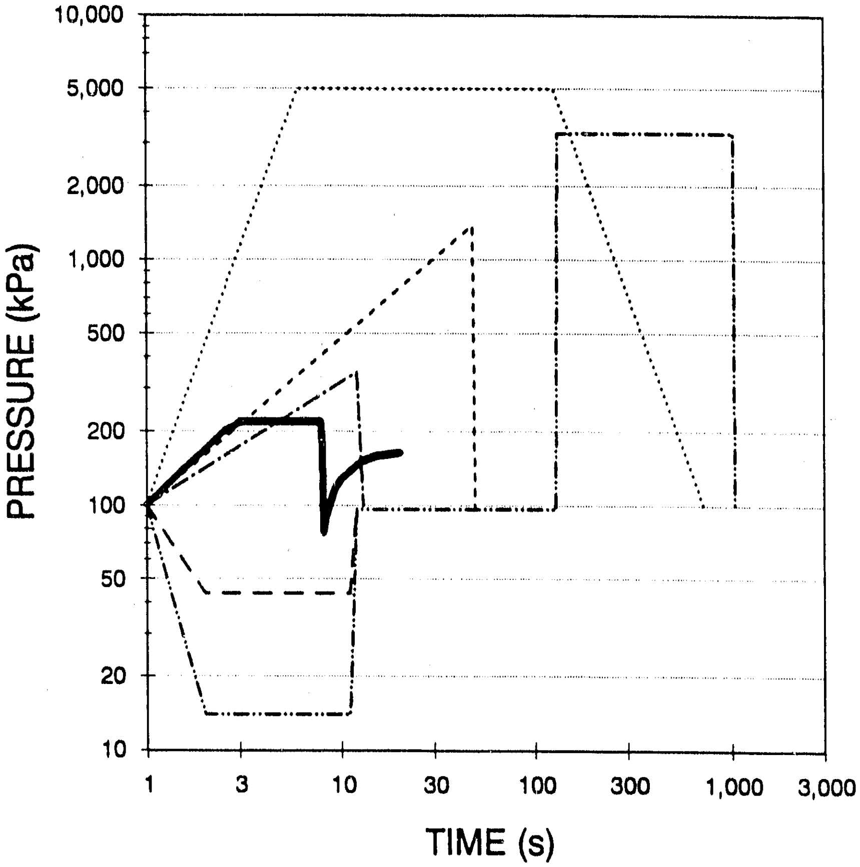

Figure 1. Hydrostatic pressure regimes that resulted in little or no mortality of fish early life stages in laboratory studies. Solid line represents the pressures that would be experienced by a surface-dwelling fish entrained in an example bulb turbine facility. Other lines are pressure regimes used in studies cited in Cada (1990).

cavitation effect is relatively restricted; assuming random distribution, most small fish entrained in the turbine may not pass close enough to an implosion to be harmed. Furthermore, cavitation is an undesirable, costly condition from the standpoint of turbine operators as well as fisheries managers, and considerable effort is expended to avoid the problem by proper design.

Contact with Runner Blades - The probability that an entrained fish will be struck by a turbine blade is a function of both the characteristics of the turbine and the size of the fish. Von Raben (1957) based the following equation on knowledge of the dynamics of turbines and his own empirical studies:

$$P = \frac{l \cdot n \cdot R \cdot a \cdot \cos \alpha}{f}$$

where

$P =$ probability of blade contact (percent);
$l =$ fish length (cm);
$n =$ number of runner blades;
$R =$ revolutions per second;
$a =$ cross-sectional area (m^2) of water passage, i.e., π(runner diameter^2 - hub diameter^2)/4;
$\alpha =$ blade angle, i.e., the angle formed by the water flow with the axial direction at the moment of impact with the edges of the runner;
$f =$ discharge (m^3/s).

This equation can be used to estimate the probability of contact for turbines that have blades, but should not be used for hydroelectric installations that have Pelton wheels. Because of the small sizes of ichthyoplankton, the probability of blade contact will also be relatively small. For example, the estimated chance of an entrained 1.0-mm-diam fish egg being struck by a turbine blade is 0.1% or less at one example bulb turbine installation (Cada 1990). Probabilities for most larvae are 2% or less. Juvenile fish (4 cm total length) have an estimated probability of contact of 5% or less (Cada 1990).

Turbulence and Shear Stresses - 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. Average velocities of the bulk flow through a turbine may be around 3 m/s or less, but under high flow, velocities can momentarily reach up to 12 m/s near the turbine blades. The tip of a large turbine blade may travel in excess of

20 m/s. The result is extreme accelerations and turbulent flows, at least on the size scale of a fish egg or larva.

A number of studies have examined the component stresses of thermal power plant entrainment independently, for example, by quantifying effects of turbulence and shear forces on fish early life stages without concomitant thermal and biocidal stresses. For example, seven species of freshwater fish larvae were passed through 2.2-cm-diam condenser tubing at velocities of up to 5.8 m/s (Kedl and Coutant 1976). The stresses generated by rapid passage through these narrow tubes resulted in less than 5% mortality. O'Connor and Poje (1979) exposed striped bass larvae to shear in condenser tubes at velocities as high as 3.0 m/s. Mortalities were not significantly different from controls. The power plant simulator used by Cada et al. (1981) subjected fish larvae and juveniles not only to moderate pressure changes (56 to 146 kPa) but also to shear forces associated with passage through 3.2-cm-diam pipes at velocities of 2.4 m/s. The combined stresses caused high mortalities among carp larvae but insignificant mortalities among larval bluegill, channel catfish, and largemouth bass. These empirical studies indicate that the shear stresses caused by average bulk flow velocities through a turbine are unlikely to cause mortality among fish eggs and larvae. Although fragile early life stages should be sensitive to shear damage, their small size apparently minimizes the velocity differentials (and therefore the shear forces) to which the fish are exposed. It should be remembered, however, that water velocities in particular areas (e.g., at the blade edges and especially near the tip) may be considerably higher. The localized shear stresses generated in these areas would be greater than those tested in laboratory studies.

Influence of Fish Behavior on Turbine-Passage Mortality

The interactions of migratory fishes with hydropower plants have been studied for many years, especially in connection with economically important anadromous species such as salmon and American shad. The juvenile forms of these species instinctively move from their natal streams to the ocean (or lake), traveling over or through any intervening dams on the way. Salmon smolts and juvenile shad are relatively large, ranging in length from approximately 5 to 20 cm, and as a result may experience high rates of injury or mortality from passing through small turbines with closely spaced blades.

In contrast, resident (i.e., nonmigratory) fishes are less likely to be exposed to turbine passage. Larger fishes are strong swimmers and, lacking the downstream migratory urge, may avoid the intake area. Some species migrate only short distances upstream to spawn, and some not at all (Hildebrand 1980a). Those early life stages that are spawned upstream will tend to drift downstream and may be entrained in the turbine intake flow. The eggs of most species of freshwater fish are found in nests or adhere to rocks and vegetation; as a consequence, hydropower impacts on eggs normally result not from turbine entrainment but rather from water-level fluctuations in either the reservoir or tailwaters (Hildebrand 1980b). Floating eggs and weakly swimming early larvae are the most susceptible stages of resident fish species. Although they may not instinctively move downstream as do anadromous species, they may be distributed in the intake water and would be unable to avoid turbine passage. Fish in these life stages range in length from about 0.1 to 3.0 cm; beyond this size, juvenile fish are less susceptible to entrainment because they are stronger swimmers, and many reside near the bottom rather than in the open waters.

Fish early life stages may be susceptible to entrainment only during brief seasons or hours of the day. This information can be used to minimize impacts. For example, some species may remain on the bottom during the day and move downstream only at night. Reducing power generation or increasing spill during the night could reduce rates of turbine passage. Other species may be found only at certain depths (e.g., surface waters), such that multilevel intakes could be used to reduce entrainment.

Discussion

It seems likely that at well-designed, well-operated hydroelectric installations the level of ichthyoplankton mortality resulting from turbine passage will be quite low. Large fish drawn from deep waters are expected to experience the greatest mortality, because of large pressure changes and an increased chance of blade contact. On the other hand, surface-dwelling eggs, larvae, and early juveniles would be expected to suffer only minimal turbine-passage mortality, perhaps no more than 5%. Much of this mortality would unavoidably result from blade contact and is to some extent predictable from turbine characteristics and size of the fish.

The turbine characteristics considered in this paper represent relatively new designs (bulb and STRAFLO turbines). Older turbines or turbines that frequently operate outside of optimal design conditions may have significantly different pressure regimes, blade/wicket gate configurations, or velocity regimes from those considered in this analysis. These characteristics could greatly influence turbine-passage mortality and should be quantified for the purpose of assessing losses of fish resources as part of licensing or relicensing activities.

Because of the difficulty of measuring turbine-passage mortality of fish early life stages directly, it may be preferable to base an assessment of the potential problem on detailed knowledge of the turbine characteristics and the fish community that is susceptible to entrainment. Information about the season or time of day that fish move downstream, the size and species of fish that are susceptible to entrainment, and their location in the water column must be obtained in order to assess the likelihood of turbine entrainment. Knowledge of the turbine characteristics described in this paper (e.g., number and spacing of blades and wicket gates; depth of water withdrawal; and velocity and pressure regimes within the turbine) can be used to estimate the consequent mortality of entrained ichthyoplankton. If mitigation of turbine-passage impacts is found to be necessary, these same studies can point to the most cost-effective technique for dealing with the problem.

Acknowledgments

I thank Virginia Tolbert and Mike Ryon for their reviews of the manuscript. This analysis was performed for the Office of Hydropower Licensing, Federal Energy Regulatory Commission. Oak Ridge National Laboratory is managed by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under contract DE-AC05-84OR21400. Publication No. 3658, Environmental Sciences Division, Oak Ridge National Laboratory.

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