A Review of Studies Relating to the Effects of Propeller-Type Turbine Passage on Fish Early Life Stages

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Abstract.—Although few studies have been conducted to directly quantify ichthyoplankton mortality at hydroelectric installations, there is a considerable body of literature on examinations of the various stresses (i.e., pressure changes, blade contact, shear) that could affect turbine-entrained eggs and larvae. A review of these studies suggests that turbine-passage mortality of early life stages of fish normally would be relatively low at the low-head, propeller-type turbine installations (e.g., bulb or STRAFLO turbines), for which relevant design information is available. The shear forces and pressure changes in low-head bulb turbines are unlikely to cause ichthyoplankton mortality. Probability of contact with turbine blades is related to size of the fish; less than 5% of entrained ichthyoplankton would be affected. Potential additional sources of mortality related to the design and operation of hydroelectric facilities, and thus mitigable, include withdrawal of deep water and cavitation.

One of the potential effects of hydroelectric development on fisheries resources is mortality resulting from turbine passage. Although mortality from turbine passage has been studied extensively for migratory adult fish and smolts (e.g., Turbak et al. 1981; Knapp et al. 1982; Eicher Associates 1987), the level of damage or mortality among early life stages (eggs and larvae) of nonmigratory species is poorly known. Increased activity related to both the development of new hydropower installations and the relicensing of existing facilities has resulted in the need to assess turbine-induced ichthyoplankton mortality. Few studies have been conducted to examine the issue directly, but the same types of stresses experienced by fish during turbine passage have been considered in other contexts, notably thermal power plant entrainment and pumped-storage projects. This paper is a review and synthesis of studies that are relevant to the problem of ichthyoplankton mortality caused by turbine passage. Emphasis is placed on propeller-type turbines, which are most commonly used at low-head (<30-m) hydroelectric plants (see Turbak et al. 1981 and Eicher Associates 1987 for descriptions of turbine types).

Turbine-Passage Stresses

An entrained fish egg or larva may experience three general types of stress during turbine passage: (1) pressure and cavitation, (2) contact with the turbine blades, and (3) shear forces and turbulence. Pressure changes and shear–turbulence occur throughout the system (Figure 1), whereas blade contact and cavitation are restricted to relatively small areas. In the following sections are descrip-

tions of the expected magnitude of each of these sources of stress, as well as studies that relate to quantifying the effects of these stresses on early life stages of fish.

Pressure and Cavitation

The types of pressure regimes experienced in passage through two low-head hydroelectric turbine installations are shown in Figure 2. The actual 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. For example, a fish entrained near the surface will be adapted to a pressure of about 101 kPa. When entrained in the intake flow of a submerged turbine, the fish may experience pressure increases caused by the change in depth before reaching the gatewell (Figure 1), and if the penstock leads downward from the gatewell, the fish will experience a slight pressure increase upstream from the turbine. 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, or even a decrease in pressure, upstream from the turbine (Figure 2).

Immediately downstream from the turbine blades, the fish may be briefly exposed to subatmospheric pressures (80 kPa or less) 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 may be a substantial pressure decrease for a bottom-adapted fish.

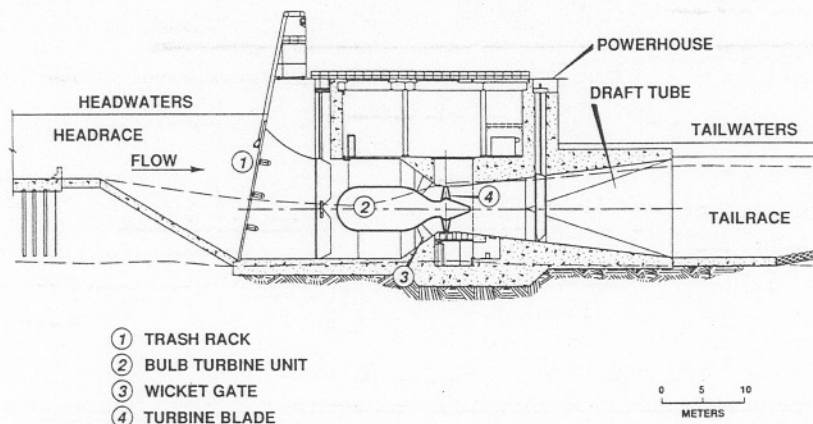Depending on flow rate, passage through the

FIGURE 1.—Cross section showing typical features of a bulb turbine installation.

turbine (and the sequence of associated pressure changes) may occur in as little as 15 s; subatmospheric pressures would be experienced for less than 1 s (Dadswell et al. 1986; Wapora 1987). A fish entrained in surface waters would be exposed to a doubling of pressure upstream from the turbine blades followed by a momentary pressure decrease to about 80% of the pressure to which it is adapted. Fish entrained in deep waters would be exposed to continuous pressure decreases; in these examples, the hydrostatic pressures would decline from 300 to 80 kPa, then return to 150 kPa in the tailwaters. The hydrostatic pressures displayed in Figure 2 represent the worst case (i.e., under high-flow conditions); lesser flow rates would result in greater travel times through the turbine but smaller pressure drops downstream from the turbine blades (Wapora 1987).

Although the pressure regimes depicted in Figure 2 have been reproduced exactly in few laboratory studies, mortality of early life stages of fish has been examined in several studies under more severe conditions. These pressure regimes are depicted in Figure 3 and are briefly described below. Lampert (1976) exposed fry of whitefish *Coregonus* sp. and common carp *Cyprinus carpio*, as well
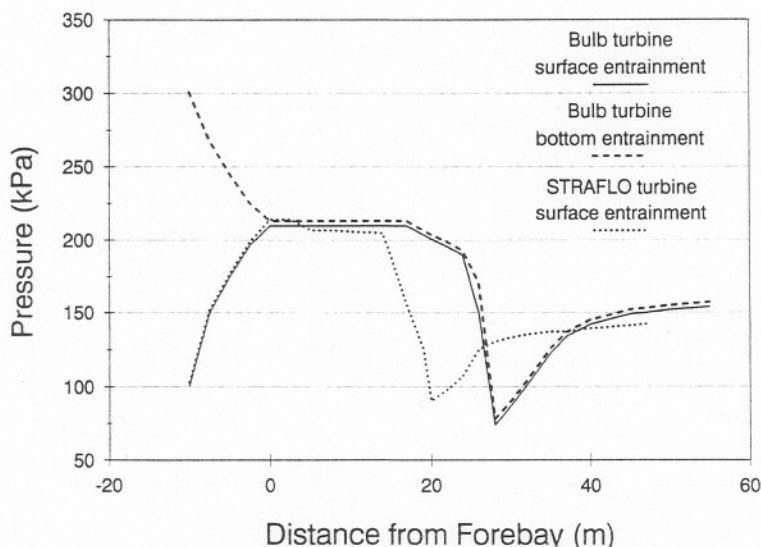

FIGURE 2.—Estimated pressure regimes experienced by fish during passage through hydroelectric power plants. The STRAFLO turbine values are taken from Dadswell et al. (1986). Bulb turbine values are taken from Wapora (1987); the solid line represents the pressures experienced by a fish drawn from the surface, whereas the dashed line represents a fish drawn from a depth of 20 m.
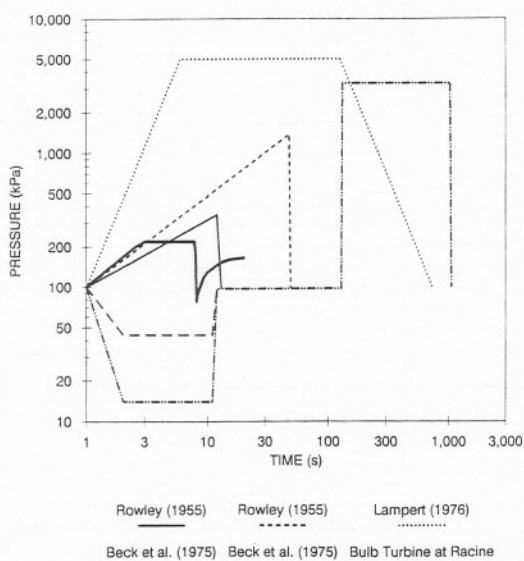
FIGURE 3.—Pressure regimes resulting in little or no mortality of early life stages of fish in laboratory studies. For comparison, the line marked "Bulb Turbine at Racine" depicts the estimated pressure regime experienced by fish entrained at a hydropower facility (see Figure 2) based on information from Wapora (1987).

as larger individuals of other species, to the simulated pressure regime of a pumped-storage hydroelectric station. Rapid increases from atmospheric pressure to over 5,000 kPa followed by a 10-min depressurization period caused no mortality. In a similar experiment, Rowley (1955) mimicked the pressure effects of penstock and turbine passage by subjecting rainbow trout *Oncorhynchus mykiss* to pressure increases of 244–1,277 kPa in less than 1 min, followed by a virtually instantaneous release of pressure. Although the fish were immobilized while under pressure, normal activity resumed immediately after depressurization, and no deaths could be attributed to the test conditions.

Beck et al. (1975) exposed eggs and larvae of striped bass *Morone saxatilis* to numerous combinations of both low and high pressures to determine the role of hydrostatic pressure changes in fish mortality at a pumped-storage plant. Exposure of various egg and larval stages to subatmospheric pressures (44 kPa) resulted in a few additional deaths relative to controls. Similarly, exposure to even more extreme pressure ranges (14 kPa, followed by a return to atmospheric pressure, followed by exposure to 3,317 kPa) caused little differential mortality in these early life stages.

Several studies designed to examine the contri-

bution of mechanical stresses to fish mortality caused by passage through thermal power plants generated information relevant to turbine-passage considerations. Kedl and Coutant (1976) passed larval bluegills *Lepomis macrochirus*, common carp, white bass *Morone chrysops*, and striped bass through a simulated power plant condenser, which exposed the organisms to turbulence, shear forces, and pressures ranging from about 50 to 200 kPa. Only low (<5%) or no differential mortalities were observed from these fluid-induced stresses alone. Ginn et al. (1978) exposed common carp larvae to pressures as low as 53 kPa during passage through a simulated power plant condenser tube. The combination of shear stresses and brief subatmospheric pressures caused no mortality. Cada et al. (1981) observed low or nonsignificant conditional mortalities among larval bluegills, largemouth bass *Micropterus salmoides,* and channel catfish *Ictalurus punctatus* exposed to fluid-induced stresses in a power plant simulator. Only newly hatched common carp larvae showed significant mortality resulting from the combined stresses of shear forces of condenser-tube passage and a pressure regime ranging from 56 to 146 kPa.

It appears from these studies that the range of pressures experienced by most fish early life stages during hydroelectric-turbine passage will not result in significant mortality. Most entrained ichthyoplankton will be drawn from depths at or above the level of the turbine, and consequently will be exposed to relatively minor, nonlethal pressure increases before returning to natural pressures in the tailwaters. Because fish are more sensitive to pressure decreases than to increases, the most stressful period of turbine passage may be the momentary decompression immediately behind the turbine blades. Tsvetkov et al. (1972) concluded that the main cause of pressure-related mortality under normal turbine-passage conditions is injury to the swim bladder from decompression. Rapid decompression causes the swim bladder to expand rapidly, perhaps to the point of rupture. Jones (1951) estimated that pressure reductions of 60% of the acclimated value could burst the swim bladders of 10-cm-long perch *Perca fluviatilis.*

The fish that would be exposed to the greatest decompression during turbine passage are those acclimated to deep waters upstream from the dam. According to the hydrostatic pressure regimes in Figure 2, for example, fish drawn up into the gatewell from bottom waters could experience a gradual initial pressure decrease of about 30% in front of the turbine, followed by a momentary pressure

decrease of as much as 75% from that to which they were originally adapted. Fish eggs and newly hatched larvae have not developed swim bladders and therefore are unlikely to be damaged by this brief exposure. However, if larger fish are drawn into the intake so rapidly that they cannot adjust the pressure within their swim bladders, they may suffer pressure-related mortality.

The time of swim bladder appearance varies widely among species; for fish species reviewed by Blaxter (1988), the swim bladder was first filled at lengths from 10 to 30 mm. Striped bass inflate their swim bladders between the fifth and seventh day after hatching (Hadley et al. 1987). Based on Jones's (1951) results, larger larvae or juveniles (with swim bladders) entrained from depths of 10 m or more may be susceptible to mortality from rapid decompression. Other data indicate that ichthyoplankton may be more tolerant to decompression than the juvenile perch tested by Jones (1951). For example, Beck et al. (1975) rapidly reduced the hydrostatic pressure on striped bass larvae by 86% with few ill effects. Their experiments indicated that the critical depth for entrainment may be 48 m or more, given the turbine-pressure regimes depicted in Figure 2.

Assessment of potential pressure effects should also consider that the velocity of water moving toward the gatewell may be slow enough that deep water-adapted fish will be able to adjust to the gradually changing pressures until they are drawn into the gatewell for the rapid trip through the turbine. Physostomous fish are more capable than physoclistous species of adjusting to rapid decompression by venting swim bladder contents. Physostomes tend to predominate among lotic fishes (Lagler et al. 1962), and many adult physoclists possess physostome swim bladders with pneumatic ducts during larval life (e.g., striped bass; Hadley et al. 1987).

Cavitation is an extreme case of subatmospheric pressures within a turbine and can cause pitting damage to the machinery with concomitantly severe effects on fish. Cavitation most often occurs at high loads, when pressure drops within the turbine are greatest. Hydrostatic pressures on the trailing edges of the blades decline to the vapor pressure of the water, and vapor pockets or bubbles are formed. These vapor pockets are subsequently transported downstream to regions of higher pressure, where they collapse violently, creating localized shock waves. The intensity of the shock waves depends upon many factors, including bubble size, static pressure in the collapse re-

gion, and dissolved gas content, but may reach tens of thousands of kilopascals at the instant and point of collapse (Rodrigue 1986). Pressure waves decrease rapidly with distance from the center of collapse. Davies (1988) noted that cavitation may be the principal pressure effect on fish.

Muir (1959) simulated cavitation effects in a laboratory device. Brief exposure of fingerling salmon *Oncorhynchus* spp. to hydrostatic pressures equal to the vapor pressure of water caused no mortality. However, when this partial vacuum was followed by instantaneous return to atmospheric pressure, thereby collapsing the vapor pocket that had formed within the test chamber, over 50% mortality was observed. Microscopic examination of the fish revealed hemorrhaging of the eyes and gill plates. Muir (1959) concluded that it was the rapid, high-pressure shock waves associated with cavitation that caused the observed mortality. Hubbs and Rechnitzer (1952) also reported on the lethality of instantaneous shock waves (in this case generated by underwater explosions) to caged marine fishes. Less abrupt pressure waves of equal or greater magnitude caused no mortality.

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 indicates that the zone of cavitation effect is relatively restricted (Eicher Associates 1987); most fish entrained in the turbine may not pass close enough to the implosion to be harmed. Further, cavitation is an undesirable, costly condition from the standpoint of the turbine operators as well as fisheries managers, and considerable effort is expended to avoid the problem by proper design. Design factors affecting cavitation include turbine setting and net head; the relationship between these two factors is known as the plant's sigma (Turbak et al. 1981). Turbine setting is the elevation of the runner's centerline with respect to the tailwater elevation. If the turbine setting is above the tailwater submergence elevation, extreme negative pressures and cavitation may result. The potential for cavitation can be minimized by increasing the plant's sigma (i.e., by decreasing the turbine setting or the net head, or both).

Contact with Runner Blades

The probability that an entrained fish will be struck by a turbine blade is a function of both characteristics of the turbine and the size of the

fish. Based on knowledge of the dynamic characteristics of turbines and his own empirical studies, Von Raben (1957; as cited in Ruggles and Collins 1981) developed the following equation:

$$P = \frac{l \cdot n \cdot R \cdot a \cdot \cos\alpha}{f};$$ (1)

P = the probability of blade contact (%);
l = fish length (cm);
n = number of runner blades;
R = revolutions per second;
a = cross-sectional area (m²) of water passage (π[(runner diameter)² − (hub diameter)²]/4);
α = 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 (m³/s).

Dadswell et al. (1986) found the incidence of blade contact injuries at a STRAFLO (low-head, propeller-type) turbine to be close to that estimated by Von Raben's equation. On the other hand, the equation greatly overestimated observed mortality in Ruggles and Collins's (1981) study of a Francis turbine; they speculated that the discrepancy may have been due to the equation's inability to account for the potential importance of clearances between wicket gates and runner blades.

Because of the small sizes of fish early life stages, the probability of blade contact will also be relatively small. Figure 4 shows the range of probability values estimated by Von Raben's equation for various sizes of ichthyoplankton at different bulb-turbine flow rates. For example, the chance of an entrained fish egg being struck by a turbine blade is 0.1% or less over the range of flows at this example installation. Probabilities for most larvae are 2% or less. Relatively long postlarvae (4 cm total length) have an estimated probability of contact of 5% or less.

Even these small probabilities may be overestimates of ichthyoplankton losses for two reasons. The first is that the equation estimates probability of blade contact, and contact does not necessarily cause mortality. Fish may be aligned with the flow streamlines and not perpendicular to the turbine blade. Contact with the blade may range in severity from head-on collisions to slight glancing blows (Davies 1988). In practice, this has led some workers to multiply P in equation (1) by a theoretical:observed "mutilation ratio" to obtain an
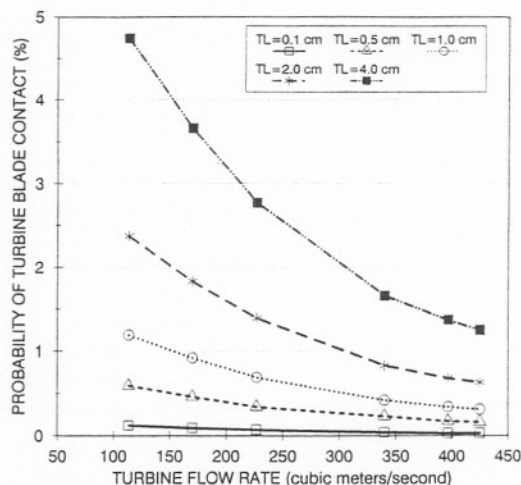

FIGURE 4.—Probability of blade contact during turbine passage for various sizes of fish early life stages. Probabilities are based on a description of turbine characteristics provided by Wapora (1987). TL = total length of fish.

estimate of obvious damage or mortality from blade contact; 0.43 was used by Von Raben (1957) and by Dadswell et al. (1986). However, given the fragile nature of fish eggs and larvae, it is probably appropriate to assume that all contacts result in mortality. A second reason that Von Raben's equation may overestimate mortality caused by blade contact is the flexibility of fish larvae. Rather than passing through the turbine as rigid bodies, larvae are curved or bent by the flow lines. As a result, they present a smaller target, and hence a smaller probability of contact, than would be predicted based on rigid length.

Turbulence and Shear Stresses

The issue of fluid-induced damage and mortality of fishes has been considered in a number of contexts, ranging from entrainment in thermal power plant cooling systems to the effects of canalization and shipping traffic (Morgan et al. 1976). 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 (Ulanowicz 1975). Accelerative forces can include changes in the speed of the overall bulk flow (as in the gatewell or draft tube), small-scale velocity changes in turbulent eddies, and collisions with solid surfaces. Shear forces occur when two bodies of water moving at different velocities are incident with each other (Davies 1988). Shear forces are most pronounced along the walls or the

leading edges of runner blades and can spin or deform the entrained organism.

Morgan et al. (1976) quantified the levels of shear that are lethal to the eggs and larvae of *Morone* spp. Such laboratory data are difficult to relate to actual effects of turbine entrainment because of the dynamic nature of turbulence and shear. At one hydroelectric installation, average velocities of the bulk flow through a turbine are around 3 m/s or less, but under high flows, velocities can momentarily reach up to 12 m/s near the turbine blades (Wapora 1987). The resulting turbulent flows are by nature stochastic, and their values at any point in the system can only be approximated. However, estimated average shear values in a thermal power plant cooling system generally fall below the range of lethal values demonstrated in laboratory experiments (Ulanowicz 1975; Marcy et al. 1978).

An indication of the effects of fluid-induced stresses on turbine-entrained ichthyoplankton can be obtained from related studies of thermal power plant cooling systems. A number of studies have been conducted to assess the relative severity of the various combined stresses of thermal power plant entrainment by examining the components independently (i.e., by quantifying effects of turbulence and shear forces on fish early life stages without concomitant thermal and biocidal stresses). In the first and most comprehensive of these experiments, Kedl and Coutant (1976) passed seven species of freshwater fish larvae through 12 m of 2.2-cm-diameter condenser tubing at velocities of up to 5.8 m/s. The stresses generated by rapid passage through these narrow tubes resulted in less than 5% mortality in all cases (Table 1). 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, and O'Connor and Poje concluded that their fluid-induced stresses were not a major component of striped bass entrainment mortality.

The power-plant simulator used by Cada et al. (1981) subjected fish larvae and juveniles not only to moderate pressure changes (56–146 kPa) but also to shear forces associated with passage through 3.2-cm-diameter pipes at velocities of 2.4 m/s. The combined stresses resulted in high mortalities among 7-mm-long common carp larvae, but mortalities among bluegills, channel catfish, largemouth bass, and mosquitofish *Gambusia affinis* were generally less than 2% and not significantly different from controls (Table 1). These empirical studies support the theoretical analysis of Marcy

TABLE 1.—Effects of fluid-induced stresses on mortality of different sizes and species of fish larvae exposed to different water velocities in power plant simulators in different studies.

Species	Fish length (mm) or stage	Water velocity (m/s)	Differential mortality[a]
Kedl and Coutant (1976)			
Bluegill	10–12	4.6	NS
	25–30	4.6	NS
Striped bass	4–6	5.8	<5%
White bass	6–9	5.8	<5%
Common carp	6–10	5.8	<5%
Mosquitofish	6–30	5.8	<5%
Brook silverside[b]	16–22	5.8	<5%
O'Connor and Poje (1979)			
Striped bass	Yolk-sac larvae	3.0	NS
	16-d-old post-yolk-sac larvae	3.0	NS
Cada et al. (1981)			
Common carp	7	1.3	16%
	7	2.4	84%
Mosquitofish	30–35	2.4	NS
Bluegill	18	1.3	NS
	27–35	2.4	NS
Channel catfish	16–26	2.4	NS
Largemouth bass	12	2.4	NS

[a] Increase in mortality above control level; NS = not significantly different from control level.
[b] *Labidesthes sicculus.*

et al. (1978), who concluded that shear stresses imposed upon striped bass eggs and larvae in power plant condenser tubes are unlikely to cause mortality. Although fragile early life stages should be sensitive to shear damage, apparently their small size minimizes the velocity differentials (and therefore the shear forces) to which the fish are exposed.

The issue of synergistic effects (i.e., when the overall mortality is greater than the sum of the mortalities due to individual stresses) has been difficult to evaluate for both steam-electric and hydroelectric power plants. In most laboratory studies, the effects of a single stress have been examined under controlled, reproducible conditions, whereas in field studies one can only measure the combined effect of the various stresses (including handling and collection) and not the individual effects. In all studies in which thermal power plant simulators have been used to quantify the individual and combined effects of thermal, chemical, and fluid-induced stresses (Kedl and Coutant 1976; O'Connor and Poje 1979; Cada et al. 1981), interactive effects were tested, but little evidence of synergism was found. The absence of statistically significant mortalities among most

species exposed to combined pressure and shear stresses (Table 1) precluded significant individual or synergistic effects from physical causes. Although these experiments indicated that individual stresses causing low or moderate levels of mortality may not have significant interactive effects, definitive studies of synergistic effects under more extreme conditions of turbine passage (e.g., large pressure changes and cavitation) are lacking.

Summary and Conclusions

Direct measurements of turbine-passage mortality are usually preferable to estimates derived by other means. However, reliable in situ mortality estimates are difficult to obtain for fish early life stages (and often for larger fish as well) because of extreme sampling conditions at many hydroelectric power plants and the fragility of fish eggs and larvae. Few studies have been conducted to examine turbine-passage mortality of early life stages of fish in the field, and in none has information been collected in a way that could be widely used to predict turbine-passage effects at other facilities. Nevertheless, there have been a number of experiments conducted under laboratory conditions to examine the same types and levels of stresses to which turbine-entrained ichthyoplankton are exposed. From these studies the following conclusions can be drawn.

(1) The range of pressures experienced by most fishes at low-head facilities would not be expected to cause statistically significant mortality (exceptions are noted below). Ichthyoplankton drawn from the upper levels of the reservoir will be exposed to brief, moderate pressure increases before returning to natural pressures in the tailwaters.

(2) Probability of contact with the turbine blade is related in part to the size of the fish. As a result, only a small percentage (<5%) of the fish eggs and larvae passing through the turbine is expected to suffer mortality from collision with the blades.

(3) Shear forces and turbulence in a turbine are extremely difficult to quantify, so the resultant level of mortality cannot be predicted precisely. A number of investigators have exposed fish larvae to extreme turbulence and shear stresses by passing them through narrow pipes at high velocities. Significant mortality was rarely observed. These stresses were probably greater than those that occur within the larger turbine passages.

It seems likely that at well-designed, well-operated hydroelectric installations the level of ichthyoplankton mortality attributable to turbine passage will be quite low, 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. Two other sources of mortality need to be assessed and minimized at particular installations. First, fish larvae dwelling in deep waters of reservoirs could experience rapid decompression near the turbine blades that is severe enough to burst the swim bladder and cause death. The probability of this occurring can be estimated from the minimum pressures developed within the turbine (variable depending on operating conditions) and the depth strata from which fish are entrained. Based on Jones's (1951) findings as a rule of thumb, sudden decompression to 40% or less of the acclimation pressure may lead to mortality from burst swim bladders. Multilevel intakes could be used to mitigate such a problem in deep reservoirs by drawing water primarily from the surface during the season when weakly swimming fish early life stages are in the bottom waters.

A second additional source of mortality stems from cavitation. Under normal operating conditions, cavitation should be minimal or nonexistent. However, conditions that lower the plant's sigma (e.g., low tailwater levels) could cause excessive cavitation. Ichthyoplankton mortality is likely under such conditions, but the degree cannot be predicted from available information. The surest way to mitigate damage to both fish and turbines is to cut back on generation when conditions leading to cavitation are present.

In the absence of directly measured turbine-passage mortality, an assessment of the effects of a particular hydroelectric installation on fish early life stages could be based on characteristics of both the turbine and the fish community. The probability of blade contact can be estimated from basic turbine design and fish-length information (Von Raben 1957). Although well-operated facilities may be expected to cause little turbine-passage mortality, others with deep intakes or a history of cavitation problems may kill significant numbers of both larval and adult fish. Useful information in this context would include the depth of water withdrawal, the pressure regime under normal and cavitating conditions, and the percent of time cavitation occurs, perhaps as indicated by the frequency and extent of cavitation damage repair. The turbine characteristics discussed in this review are examples of relatively new designs. Older turbines, different turbine types (e.g., Francis-type reaction turbines or impulse turbines), and turbines that frequently operate outside of optimal conditions

may have substantially different configurations, pressures, and velocities, all of which can influence mortality.

Susceptibility of the fish community to entrainment should also be determined. Among North American freshwater fishes, only the freshwater drum *Aplodinotus grunniens* has pelagic eggs. Thus, fish egg entrainment is not likely to be a serious problem at most sites. The larvae and juveniles of nonmigratory fish species may be only incidentally susceptible to turbine entrainment, and the resultant effects not significant to the dynamics of the reservoir's resident fish community. On the other hand, even a relatively small mortality rate of 5% might be excessive to an anadromous fish population that must negotiate numerous hydropower installations.

Acknowledgments

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