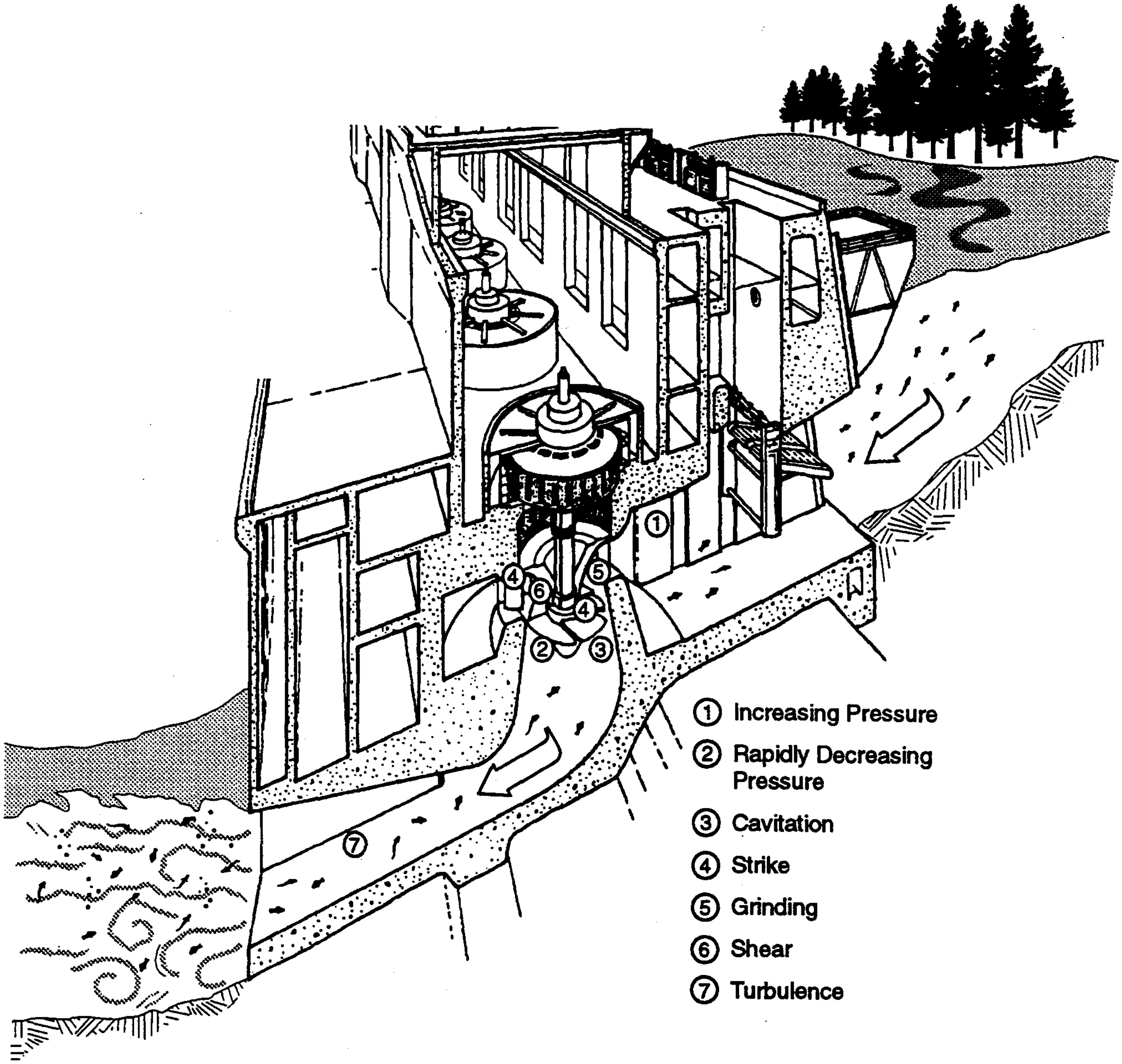
DOE/ID-10578

Development of Biological Criteria for the Design of Advanced Hydropower Turbines



U.S. Department of Energy
Idaho Operations Office

Development of Biological Criteria for the Design of Advanced Hydropower Turbines

Glenn F. Čada, Charles C. Coutant
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, TN

and

Richard R. Whitney
Leavenworth, Washington

March 1997

prepared for

U.S. Department of Energy
Idaho Operations Office
Idaho Falls, ID

Acknowledgments

We thank Mark Bevelhimer, Michael Sale, and Webster Van Winkle, all of Oak Ridge National Laboratory (ORNL), Tom Poe of the Biological Resources Division, U.S. Geological Survey, and the Technical Committee of the U.S. Department of Energy's Advanced Hydropower Turbine System Program for their reviews of this report. John Ferguson, Ed Meyer, and Tom Poe provided useful literature. We also thank Peggy Brookshier and John Flynn of the U.S. Department of Energy and Jim Francfort, Ben Rinehart, and Garold Sommers of the Idaho National Engineering and Environmental Laboratory for their active participation and encouragement. Synthesis of information from the Columbia River basin was aided by participation of C. C. Coutant and R. R. Whitney in the Northwest Power Planning Council's Independent Scientific Group.

Oak Ridge National Laboratory is managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464. This work was sponsored by the Office of Geothermal Technologies, U.S. Department of Energy. Portions of this research were also funded by the Northwest Power Planning Council and the Bonneville Power Administration. Publication No. 4639, Environmental Sciences Division, ORNL.

Executive Summary

A review of the literature related to turbine-passage injury mechanisms suggests the following biological criteria should be considered in the design of new turbines:

Pressure - Pressure increases of the magnitude found in hydroelectric turbines do not appear to cause direct damage to entrained fish. Pressure decreases within the turbine are a greater concern. Because the decrease to subatmospheric pressures is virtually instantaneous, fish with swim bladders will be unable to vent gas from the rapidly expanding swim bladder. The swim bladder may distend or rupture, causing direct mortality or reduced ability to escape predators in the tailrace. 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 effects of low pressures.

Cavitation - 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.

Shear and Turbulence - Laboratory studies to date have exposed fish to a high-velocity water jet in a static tank. These tests examine the injury and mortality rates of fish in which high shear values are applied to only a part of the fish's body. Other, larger-scale effects of shear 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 by shear and turbulence and may suffer greater indirect mortality (predation) below the turbine discharge.

Mechanical Injury - Because of numerous variables related to the entrained fish (e.g., individual size, condition, and behavior) and the relationship of the fish to the runner and other turbine structures (e.g., region of passage, orientation, and relative velocity), the probability of injury from strike and grinding 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. Aspects of the turbine system that could be modified in order to minimize strike injury are discussed.

Among the injury mechanisms considered in this report, the effects of water pressure on fish seem to be the best understood. 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 deal with 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, or whether the behavioral response is reliable enough to point toward turbine design changes. Least understood are the effects of shear forces and turbulence on fish.

Adverse water quality may also 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 operating turbines water quality problems may add to the overall level of stress and may contribute to greater-than-expected turbine passage mortality.

Most of the studies of turbine-related injury mechanisms have examined only direct mortality. 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 would be useful to ensure that reductions in direct mortality due to turbine design changes are not nullified by high levels of indirect mortality.

Coordinated laboratory and field studies are needed to reduce uncertainties about the relative importance of the potential injury mechanisms associated with turbine passage. Pressure changes are easy to study in the laboratory under controlled conditions. The rapid pressure increases and decreases experienced by an entrained fish can be reliably simulated in the laboratory, and as a result more is known about this stress than any other. On the other hand, techniques for studying fluid shear stresses and turbulence are not well developed. Shear and turbulence have been difficult to recreate in laboratory experiments, and little is known about the levels of injury, direct mortality, and indirect mortality (predation and disease) that may result from exposure to these stresses in a hydroelectric turbine.

The substantial developments in video and hydroacoustics techniques in recent years might used to visualize the path taken by entrained fish in an operating turbine. This information is needed to develop a better understanding of the risk of strike and grinding, as well as the pressure vs. time, shear vs. time, and turbulence vs. time histories experienced by fish passing through existing and advanced turbines. Low-light sensitive video cameras, perhaps in conjunction with light-emitting tags attached to the fish, show promise for tracking the path of entrained fish. Split-beam hydroacoustics techniques can potentially detect and record a fish's movements in three dimensions with little concern about altering the fish's behavior. However, the ability of hydroacoustics to track fish reliably inside of a turbine, under conditions of high velocities, high turbulence, crowding of entrained fish, and electronic interference, has yet to be demonstrated.

We evaluated the literature on fish behavior as it relates to passage of fish near or through hydropower turbines. The goal is to foster compatibility of engineered systems with the normal behavior patterns of fish species and life stages such that entrainment into turbines and injury in passage are minimized. In particular, we focused on aspects of fish behavior that could be used for computational fluid dynamics (CFD) modeling of fish trajectories through turbine systems. Downstream-migrating salmon smolts are generally surface oriented and follow flow. They can be diverted from turbines by surface spills, with varying degrees of effectiveness. Smolts orient to the ceilings of turbine intakes but are horizontally distributed more evenly, except as affected by intake-specific turbulence and vortices. Smolts often enter intakes oriented head upstream, but may change orientation in the flow fields of the intake. Non-salmonids are entrained most often from vicinities of shorelines and episodically, suggesting accidental capture of schools (often of juveniles or in cold water) and little behavioral control during turbine passage. Models of fish trajectories should not assume neutral buoyancy throughout the time a fish passes through a turbine, largely because of pressure effects on swim bladders. Fish use their lateral line system to sense obstacles and change their orientation, but this sensory-response system may not be effective in the very rapid passage times of turbine systems. Effects of pre-existing stress levels on fish performance in turbine passage (especially as they affect trajectories) are not well known but may be important. There are practical limits of observation and measurement of fish and flows in the proximity of turbine runners that may inhibit development of much information that is germane to developing a more fish-friendly turbine.

Based on our review of fish behavior in relation to hydropower facilities, we provide the following recommendations to guide both turbine system design and additional research:

1. The first priority for a fish-friendly turbine *system* in migratory salmonid waters should be one that bypasses as many downstream-migrating fish as possible along these fish's natural surface-oriented migration pathway away from deep turbine intakes.

2. Further report evaluation and data collection and analyses are needed to specify fish cross-sectional distribution in a mathematically rigorous way for species, sizes, and intake geometries in order to specify quantitatively the fish trajectories through turbines.

3. Further analysis is needed using hydroacoustic and underwater television data, both new and as related to submerged traveling screens, as indicators of species- and size-specific fish orientation as they enter turbines.

4. Considerably more justification would be needed for commitment of major expenses for fish-friendly turbines in freshwaters occupied by non-migratory species.

5. Simulation of many non-salmonids as passive objects in CFD modeling seems appropriate.

6. The significance of differences from neutral buoyancy and of changes in buoyancy during fish trajectories through a turbine should be established from modeling studies of fish with a range of constant and changing densities.

7. Further studies of fish's reaction times to structures or high shear/turbulence areas within the turbine passage are needed. Models can tentatively assume that orientation of fish as they enter the scroll case will be retained as they transit the turbine itself (or at least that the fish will not be able to control its orientation in a turbulent environment), under

the assumption that reaction times are too long for the rapid flow rates.

8. Research on the orientation in and use of unsteady flows by migrating juvenile salmonids is needed.

9. Testing of fish behavior in turbines should include background information on pre-existing stress levels, and experiments should use fish in both test and control lots that have been given known amounts of prior stress.

10. Innovative means for obtaining information on fish behavior near turbine runners should be pursued, but there should be realistic expectations about the feasibility of this research.

Contents

Acknowledgments i

Executive Summary iii

List of Figures ix

List of Tables xi

1. Introduction 1

2. Review of Literature Relating to Injury Mechanisms Associated with Turbine Passage 3
   2.1 Pressure Effects 4
   2.2 Cavitation Effects 11
   2.3 Shear Stress Effects 12
   2.4 Turbulence Effects 17
   2.5 Mechanical Effects (Strike and Grinding) 17
   2.6 Conclusions and Recommendations 21
      2.6.1 Biological Criteria for New Turbine Designs 21
         Pressure 21
         Cavitation 23
         Shear 23
         Strike 24
      2.6.2 Relative Importance of Turbine-Passage Injury Mechanisms 24
      2.6.3 Need for Additional Studies 27

3. Laboratory and Field Techniques for the Study of Injury Mechanisms Associated with Turbine Passage 29
   3.1 Laboratory Techniques 30
      3.1.1 Mechanical Injury (Strike and Grinding) 30
      3.1.2 Pressure 32
      3.1.3 Cavitation 35
      3.1.4 Shear Stress and Turbulence 36
   3.2 Field Techniques 40
      3.2.1 Low-Light-Sensitive Underwater Video Camera 40
      3.2.2 Hydroacoustic Techniques 43
   3.3 Conclusions and Recommendations 45

4. Fish Behavior in Relation to Entrainment in Hydropower Turbines 47
   4.1 Sources of Mortality in Turbines 48
   4.2 Behavior of Salmonids 49

4.2.1 Orientation with Bulk Flow 50
4.2.2 Surface orientation 52
4.2.3 Body Orientation in Flow 55
4.3 Behavior of Non-Salmonids 58
4.4 Basic Studies of Fish Behavior 60
4.4.1 Buoyancy and Stability 60
4.4.2 Obstacle Recognition and Avoidance 63
4.4.3 Sensing acceleration 64
4.4.4 Behavior in Turbulent Flow 65
4.4.5 Stress 66
4.5 Measurement Concerns 66
4.6 Conclusions and Recommendations 67

5. Literature Cited 70

List of Figures

1. Fish mortalities following exposure in the laboratory to brief and rapid pressure reductions 10

2. Four blade tip profiles used for strike experiments of Turnpenny et al. (1992) 20

3. Hypothetical distribution of mortality and its causes from passage through hydraulic, low-head turbines in relation to body length of aquatic organisms 26

4. General arrangement of the fish/blade strike simulator used by Turnpenny et al. (1992) 31

5. Example of the repeatability of the pressure vs. time regimes created in the test chambers used by Montgomery Watson (1995) 34

6. Calculated relationship between shear stress (N/m^2) and flow rate of the jet used in the shear stress studies of Turnpenny et al. (1992) 38

7. Calculated variation in shear across the jet centerline with distance for the Fawley nozzle used in the shear stress studies of Turnpenny et al. (1992) 38

8. Generalized hydropower facility showing alternative water pathways through powerhouse turbines or spillway. Insets show cross-sections of a typical spillway and a spillway modified as a surface spillway 50

9. Generalized cross section of a Columbia River basin hydropower powerhouse, showing distribution of downstream-migrating juvenile salmon and fish-passage devices 54

List of Tables

1. Mortality of fish exposed to rapid and brief pressure reductions in laboratory test chambers . 9

2. Effects of exposure of juvenile coho salmon to the margins of water jets moving at various calculated velocities 14

3. Influence of juvenile salmon size on the effects of water jets moving at various calculated velocities 14

4. Influence of juvenile salmon size on the effects of water jets moving at various calculated velocities 14

5. Effects of exposure of various fish to the margins of water jets moving at different velocities 16

6. Calculated probabilities (expressed as percentages) that fish of various lengths and weights will be injured by blade strike in a low-head, axial flow tidal power turbine 22

7. Summary of primary injuries to fish observed in laboratory studies by Turnpenny et al. (1992)of pressure, shear, and blade strike 28

8. Specifications of low-light sensitive underwater video cameras used at McNary Dam by Nestler and Davidson (1995a) 41

1. Introduction

Hydroelectric power plants can impact fish populations by interfering with both upstream and downstream movements. These impacts are most serious for anadromous fish species, such as salmon, steelhead, and American shad, whose life histories require passage between marine and freshwater environments. Fish ladders or lifts are commonly installed to provide for upstream movements around dams, whereas a wide variety of screens and other mitigative measures have been employed to reduce the numbers of downstream-migrating fish that are entrained in the intake flow and pass through the turbines (Sale et al. 1991; Čada and Sale 1993; Francfort et al. 1994; OTA 1995).

Turbine intake screens and other related measures have had mixed success in promoting safe downstream passage of fish. At some hydropower plants, these measures have significantly reduced turbine entrainment, but at other plants unacceptably large numbers of fish still suffer turbine-passage mortality or are harmed by the fish passage mitigation measure itself (Čada and Francfort 1995; Čada In Press). Even effective, well-designed screening and bypass systems may protect only a portion of the fish entrained in the intake flows; the remainder will pass through the turbines. Hence, there is a need not only to develop fish screens to reduce turbine passage, but also to develop turbines that increase the survival of fish that are entrained.

Recognizing the need for multiple solutions to the downstream fish passage problem, the U.S. Army Corps of Engineers conducts research aimed at reducing mortality of fish (especially salmon) caused by passage through Kaplan turbines at their hydropower plants (USACE 1995). On a wider scale, the U.S. Department of Energy, through its Advanced Hydropower Turbine System Program, supports the development of "environmentally friendly" turbines, i.e., turbine systems in which environmental attributes such as entrainment survival are emphasized (Brookshier et al. 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 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. Possible causes for entrainment mortality, physical injuries, sublethal physiological stress, and disorientation are many and varied; a recent workshop (USACE 1995) concluded that entrainment injuries could result from rapid and extreme water pressure changes, cavitation, shear, turbulence, and/or mechanical injuries (strike, grinding and abrasion). 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. For example, the sensitivity of fish to the levels of shear or turbulence that are predicted to occur in a turbine is not well understood, and as a result we do not know what effect altering the amount of shear in a new turbine design will have on survival. Passage through different regions of the turbine (e.g., close to the blade hub or out near the blade tip) will entail exposure to different pressure, shear, and turbulence regimes and different probabilities of mechanical injuries. The behavior of the fish while passing through the turbine may alter the passage route, leading to greater or lesser exposure to these injury mechanisms than would be expected from consideration of the entrained organism as a passive object.

The purpose of this report is to review published laboratory bioassays and similar studies of the responses of fish to the component stresses of turbine passage: pressure, cavitation, shear, and blade strike (*Section 2*). We have examined each of these component stresses of turbine entrainment with the goal of deriving biological criteria for the turbine designers. In many cases there are few or no data to support quantitative biological criteria, so in *Section 3* we describe laboratory and field experimental techniques that could be used to fill gaps in existing information. Finally, we examine the role of behavior in mediating the effects of turbine passage stresses (*Section 4*). Entrained fish are not necessarily passive objects; by their behavior during turbine passage they may be able to swim out of (or into) areas of the turbine that cause damage. The published literature on fish behavior may suggest whether particular species or sizes of fish are likely to exhibit predictable, directed movements, knowledge of which would be useful to turbine designers.

2. Review of Literature Relating to Injury Mechanisms Associated with Turbine Passage

Phases I and II of the U.S. Department of Energy's Advanced Hydropower Turbine System Program (AHTSP) involve considerable Computational Fluid Dynamics (CFD) modeling and engineering design studies to develop novel designs for fish-friendly turbines, i.e., turbines in which mortality of entrained fish is small. In order to accomplish this, the designers need quantitative environmental criteria as input. That is, the engineers need numbers which define a "safety zone" for fish within which all of the injury/mortality mechanisms experienced by turbine-passed fish (water pressure changes, shear forces, cavitation, and chance of mechanical strike) are at acceptable (definable) levels for survival. If one of these injury mechanisms has over-riding importance compared to others, the designers could focus their efforts to "design out" this stress in the new generation of turbines.

Literature reviews of turbine-passage mortality studies have often focused on field studies of "high-mortality" and "low-mortality" turbines in an attempt to discern the design causes for the differences in mortality. Such studies of the whole-system performance have the advantage of addressing real-world conditions and will provide necessary base case numbers for turbine-passage mortality at existing turbines. Field studies of entrainment mortalities at particular sites are limited because they reflect the impacts on survival of all of the injury mechanisms together, but cannot distinguish effects of individual stresses. The relative importance of each of these stresses is difficult to discern from field studies at hydropower plants, especially when the observable physical damage to fish is similar for many of the stresses

This first section of the report examines the injury/mortality mechanisms associated with turbine entrainment, as studied separately under controlled conditions in the laboratory and field rather than in combination at hydropower sites. This literature can be used to derive biological criteria for the design engineers. For example, pressure zones are defined within which fish would not be harmed, and outside of which pressures could cause mortality. These pressure values would provide the CFD modelers and turbine design engineers with target values for their design work. "Safety zones" for other components of entrainment (e.g., shear, cavitation, blade strike) are also proposed where sufficient information exists in the literature. Gaps in available information are identified in order to direct future investigations.

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 (USACE 1995). Each of these mechanisms can cause *physical* injuries that are severe enough to kill the fish directly; these include descaling; loss of the protective mucous layer; torn gill covers; decapitation; bruises; burst swim bladder; hemorrhaging; and other internal injuries. If the entrainment stresses are not immediately lethal, the fish may nonetheless be *physiologically stressed* and *disoriented*, so that they are more susceptible to predation in the tailwaters

(Mesa 1994) or disabled so that they later succumb to disease (indirect mortality). The following sections review literature relevant to understanding the importance of each of these factors to turbine-passage mortality. Most of the studies examine only direct mortality; much less is known about the effects of sublethal injuries on indirect mortality.

2.1 Pressure Effects

Pressure at any point is the force per unit area acting upon the point. Pressure is commonly expressed as pounds per square inch (psi) in the English system and as newtons per square meter (N/m^2) in the International (SI) system. An alternative unit of pressure in the SI system is the pascal (Pa); one pascal is equal to one N/m^2. Water pressures normally experienced by fish are most easily expressed as kilopascals (kPa). Pressures have been expressed in a variety of units in the studies reviewed in this report. Wherever possible, pressures have been converted to the SI system and expressed as kPa, followed by psi in parentheses. For example, water pressure at one atmosphere is equivalent to 101.325 kPa (14.73 psi).

Among fish with swim bladders, the response to rapid pressure changes encountered within a turbine is affected by whether the fish is *physostomous* or *physoclistous*. Physostomous fish have a duct, the pneumatic duct, which connects the swim bladder with the esophagus (Lagler et al. 1962). Gas can be quickly taken into or vented from the swim bladder in these species through the mouth and pneumatic duct, so that adjustment to changing water pressures can take place rapidly, often on the order of seconds. As a general rule, physostomes include the soft-rayed fishes like salmon, trout, catfish, minnows, and gar. On the other hand, physoclists lack a direct connection between the swim bladder and the esophagus. In these fish the contents and pressures within the swim bladder must be adjusted by diffusion into the blood, a process measured on the order of hours. Physoclistous fish include many of the spiny-rayed fishes such as perch, bass, and sunfish.

Once inside a turbine, physoclistous fish cannot adjust the volume of their swim bladder rapidly enough to compensate for changing water pressures; the swim bladder will be compressed and the fish will become more dense under increasing water pressures. Conversely, in a region of low pressure, downstream from the turbine blades, the swim bladder will expand, potentially to the point of bursting. Physostomes have more control over the volume of gas in the swim bladder than physoclists. If a deep-water-adapted physostome is drawn toward a surface intake, decreasing water pressure will cause the swim bladder to expand. Excess gas can be vented if the rate of ascent is sufficiently slow. However, even physostomous fish may not be capable of venting excess gas in response to the rapid pressure reductions (often less than 1 sec) that occur within the turbine and draft tube.

Harvey's (1963) work with sockeye salmon reinforced numerous other studies that found fish can tolerate very high hydrostatic pressures. He exposed sockeye fry and smolts to pressures in test chambers as high as 2064 kPa (300 psi) with no significant mortality. However, the rate of pressure increase in the test chambers during most tests was slow (1 psi/sec), so that maximum pressures were reached only after 5 minutes. This gradual increase in hydrostatic pressure does not duplicate the rapid pressure changes (measured in seconds) experienced by turbine-entrained fish upstream from the turbine blades. Rowley (1955) subjected rainbow trout to a similar pressure regime [gradual increase from atmospheric pressure to as high as 1376 kPa (200 psi) followed by instantaneous release to atmospheric pressure] and observed no detrimental effects.

Foye and Scott (1965) exposed six species of freshwater fishes (chain pickerel, yellow perch, fallfish, common shiners, lake trout, and Atlantic salmon) to instantaneous pressure increases to 2064 kPa (300 psi), followed by decompression back to atmospheric pressure over a 10-minute period. No mortality was observed among salmon, lake trout, or fallfish (a minnow species) over the subsequent 7-day holding period. Long-term mortalities among the other three species showed considerable variation, but inadequate controls precluded a quantification of mortality or, indeed, a determination that mortality among test fishes was caused by the pressure increases.

Of greater relevance to hydroelectric turbine passage, Harvey (1963) also measured the effects of decompression experienced at rapid rates. In these decompression studies he lowered hydrostatic pressures in as little as 0.1 seconds (decompression rates as high as 7,500 psi/sec) to pressure values as low as 1.6 kPa (0.23 psi). An initial series of tests indicated that briefly increasing the pressure above atmospheric (to 50 or 300 psi) before decompression did not affect mortality rates. Rather, increasing vacuums led to increasing mortalities. At pressures less than 84.6 kPa (12.3 psi) mortalities of test fish exceeded controls; sockeye mortalities averaged about 2 percent following brief exposures to 17.2 kPa (2.5 psi). The rate of decompression was important. Smolts gradually exposed to a reduction in pressure below atmospheric showed no apparent ill effects, even at pressures as low as 16.5 kPa (2.4 psi).

In another series of tests, smolts acclimated to surface waters, brief high pressures, and then rapid decompression to subatmospheric pressures experienced little mortality (Harvey 1963). However, outmigrating smolts that had been acclimated to deep water of a lake before being exposed to a sudden reduction in pressures suffered mortalities as high as 35 percent. Death was due to minute gas emboli, most commonly lodged in the heart or ventral aorta. Sockeye smolts held at a lake depth of 35 feet for 7 days (i.e., acclimated to a pressure of about 30 psi) suffered 21 percent mortality following decompression tests.

Harvey (1963) concluded that sockeye juveniles exhibited a tolerance to pressure increases, but could succumb to rapid decompression under conditions permitting swim bladder gas to appear as emboli in the blood stream. Compared to other species of fish, particularly physoclistous fish, sockeye are less susceptible to adverse pressure changes because the volume of the swim bladder is a small percentage of the fish's volume, the bladder is very extensible, and gas can be readily released through the pneumatic duct under slowly decreasing hydrostatic pressures. However, very rapid decompression, such as that experienced in fractions of a second downstream from turbine blades, may not permit the escape of swim bladder gas even in physostomous fish like salmon, and swim bladder damage and mortality among depth-acclimated fish would occur. Histological examination showed that the pneumatic duct is poorly adapted to rapid release of gas [Harvey and Hoar, unpublished manuscript, cited in Lucas (1962)], so that swim bladder rupture under severe vacuum conditions is possible even for physostomous fish like sockeye salmon. Harvey's (1963) belief that swim bladder damage was an important cause of pressure-related death was supported by his limited series of pressure tests on sculpins, which do not have swim bladders. The sculpins evidenced little discomfort and no mortality upon sudden exposure to vacuum conditions.

Similar conclusions were drawn by Tsvetkov et al. (1972), who examined pressure effects on a variety of freshwater salmonids, minnows, sturgeons, and perch. In their laboratory experiments fish were allowed to acclimate to excess pressures (up to 608 kPa; 88 psi) before being rapidly depressurized to atmospheric pressure (depressurization rates as high as 608 kPa/s). This technique was used to mimic the experience of depth-acclimated fish exposed to rapid depressurization downstream of hydroelectric turbines. Physostomous fish survived far better than physoclistous fish, but even physostomous fish were killed at decompression rates greater than 91 kPa/s. Because larvae and fingerlings of physostomous fish released swim bladder gases with greater difficulty than older fish, they were killed by relatively lower absolute pressure decreases and lower rates of decompression. The two species of sturgeon tested by Tsvetkov et al. (1972) were resistant to pressure effects. Despite many hours of exposure to pressures up to 608 kPa (88 psi), the investigators were unable to determine whether the sturgeon became acclimated to increased pressure. Subsequent rapid decompression was not lethal.

Feathers and Knable (1983) acclimated largemouth bass to elevated pressures (191, 280, and 369 kPa), then reduced the pressure to atmospheric (101 kPa; 14.7 psi) in less than one minute. Mortality was directly related to the magnitude of depressurization, ranging from an average of 25 percent at an acclimation pressure of 191 kPa (27.8 psi) to an average of 46 percent at an acclimation pressure of 369 kPa (53.8 psi). Depressurization mortality commonly occurred within 1 hour at the higher acclimation pressures, whereas mortality occurred over a 5-day period as a result of depressurization from the 191 kPa acclimation pressure. These tests indicate that relatively small but rapid pressure decreases can be harmful to physoclistous fish. Mortalities following depressurization from 191 kPa were largely attributed to respiratory failure and the stress of floating on the surface due to an expanded swim bladder. On the other hand, rapid depressurization to atmospheric pressure from 280 and 369 kPa caused severe hemorrhaging and large gas-bubble formation, especially in the areas of the heart and associated blood vessels, gills, and the brain.

Hogan (1941) exposed freshwater fishes to the types of vacuum conditions experienced within siphons used to transfer water over levees. The general procedure was to acclimate fish in an aquarium to atmospheric pressures, reduce the pressure to about 17 kPa (2.5 psi) in 15 seconds, hold the fish at the subatmospheric pressure for 10-30 seconds, and allow the pressure to return to atmospheric in 15 seconds. This was believed to simulate the time-pressure history experienced by fish entrained in the siphons. As a general rule, physostomous fish (golden shiners, carp, bullhead catfish, and long-nosed gar) survived the tests better than physoclistous fish (bluegill sunfish, crappie, and largemouth bass). Most physoclists were killed or showed obvious physical distress from these pressure changes; the longer the exposure to subatmospheric pressures, the greater the mortality. On the other hand, none of the physostomes died, although many temporarily lost equilibrium. Hogan (1941) observed minnows and gar discharging air through the pneumatic duct as vacuum was applied. He believed that this explained the relatively greater resistance of the physostomes to subatmospheric pressures.

Turnpenny et al. (1992) tested a variety of marine fishes under pressure regimes likely to be experienced during passage through a low-head tidal power turbine. All fish were acclimated to ambient pressure (ca. 101 kPa), then exposed to one of three pressure series. In the first series, the Protracted Low Pressure Series, test fish were raised to a pressure of 405 kPa (59 psi) in 10 seconds, then decompressed in 0.1 second to pressures ranging from 15 kPa to 101 kPa for 30 seconds. In a second series of tests, the Protracted High Pressure Series, pressures were raised from 101 kPa to as high as 405 kPa in 5 seconds, held at the increased pressure for 15 seconds, then returned to atmospheric pressure. Finally, tests under the Simulated Operating Regime Series were designed to mimic the pressure regime experienced by fish entrained in low-head turbines; surface- (101 kPa) or midwater- (202 kPa) acclimated fish were exposed to pressures as high as 345 kPa (50 psi), decompressed to subatmospheric pressures in a fraction of a second, then quickly returned to near atmospheric conditions; total exposure time to pressure fluxes in this third series was less than 5 seconds.

Atlantic salmon smolts, brown trout, and rainbow trout were generally tolerant to the pressure regimes tested by Turnpenny et al. (1992). No external damage (e.g., popped eyes, superficial hemorrhaging) was observed, and internal damage was restricted to swim bladder rupture among approximately 10 percent of the fish exposed to the most widest range of rapid decompression. Similarly, clupeids (herring and shad) and eels were tolerant of the pressure fluxes. The authors attributed this pressure tolerance to the ability of the physostomous salmonids and clupeids to rapidly vent excess gas from their swim bladders under decompression conditions (and the absence of an inflated swim bladder in the eels). On the other hand, physoclistous fish (e.g., seabass) that were unable to reduce the swim bladder volume quickly suffered high rates of swim bladder rupture and mortality. In separate tests, Turnpenny et al. (1992) estimated that for physoclistous species under sustained decompression, swim bladder rupture occurs at around a doubling of the swim bladder volume (or a halving of the acclimation pressure). Although physostomes were much more resistant of decompression, the most rapid and extreme pressure drops (surface-acclimated salmonids exposed to an equivalent of an eight-fold increase in swim bladder volume in 0.1 second) exceeded the response rate of the venting system and caused rupture of the swim bladder.

Traxler et al. (1993) subjected caged freshwater fishes (largemouth bass, bluegill sunfish, and channel catfish) to underwater explosions. Pressure fluxes resulting from the explosions were low, never exceeding 37 kPa (5.4 psi). No adverse effects on the fishes were observed.

The general conclusion that can be drawn from these studies is that pressure increases of the magnitude found in hydroelectric turbines are unlikely to injure or kill entrained fish. Rapid, brief pressure increases caused little or no direct mortality in a variety of studies using a variety of fish. However, high pressures may alter the behavior of fish such that they may have increased susceptibility to other, non-pressure-related sources of mortality. Some investigators have noted that fish exposed to high pressures were momentarily stunned. Although the test fish fully recovered in the laboratory holding tanks, temporarily stunned fish may be more susceptible to predators in the tailwaters of a hydroelectric dam. Further, in response to increasing pressures fish may actively swim within the turbine to areas that would not be predicted based on modeling of flow fields and neutrally buoyant objects. Harvey (1963) observed an increase in the rate of pectoral fin movements and angle of the body (head upwards) among sockeye salmon in response to pressure increases. Many investigators have observed a tendency for salmonids to swim downwards (sound) in response to increased pressure (Harvey 1963; Muir 1959). This sounding behavior would reinforce the natural tendency of the fish to sink under increased pressures (because the swim bladder becomes compressed). Consequently, actively swimming salmonids may not act like neutrally buoyant objects within the high-pressure region of turbines, but rather may move to regions of the turbine that pose relatively greater or lesser risk. The effects of the combination of increased density, sounding behavior, and other directed and random fish movements on turbine-passage mortality is unknown.

From a direct mortality standpoint, laboratory studies indicate that the brief exposure to subatmospheric pressures within the turbine are more likely to be damaging to fish with swim bladders. Table 1 and Figure 1 display mortalities that have been observed following exposure in the laboratory to rapid and brief pressure reductions. These data were selected using the following criteria: (1) fish had been held at a particular pressure (usually atmospheric pressure) long enough to become acclimated; (2) reduction from acclimation pressure (P_a) to exposure pressure (P_e) was rapid and brief; i.e., no more than a few seconds, in order to simulate the duration of low pressure exposure within a turbine. This second criterion was relaxed somewhat for studies which used physoclistous species. Physoclistous fish do not have a pneumatic duct, so they cannot rapidly vent gases from the expanding swim bladder. Consequently, exposure studies with more gradual pressure reductions (on the order of 10 to 15 seconds) were plotted in Figure 1 for physoclistous species. For example, Hogan (1941) exposed both physoclistous fish (largemouth bass, bluegill sunfish, and crappie) and physostomous fish (minnows, catfish, and gar) to pressure reductions that took 15 seconds to achieve. For physoclistous species that take many minutes to adjust to changing water pressures, this gradual pressure reduction adequately mimics the virtually instantaneous pressure reduction in a turbine. On the other hand, under the assumption that the rate of pressure reduction was sufficiently slow to allow the physostomes to vent expanding gases from the swim bladder, Hogan's tests would not reproduce relevant turbine conditions for physostomes, and these data are not plotted.

Figure 1 plots the percent mortality among test fishes versus the ratio of exposure pressure to acclimation pressure, P_e/P_a (see

Table 1. Mortality of fish exposed to rapid and brief pressure reductions in laboratory test chambers.

Test	Species	Acclimation pressure, P_a (kPa)	Exposure pressure, P_e (kPa)	P_e/P_a	Mortality (%)	Source
1	sockeye salmon	101	67	0.66	0	Harvey (1963)
2	sockeye salmon	343	101	0.29	0.5	Harvey (1963)
3	sockeye salmon	101	67	0.66	2	Harvey (1963)
4	sockeye salmon	205	67	0.33	21	Harvey (1963)
5	perch	303	101	0.33	70	Tsvetkov et al. (1972)
6	largemouth bass	101	101	1.00	0	Feathers and Knable (1983)
7	largemouth bass	191	101	0.53	25	Feathers and Knable (1983)
8	largemouth bass	280	101	0.36	41.7	Feathers and Knable (1983)
9	largemouth bass	369	101	0.27	45.8	Feathers and Knable (1983)
10	bluegill sunfish	101	17	0.17	33	Hogan (1941)
11	bluegill sunfish	101	17	0.17	50	Hogan (1941)
12	crappie	101	41	0.40	100	Hogan (1941)
13	crappie	101	17	0.17	50	Hogan (1941)
14	largemouth bass	101	17	0.17	80	Hogan (1941)
15	largemouth bass	101	17	0.17	100	Hogan (1941)
16	largemouth bass	101	17	0.17	50	Hogan (1941)
17	Atlantic salmon, brown trout, rainbow trout	101	15	0.15	0	Turnpenny et al. (1992)
18	brown trout	343	30	0.09	10	Turnpenny et al. (1992)
19	rainbow trout	343	30	0.09	0	Turnpenny et al. (1992)
20	herring	343	30	0.09	4	Turnpenny et al. (1992)
21	coho salmon	101	7	0.07	0	Muir (1959)
22	coho salmon	101	7	0.07	10	Muir (1959)

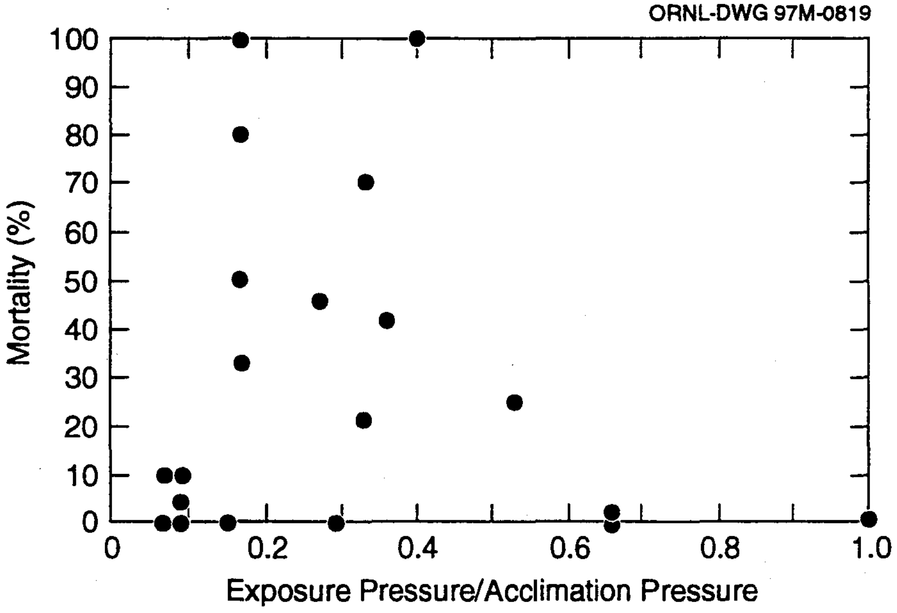


Figure 1. Fish mortalities following exposure in the laboratory to brief and rapid pressure reductions. See text and Table 1 for description of studies.

Table 1 for data). P_e/P_a is an indication of the severity of pressure reduction - the lower the value of the ratio, the greater the reduction in water pressure from that to which the test fish were acclimated. Many of these studies are old, poorly documented, have inadequate or no controls, and used only small numbers of fish. Not surprisingly, Figure 1 indicates that there is considerable variation in the response of fish to pressure reductions. However, the highest mortalities occurred when the pressure reduction was greatest, i.e., when the exposure pressure was a relatively small proportion of the acclimation pressure. There are few data above a P_e/P_a ratio of 0.40, but the three tests in which exposure pressure was greater than 60 percent of the acclimation pressure (P_e/P_a ratio > 0.60) resulted in little or no mortality. Below a P_e/P_a of 0.40 the highest mortalities were recorded among physoclistous fish (bass, bluegill, crappie, perch); this is consistent with the observations of Jones (1951) that a 60 percent reduction in pressure (P_e/P_a = 0.40) burst the swim bladders of perch. The higher survival of physostomes may indicate that these fish have greater resistance to swim bladder expansion and/or some ability to vent swim bladder gases even under conditions of very rapid pressure reductions. These sparse data indicate that pressures within the turbine should fall to no less than 60 percent of the value to which entrained fish are acclimated. For surface-oriented fish, a pressure of 60 kPa (8.8 psi) or greater at all points within the turbine and draft tube would be expected to protect most fish from direct mortality of low pressures.

Based on a consideration of salmonid data in USACE (1991), ARL (1996) suggested that minimum pressures within the turbine be no less than 30 percent of the fish's initial acclimation pressure. For fish distributed within the top 34 feet of water, this would dictate a minimum pressure of about 10 psi (69 kPa). This suggested minimum pressure criterion (30 percent of acclimation) is less restrictive than the "60 percent of acclimation" criterion suggested above. Whereas it may protect deep-adapted salmonids (and other physostomes) that are able to vent some of the expanding gases in the swimbladder as they are drawn upwards toward the intake, the 30 percent criterion may not be sufficient to protect other species of physoclistous fish.

2.2 Cavitation Effects

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 1983a; Rodrigue 1986). These pressure waves decrease rapidly from the center of collapse, but nearby fish could be injured.

Muir (1959) simulated cavitation effects in a laboratory device. Brief exposure of 1.5- to 4-inch-long coho fingerlings to hydrostatic pressures equal to the vapor pressure of water caused no mortality. However, in other tests fish were rapidly decompressed to vapor pressure for 0.4 seconds, then returned instantaneously to atmospheric pressure. The vapor pocket that had formed in the test chamber collapsed, resulting in the death of 12 of the 20 test salmon (60 percent mortality). 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 collapse of the cavitation bubble that caused the observed mortality. Hubbs and Rechnitzer (1952) also reported on the lethality of instantaneous shock waves (in this case caused by underwater explosions) to caged marine fishes. Less abrupt pressure waves of equal or greater magnitude caused no mortality.

The nature of cavitation bubble collapse and its likely effects on turbine-passed fish was discussed by Turnpenny et al. (1992). They pointed out that a bubble collapsing in midwater, away from any surface, will have the viscous forces resisting collapse distributed symmetrically around the bubble and therefore will tend to collapse symmetrically; the resultant shock wave will emanate more or less spherically from the point of collapse. On the other hand, a bubble collapsing near a surface (e.g., turbine blade, wall, fish's body) will not have the viscous forces distributed symmetrically. Collapse near a rigid surface will pull in water preferentially from the side away from the surface (distal side), causing the bubble to flatten out and collapse toward the surface (proximal direction), sometimes accompanied by the formation of a high-velocity microjet. Conversely, cavitation bubble collapse near an elastomeric (flexible) surface or a free-surface (e.g., air-water interface) will tend to be in the distal direction, moving away from the surface.

Turnpenny et al. (1992) recognized the importance of determining whether a fish acts as a rigid surface or an elastomeric surface in assessing the risk of damage from cavitation. They developed a laboratory apparatus that enabled them to create a cavitation bubble, photograph the bubble's collapse, and observe the effects of bubble implosion on fish tissue. A series of tests with brass plates as controls supported the idea that cavitation bubbles generated near a rigid surface would collapse asymmetrically, with the implosion being directed towards the metal plate. Subsequent tests with recently killed fish led to similar results - bubble collapse was asymmetrical and directed toward the surface of the fish in 33 of 35 (94 percent) of the exposures. However, no evidence of tissue damage was found on any fish as a result of the bubble implosions. This limited set of tests did not examine mortality and did not quantify the forces associated with cavitation bubble collapse. Turnpenny et al. (1992) pointed out that although their bubble collapse experiments did not cause any apparent tissue damage, fish are not safe from cavitation damage during turbine passage because the energy levels in a turbine may be vastly higher. They assumed that cavitation that can damage turbo-machinery can also damage fish, and that the closer fish passes to a vapor cavity the greater the probability of injury.

As noted in the section on pressure effects, decompression can be harmful to turbine-passed fish even if water pressures do not drop below vapor pressure. If turbines are designed and operated so that water pressures do not drop below 60 percent of ambient pressure anywhere in the turbine, cavitation will not occur and there will be no injury to fish (or damage to turbomachinery) from the collapse of cavitation bubbles. If cavitation cannot be eliminated entirely, another mitigation alternative is to introduce air into the turbine to reduce the effects of cavitation on noise, vibration, and damage to fish and machinery (Daily 1986; Hamilton 1983b, 1984). Entrained air can ameliorate the shock waves created by cavitation because (1) any air present in the vapor cavities will cushion the cavity collapse and reduce the resulting water hammer pressure, and (2) the presence of air bubbles will reduce the speed of the shock wave, and hence the magnitude of the shock waves on a surface (Chanson 1989). Turbine designs that introduce air or oxygen bubbles into the flow for tailwater aeration could have the additional benefit of mitigating some of the fish mortality resulting from cavitation.

2.3 Shear Stress Effects

Shear stress, like pressure, is 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). Shear stress has the same units as pressure, N/m^2. In this report, studies of shear stress have been expressed wherever possible as N/m^2 and kPa, where one kPa equals 1,000 N/m^2.

Groves (1972) exposed juvenile salmon (total lengths ranging from 3.5 to 13.5 cm) to a water jet submerged in a tank of static water. In his experimental protocol the jet was brought to full speed [mean calculated velocities ranged from 9 to 37 m/s (30 to 120 ft/s)] and the fish were immediately introduced to the tank near the nozzle. Each test lasted only for the time needed to introduce the fish, usually less than a second. Thus, exposure to shear in this experiment was a brief, one-time exposure to high velocity water at the edge of the jet. The actual velocities and shear stresses experienced by fish were not measured. Some of the tests included high speed photography to track the fishes' movements, and all tests examined the resultant types of injuries and mortality.

Juvenile salmon were unaffected by exposure to the lowest velocity jet tested, 9 m/s (30 ft/s). As jet velocities increased the rates of disorientation, visible injury, and mortality also increased (Groves 1972). Fish disabled (disoriented) but without visible injury usually regained normal capacities in 5 to 30 minutes. Visible injuries were mostly in the head region and included bulged or missing eyes, broken and ripped gill covers, and torn gills. Whereas visible injuries and mortalities were zero at 9 m/s, velocities of 15 m/s (50 ft/s) caused injuries in 2 to 59 percent of the fish in the test batches (Tables 2 to 4). At any given jet velocity, injury rates were inversely related to the size of the fish, i.e., 3-cm salmon were more often injured than 13-cm-long salmon.

Injury from the water jet was related to the part of the fish contacted and to the position of the fish relative to the jet flow direction at the time of contact (Groves 1972). Greatest injuries occurred when the jet contacted the head region and was moving from the rear towards the head of the fish. Larger fish were less affected if the jet initially contacted some other portion of the body than the head, or if the fish was facing into the jet stream. On the other hand, smaller fish were damaged irrespective of their orientation. Groves attributed this size-related difference in injury rates to the proportion of the fish's surface area struck by the jet. The jet struck a relatively larger portion of a small salmon's body, and at the higher velocities some were literally torn apart. Larger fish had a proportionately small portion of their bodies contacted by the margin of the jet, so injuries tended to be more frequent when initial contact was with more protruding or less rigidly attached parts of their head region, such as the gill structures and eyes.

Morgan et al. (1976) used rotating concentric cylinders to create shear zones in 30.5-cm-diameter chambers. Striped bass and white perch eggs and larvae were introduced into the layer of water between the cylinders, and consequently exposed to calculated shear forces ranging from 76 to 404 dynes/cm^2 (7.6 to 40.4 N/m^2; 0.0076 to 0.040 kPa) for periods of 1 to 20 minutes. Both eggs and larvae were sensitive to these low levels of shear. For example, shear forces of 350 dynes/cm^2 (35 N/m^2 ; 0.035 kPa) killed an average of 38 percent of the white perch larvae in 1 minute, 52 percent in 2 minutes, and 75 percent in 4 minutes. The authors developed a set of regression equations which related the amount of shear to expected mortality among these fish early life stages.

McEwen and Scobie (1992) estimated that shear forces within a reference turbine could average over 500 N/m^2 (0.5 kPa); maximum values were estimated to be 3,740 and 5,421

Table 2. Effects of exposure of juvenile coho salmon to the margins of water jets moving at various calculated velocities. Fish ranged from 8.5 to 11 cm in size (mean = 10 cm). Test series 1 from Groves (1972).

Jet velocity, fps	Number of fish	Percent disoriented, injured, and/or killed	Percent visibly injured	Percent dead after 48 hours
30	50	0	0	0
50	50	18	8	2
70	50	42	28	8
90	50	56	24	16
100	50	62	20	22
120	50	74	14	32

Table 3. Influence of juvenile salmon size on the effects of water jets moving at various calculated velocities. Test series 2 from Groves (1972).

Jet velocity, fps	3 to 6 cm long			9 to 13 cm long		
	Number of tests	Number of fish	Percent injured	Number of tests	Number of fish	Percent injured
30	1	10	0	6	27	0
50	4	32	59	7	31	16
70	1	5	100	7	34	38

Table 4. Influence of juvenile salmon size on the effects of water jets moving at various calculated velocities. Test series 3 from Groves (1972).

Jet velocity, fps	3.5 to 5 cm long			6 to 8 cm long			9.5 to 13.5 cm long		
	No. of tests	No. of fish	Percent injured	No. of tests	No. of fish	Percent injured	No. of tests	No. of fish	Percent injured
30	3	75	0	6	50	0	10	50	0
50	3	75	37	13	174	26	15	75	9
70	7	164	52	31	201	35	14	100	29

N/m^2 (3.7 and 5.4 kPa) for "on-design" and "off-design" conditions, respectively. On the basis of these calculations, Turnpenny et al. (1992) designed a laboratory apparatus that could expose fish to localized shear forces of this magnitude. They introduced fish into a high-velocity water jet submerged in a tank of static water, then examined the fish for injuries and long-term mortality. Jet velocities tested ranged from 5 to over 21 m/s (16 to 69 ft/s), resulting in maximum shear stresses ranging from 206 to 3410 N/m^2 (0.2 to 3.4 kPa).

Salmonids (Atlantic salmon, rainbow trout, and brown trout) tested at the lowest shear stresses (maximum values of 206 and 774 N/m^2) experienced little scale loss, no loss of mucous coating, no other apparent injuries, and no mortality up to 7 days after the single exposure (Table 5). Greater jet velocities and shear stresses resulted in more injuries and lower long-term survival (Turnpenny et al. 1992). For example, at the highest shear stresses tested (maximum value near the jet of 3410 N/m^2), localized loss of mucous cover and some eye damage (corneal rupture; pop-eye; hemorrhaging in the eye) was noted; survival was around 90 percent 7 days after the test. Fish that died after exposure to the higher shear stress levels were heavily coated with fungus, probably because the loss of mucous increased their susceptibility to fungal infections.

Clupeids (shad, herring) were much more susceptible to shear stresses in the experiments of Turnpenny et al. (1992). All fish tested in the apparatus, even at the lowest maximum shear stress of 206 N/m^2 (0.2 kPa), died within 1 hour (Table 5). Many clupeids suffered eye damage, eye loss, torn and bleeding gills, and substantial loss of scales and mucous layer. At the other end of the scale, eels suffered no evident damage, other than some loss of mucous coating, and no 7-day mortality even at the highest shear stress levels tested.

Turnpenny et al. (1992) observed visible creases on the body surfaces of some fish entrained in the turbulent jet, which led to crushing of internal organs and internal hemorrhaging. Eye damage (corneal rupture, pop-eye, or red-eye) or eye removal were also common injuries among the fish exposed to these localized shear forces. Finally, osmotic imbalance caused by loss of much of the mucous layer and underlying scales is believed to be the reason for the sensitivity of clupeids to even low levels of shear. Eels, which have substantial mucous layers, were not injured by high shear forces.

Turnpenny et al. (1992) noted that their experimental apparatus demonstrated the effects of contact of part of the fish's body with a small zone of high shear stress, i.e., small-scale effects. Groves' (1972) experiments were also similarly limited. Larger-scale effects of shear and turbulence, in which the entire fish is additionally subjected to forces of elongation, compression, and torsion, were not adequately modelled in their studies. Although Morgan et al. (1976) only examined sensitive fish eggs and larvae, the experimental protocol enabled them to take into account the mortality caused by these other, larger-scale effects, i.e., the rotational and deformational components of shear that impact the entire animal. At some level these additional stresses might also cause physical damage to fish, while lower, non-injurious levels of rotation and deformation would be expected to disorient the fish, such that it would be hindered in its ability to escape predators in the tailrace.

Table 5. Effects of exposure of various fish to the margins of water jets moving at different velocities. Modified from Turnpenny et al. 1992.

Species	Jet velocity (m/s)	Maximum shear stress (N/m^2)	Age Group	Survival at 7 days (%)	Mean scale loss (% per fish)	Eye damage (% of fish)	Gill damage (% of fish)
Atlantic salmon (*Salmo salar*)	0	0	2	96	5.8	0	0
	5.4	206	2	100	5.7	0	0
	10.4	774	2	100	4.4	0	0
	16.4	1920	2	92	8.0	28	0
	>20.9	3410	2	88	4.6	32	0
Rainbow trout (*Onchorhynchus mykiss*)	0	0	1	-	3.3	0	0
	16.4	1920	1	-	3.8	0	-
	>20.9	3410	1	-	5.0	0.3	2.0
Brown trout (*Salmo trutta*)	0	0	1/2	100	0	0	0
	10.4	774	1/2	100	0	0	0
	16.4	1920	1/2	80	5	10	0
	>20.9	3410	1/2	90	5	10	10
Atlantic herring (*Clupea harengus)*	0	0	0	100	5.0	18	0
	5.4	206	0	0	8.2	30	0
	10.4	774	0	0	24	60	0
	16.4	1920	0	0	58	60	40
	>20.9	3410	0	0	90	60	20
Twaite shad (*Alosa fallax*)	0	0	0	100	5.0	0	0
	>20.9	3410	0	0	90	40	20
Eel (*Anguilla anguilla*)	0	0	-	100	-	0	0
	5.4	206	-	100	-	0	0
	10.4	774	-	100	-	0	0
	16.4	1920	-	100	-	0	0
	>20.9	3410	-	100	-	0	0

The Groves (1972) and Turnpenny et al. (1992) high-velocity water jet studies noted size- and species-specific differences in sensitivity to brief exposure to shear stresses. Groves pointed out that smaller salmon (ca 3 cm long) suffered greater injury and mortality rates than larger salmon (up to 13.5 cm long), probably because of lesser tissue strength and exposure of a greater proportion of the body to initial contact with the jet. Turnpenny et al. observed little effect among eels (which may be resistant to shear because of their substantial mucous coating) and high sensitivity among clupeids (whose mucous coating and scales were readily lost). Salmon and trout appeared to be intermediate in their sensitivity to the shear created by the high-velocity jet.

2.4 Turbulence Effects

Turbulent flow occurs when fluid particles move in a highly irregular manner, even if the fluid as a whole is traveling in a single direction. That is, there are intense, small-scale motions present in directions other than that of the main, large-scale flow (Vogel 1981). Unlike laminar flow, which can be described by a linear equation, turbulent flow can only be defined statistically (Gordon et al. 1992); descriptions of the overall motion within turbulent flows cannot be taken as describing the paths of individual particles. Turbulence exists at all scales in nature, from the swirling motion created when a salmon scoops out a redd (scales smaller than the size of the fish) to large whirlpools in a river (scales much larger than a fish). Similarly, within a hydropower turbine turbulence occurs at different scales. Smaller-scale turbulence, which occurs throughout turbine passage, can distort and compress portions of the fish's body. Large-scale turbulence, which may be most pronounced in the draft tube, creates vortices (swirl) which spin the fish and may cause disorientation. It is believed that this turbulence-caused disorientation, while perhaps not injuring the fish directly, may leave turbine-passed fish more susceptible to predators in the tailrace.

The effects of turbulence on survival of paddlefish yolk-sac larvae was examined in the laboratory by Killgore et al. (1987). Paddlefish larvae were placed in circular containers and exposed to differing frequencies and intensities of turbulence created by water jets. Turbulence in the laboratory chambers was expressed in terms of both water velocities (cm/s) and pressures (dynes/cm^2). The investigators found that turbulence intensity was more lethal than frequency of disturbance. Low turbulence (1,774-1,902 dynes/cm^2; 21.5-22.8 cm/s) caused 3 and 13 percent short-term mortality, whereas high turbulence (6,219-6,421 dynes/cm^2; 56.5-59.3 cm/s) resulted in 87 and 80 percent short-term mortality. Longer-term direct mortality, indirect mortality, and physiological stress were not examined. Based on these laboratory studies and field measurements of pressures near commercial barges (which sometimes exceeded 50,000 dynes/cm^2 near the propellers), Killgore et al. (1987) suggested that turbulence generated in the immediate vicinity of commercial vessels could cause mortality among paddlefish larvae.

2.5 Mechanical Effects (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. This mechanism is called *strike*. The probability of a fish being injured or killed by mechanical 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, revolution rate, 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 (gaps) between structures in the turbine passageway (USACE 1995). Within Kaplan turbines, the smallest clearances are gaps between adjustable turbine blades and the hub, between blade tips and the discharge ring, and between the top and bottom of the wicket gate seal plates when gates are set at higher openings. 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.

Turnpenny et al. (1992) noted that theoretically the probability of strike can be estimated from information on water velocity through the turbine, blade and guide vane angle, blade rotational speed, and fish lengths; these ideas have been explored by von Raben (1957), Montén (1985) and Solomon (1988). However, Solomon (1988, as cited in Turnpenny et al. 1992) pointed out that this probabilistic approach to estimating strike relies on several assumptions, including:

(a) the distribution of fish is either random or can be specified (this assumption is important because the probability of injury is higher towards the runner tip due to higher collision velocity);

(b) the fish enter the turbines randomly with respect to time, or else according to a specifiable temporal pattern;

(c) the fish either move passively through the turbine or attempt to resist entry by swimming at a known rate (active swimming against the flow of water reduces the rate of passage and thereby increases the risk of the fish being caught by the blade sweep; alternatively actively burst swimming at an angle to the flow could carry the fish into or out of regions of high strike probability);

(d) the fish are aligned randomly or else are aligned along the streamlines (this affects their effective length relative to the probability of striking a moving blade); and

(e) the consequences of strike are the same, irrespective of where or with what force the fish is struck.

Most of these simplifying assumptions are difficult to prove (or specify reliably) in a general sense because they may vary based on site- and species-specific conditions. In addition, some of these factors are greatly affected by the behavior of individual fish; one fish may pass through the turbine like a rigid, immobile, neutrally buoyant object aligned with the stream flow, whereas the next fish (of the same species and size, and entering the intake at the same location) may elect to change positions near the runner blade by active swimming movements. Consequently, estimates of the probabilities of strike and strike-related injury/mortality may have wide confidence boundaries because of the often unpredictable behavior of individual fish.

Recognizing that most of the assumptions listed above are site- and species-specific, Turnpenny et al. (1992) concentrated on investigating in the laboratory the process of approach and collision between fish and various blade profiles. In addition, they attempted to establish how fish size, orientation, and position relative to the blade influence injury and mortality. Their laboratory apparatus consisted of a portion of a turbine blade attached to a set of rails within a glass viewing tank. By means of springs, the blade section could be moved rapidly along the rails in order to strike a test fish positioned in the tank. Four blade tip profiles were used (Figure 2), ranging from blunt (near the hub) to narrow (near the blade tip). The blade section struck the test fish at a velocity of around 5-7 m/s, which was comparable to the calculated collision velocity near the hub of a full-sized turbine. The experimental apparatus was unable to reproduce the estimated peripheral runner collision velocity of around 20 m/s. Strike experiments included estimation of survival, investigation of the effects of the "bow wave" from the blade pushing fish to one side or another, and the effects of fish length, mass, and orientation on strike probabilities.

At a collision velocity of 5.2 m/s and a wide (hub) blade profile, little damage and no mortality was observed among brown trout, sea bass, or eel (Turnpenny et al. 1992). This experiment reproduced the expected conditions associated with a fish striking a turbine blade near the hub. On the other hand, strikes from the three narrower blade profiles, even at relatively low velocities of 6.9-7.1 m/s, caused severe damage to test fish in most cases. Principal symptoms were scale and mucous loss, bruising, eye damage, and internal bleeding. Some fish had broken spinal columns or deep grooves left by the blade impact.

In tests with freshly killed fish, Turnpenny et al. (1992) noted that mass and center of gravity (orientation) relative to the blade had important influences on the probability of strike. In general terms, water approaching the turbine blade divides and moves laterally to pass around the blade. Small objects suspended in the water (e.g., small fish and plankton) are often swept around the blade with the water flow and do not collide with the leading edge. However, larger fish, because of their inertia, tend not to follow the streamlines along the blade but rather follow their original trajectory. Whether or not a large fish collides with the leading edge of the blade depends upon the balance between sideways drag of the water and the inertia of the fish. The investigators found that small fish (<20 g) were generally swept aside by the water moving around the blade unless their center of gravity fell within the direct path of the blade. Even then only a small percentage of small fish (13.7%) were struck. Heavier fish had a greater probability of collision owing to the inertial effect. Fish with a body mass of up to 200 g had a 75% change of being struck when the center of gravity fell within the path of the blade, and heavier fish had a 100% chance. As a large fish's center of gravity was increasingly offset from the blade centerline, flexibility and tendency to follow the streamlines reduced the chance of a strike. For example, if a large fish was offset from the blade centerline by 0.4 body length the probability of collisions dropped to near zero.

Turnpenny et al. (1992) used these experimental observations to develop equations that were used to calculate the

ORNL-DWG 97M-0820

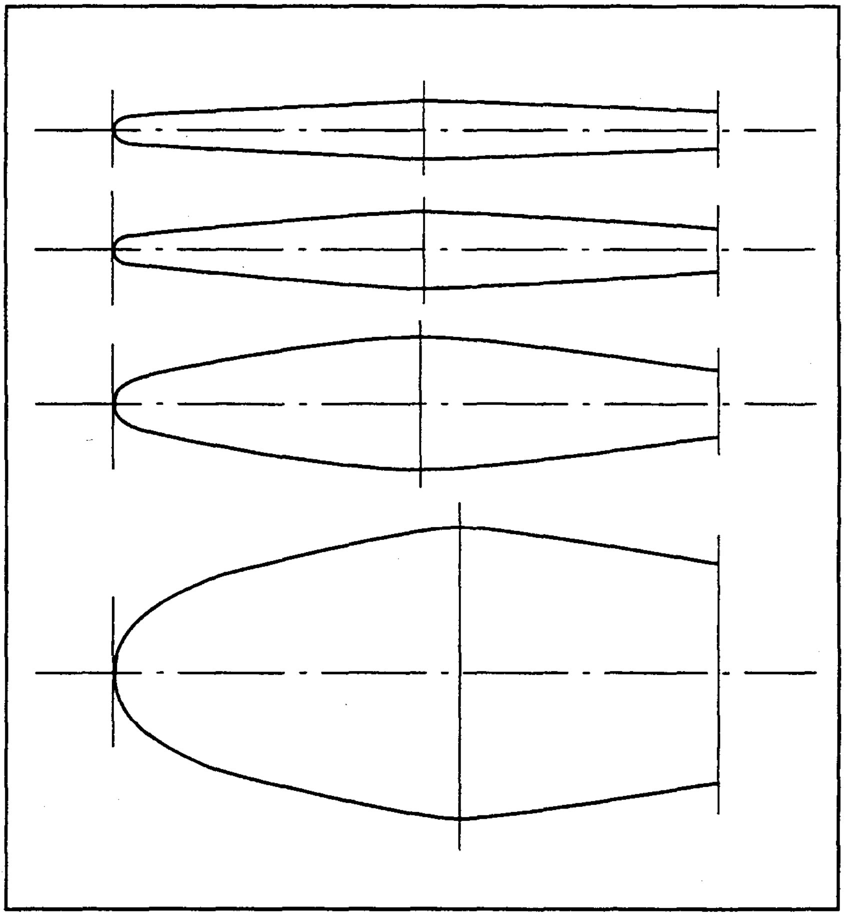


Figure 2. Four blade tip profiles used for strike experiments of Turnpenny et al. (1992). Top profile represents the blade leading edge near the tip; bottom profile represents the blade leading edge near the hub.

probability of blade strike for a low-head, axial flow tidal power turbine and a variety of fish weights and lengths. The equations take into account the effects of fish length, fish location, fish orientation, fish swimming speed, water velocity, open space between blades, blade thickness, and blade speed. Separate probabilities were calculated for fish oriented randomly with the flow, fish aligned with the flow but not swimming, and fish aligned with the flow and swimming against the flow at 6.5 body lengths/s (which increases the exposure time and thus the chance of blade strike). Estimated strike probabilities for this turbine ranged from as little as 0.32% for small fish to as much as 86% for large fish (Table 6).

A recent turbine passage survival workshop (USACE 1995) noted that turbine designers have a number of options that can affect the incidence of strike, including altering the number of blades, length of blades, area per blade channel, thickness and bluntness of blade entrance edges, and blade tilt. Optimizing these factors for fish passage survival may have power production consequences. Blade speed can also have an important influence of probability of strike, and is a factor in the strike probability equations developed by von Raben (1957), Montén (1985) and USACE (1991). Based on a plot of fish mortality vs. tip speed (peripheral runner velocity) in Francis turbines (EPRI 1987), ARL (1996) suggested that peripheral runner velocities of 40 ft/s or less would have a low potential for causing strike-related mortality.

There are no data to assess the relative importance of grinding as a contributor to mechanical injuries in hydropower turbines. Participants in the USACE (1995) workshop felt that grinding injuries could occur among fish entrained in water leaking through gaps between the turbine blade leading edge and the hub, the blade tips and the throat ring, the wicket gates and stay vanes, and the wicket gates and distributor ring. ARL (1996) suggested that grinding injuries could be prevented by limiting clearances between rotating and stationary turbine components to no greater than 2 mm. Limiting clearances to this small size would preclude all but the smallest fish from passing through gaps. The suppositions of the USACE (1995) workshop participants and ARL (1996) about the potential effects of gaps on turbine-passage injuries are reasonable. However, because this issue has not been adequately studied there is presently no basis in the literature to support the need for such narrow clearances or, indeed, whether reductions in gaps will significantly reduce turbine passage mortality.

2.6 Conclusions and Recommendations

2.6.1 Biological Criteria for New Turbine Designs

A review of the literature related to typical turbine-passage injury mechanisms suggests the following biological criteria should be considered in the design of new turbines:

Pressure

Pressure **increases** of the magnitude found in 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. One possible area of concern regarding pressure increases is the resultant increase in density of the fish. Rapid pressure increases will compress the swim bladder, making the fish more dense and causing it to sink. This would change the flow path of fish

Table 6. Calculated probabilities (expressed as percentages) that fish of various lengths and weights will be injured by blade strike in a low-head, axial flow tidal power turbine. Probabilities do not include collision with the widest blade profile near the hub. Modified from Turnpenny et al. (1992).

Fish weight (g)	Fish standard length (mm)	Random orientation of fish				Fish aligned with flow, not swimming				Fish aligned with flow, swimming against flow at 6.5 body lengths/s			
		3 m head, 382 m^3/s	5 m head, 507 m^3/s	6 m head, 739 m^3/s	8 m head, 554 m^3/s	3 m head, 382 m^3/s	5 m head, 507 m^3/s	6 m head, 739 m^3/s	8 m head, 554 m^3/s	3 m head, 382 m^3/s	5 m head, 507 m^3/s	6 m head, 739 m^3/s	8 m head, 554 m^3/s
<20	25	0.57	0.45	0.32	0.41	0.86	0.66	0.47	0.61	0.88	0.67	0.48	0.62
	50	1.1	0.83	0.59	0.76	1.7	1.3	0.89	1.2	1.7	1.3	0.91	1.2
	75	1.6	1.2	0.85	1.1	2.5	1.9	1.3	1.7	2.7	2.0	1.4	1.8
	100	2.1	1.5	1.0	1.4	3.3	2.5	1.7	2.3	3.6	2.7	1.8	2.4
20 to 200	100	2.1	1.5	1.0	1.4	3.4	2.6	1.8	2.4	3.7	2.8	1.9	2.6
	150	2.8	2.0	1.3	1.8	4.9	3.7	2.6	3.4	5.7	4.2	2.8	3.8
	200	3.6	2.6	1.6	2.3	6.4	4.8	3.3	4.4	8.0	5.7	3.7	5.1
	250	4.4	3.1	1.9	2.8	7.9	5.9	4.1	5.4	11	7.3	4.7	6.6
>200	250	4.8	3.6	2.4	2.9	8.0	6.2	4.4	5.7	11	7.5	5.0	6.7
	500	8.7	6.3	4.0	5.7	15	12	7.9	11	30	18	11	16
	750	13	9.0	5.6	10	22	17	11	15	86	38	19	32
	1000	17	12	7.2	13	30	22	15	20	1857?	86	31	64

within a turbine compared to a neutrally buoyant object. Within limits the fish can counteract this tendency to sink by active swimming, but it is not known whether a fish would do this within a turbine environment.

Pressure **decreases** within the turbine are a greater concern. The problem is not so much a matter of the lowest pressure experienced by fish in the turbine as it is 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, a fish acclimated to deep water (300 kPa) will experience a relatively large pressure decrease passing through the same region of the turbine. Because the decrease is virtually instantaneous, all fish with swim bladders (even physostomous fish with pneumatic ducts) will be unable to vent gas from the rapidly expanding swim bladder. The swim bladder may distend or rupture, causing direct 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 effects of low pressures. As with compression, sublethal decompression may momentarily stun the entrained fish or otherwise alter its behavior so that its susceptibility to predation in the tailwaters could be changed.

Cavitation

Turbine designs that minimize pressure reductions to no greater than 60 percent of ambient (see above) 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 and areal extent of cavitation and the likelihood that fish will pass near enough to be affected by the pressure waves and/or high-velocity microjet. Presently, there is insufficient information in the literature to predict how close to areas of cavitation bubble collapse fish can pass without injury.

Shear

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 in 1 minute, 52 percent in 2 minutes, and 75 percent in 4 minutes. Striped bass larvae were nearly as sensitive.

Other, larger-scale effects of shear 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 physiologically stressed and disoriented by shear and turbulence and may suffer greater indirect mortality (predation) below the turbine discharge.

Strike

Because of numerous variables related to the entrained fish (e.g., individual size, condition, and behavior) and the relationship of the fish to the runner and other turbine structures (e.g., region of passage, orientation, and relative velocity), the probability of injury from strike and grinding 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. Note, however, that recent studies at Wanapum Dam suggest that greater turbulence and cavitation near the hub, as well as the possibility of grinding injuries in the blade-hub gaps, may lower survival of fish that pass through the turbine near the hub;

- Gaps between fixed and moving parts of the turbine should be minimized to reduce injury and mortality due to the mechanism of grinding.

2.6.2 Relative Importance of Turbine-Passage Injury Mechanisms

The relative importance of these mechanisms will depend on the species, size, and life stage of entrained organisms. For example, Dadswell and Rulifson (1994) published a hypothetical distribution of mortality mechanisms among marine animals passing through low-head hydropower turbines (Figure 3). In their conceptualization, mortality resulting from mechanical strike increased with increasing length of the entrained animal, being very low among 2-cm-long juveniles and approaching 100 percent in animals 2 m long or greater. Shear-related mortality is relatively low for all sizes of animals; it is highest among 20-cm-long juveniles and less damaging to smaller and larger fish. They hypothesized that mortalities from cavitation were constant over a wide size range, but that pressure effects were greatest among the smallest organisms and declined precipitously with size.

Many of the trends in Dadswell and Rulifson's (1994) hypothetical distribution are reasonable, based on the present review of literature. Certainly, the probabilities (and consequences) of mechanical strike will increase with increasing fish size. Also, cavitation can cause point-source injuries (from the microjet) or shock wave-caused mortality that would likely affect a wide size range of fish equally. For most turbines, cavitation occurs in a limited area, and therefore cavitation-caused mortality should also occur among a limited proportion of entrained fish.

There is less support from laboratory and other controlled studies for the shear and pressure trends shown in Figure 3. Shear has been shown to have a significant species-specific component unrelated to length; for example, eels with thick layers of mucous are much more resistant to shear forces than shad. Relatively low levels of shear and turbulence can be very damaging to fish eggs and larvae. Definitive studies of the effects of shear stresses and turbulence on fish are needed, but the few studies that have been conducted indicate that, for a particular species, mortality due to shear may be similar to the pressure line in Figure 3, i.e., high mortality among smaller, more fragile life stages and decreasing mortality with increasing size.

The present review of literature indicates that mortality resulting from the pressure-related component of turbine passage may be lowest among the smallest fish and increase to a relatively constant level in medium and large-sized fish. Fish of all sizes appear to be resistant to rapid and large pressure increases. Rapid pressure decreases, on the other hand, can be damaging, and the extent of the damage appears to be related to the tolerance of the fish to the rapid swim bladder inflation that occurs at lowered pressures. Fish larvae, early juveniles, and some species of adult fish (e.g., sculpins) do not have developed swim bladders, and these fish appear to have resistance to lowered pressures as well. Most fish have developed swim bladders at a length of a few centimeters; these fish could experience burst swimbladders in the areas of subatmospheric pressure downstream of the turbine blade. It is possible that physostomous fish (that can vent expanding gases from the swim bladder through the pneumatic duct) and physoclistous fish (that cannot vent gases) may have different sensitivities. However, the pressure drops occur so rapidly in a turbine that it is unlikely that physostomous fish can completely accommodate the changes.

Adverse water quality may also 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

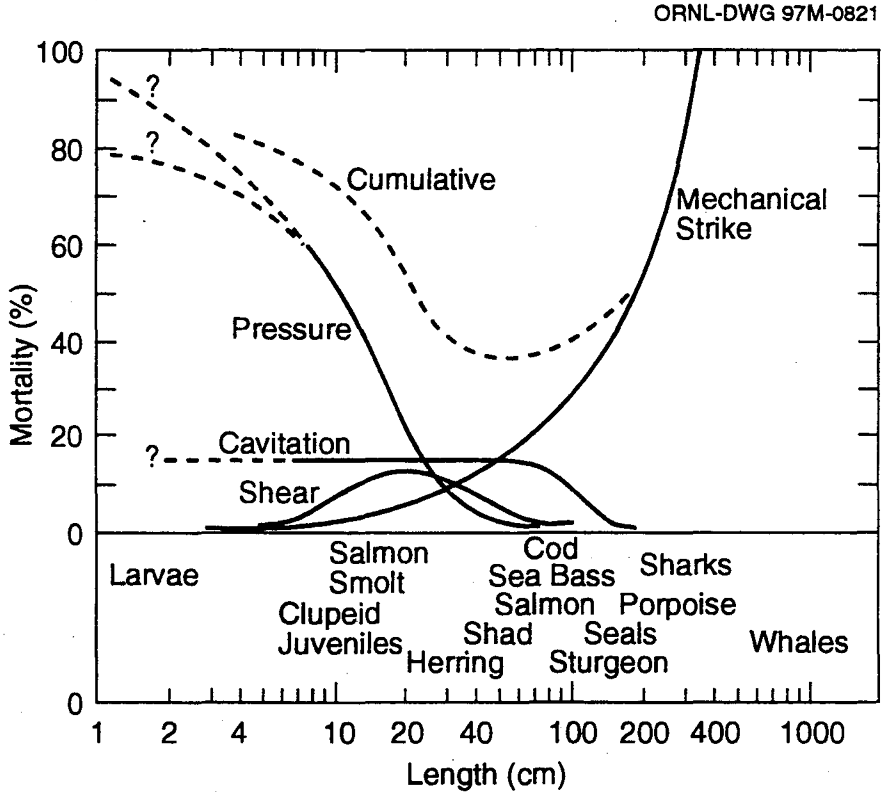


Figure 3. Hypothetical distribution of mortality and its causes from passage through hydraulic, low-head turbines in relation to body length of aquatic organisms. From Dadswell and Rulifson (1994).

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. Adverse 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 well known in the toxicology literature, but they have not been widely studied for the types of stresses considered in this report. Laboratory studies conducted by Čada et al. (1980) suggested that combined effects of thermal shock, shear, pressure changes, and pump passage had synergistic effects for some freshwater fish species. Multiple disturbances (handling stresses) have been shown to have a significant cumulative effect on physiological stress responses in juvenile chinook salmon (Barton et al. 1986), which in turn may result in increased losses to predation (Mesa 1994). Uncertainties about the possible cumulative effects of multiple stresses were discussed in USACE (1995).

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. Figure 3 could be revised to include additional, indirect mortality. However, the revised figure could conceivably look several ways: (1) identical to Figure 3 because indirect mortality is insignificant; (2) all lines depict 100 percent mortality at all fish lengths because the eventual mortality among turbine-passed fish from predation and disease is complete; or (3) some intermediate condition. Some attempts have been made to examine long-term mortality among turbine-passed fish. For example, Ferguson (1991) investigated long-term survival by comparing the numbers of turbine-passed juvenile salmon with subsequent adult returns. Further investigations of this type would be useful to ensure that reductions in direct mortality due to turbine design changes are not nullified by high levels of indirect mortality.

2.6.3 Need for Additional Studies

The disparities between the hypothetical mortality distributions of Dadswell and Rulifson (1994) and the distributions that could be drawn based on the studies reviewed in this report may be due in part to differences in turbine design. Different turbine designs will have different pressure regimes, shear regimes, and probabilities of strike. However, some of the disagreement about probable causes of mortality is due to the lack of reliable information about the importance of each of injury mechanisms associated with hydropower turbine passage. Most turbine-passage studies to date have been carried out at operating hydropower sites (see EPRI 1987). While these studies are necessary to estimate overall mortality associated with turbine passage for those particular sites and species, they are not very useful for determining the relative importance of the different injury mechanisms. Most field studies that have attempted to partition the observed injuries among the possible mechanisms have been frustrated by the fact that different stresses can cause the same injuries (USACE 1995; Voith Hydro 1996; ARL 1996). Turnpenny et al. (1992) summarized a series of single-mechanism laboratory studies (Table 7) and noted considerable overlap in injury symptoms. They found for example, that eye hemorrhaging can be caused by both pressure changes and shear forces, whereas scale and mucous loss can be caused by both shear and blade strike. Because of the overlap in injury symptoms, reliable biological criteria for the turbine designers will need to be based on controlled laboratory or field studies in which each injury mechanism is examined separately.

Table 7. Summary of primary injuries to fish observed in laboratory studies by Turnpenny et al. (1992) of pressure, shear, and blade strike.

Cause/symptom	Pressure	Shear	Blade strike
Ruptured swimbladder	yes	no	no
Eye hemorrhaging	yes	yes	no
Corneal rupture/eye loss	no	yes	yes
Scale loss	no	yes	yes
Mucous loss	no	yes	yes
Internal hemorrhaging	no	yes	yes
Egg loss	yes	no	no
Gill/operculum damage	no	yes	no

Among the injury mechanisms considered in this report, the effects of water pressure on fish seem to be the best understood. 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 deal with 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, or 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 are known to disorient the fish so that they may have increased susceptibility to predators.

3. Laboratory and Field Techniques for the Study of Injury Mechanisms Associated with Turbine Passage

Biological criteria can be developed through the use of both laboratory studies and field studies. The primary advantage of laboratory studies is that individual injury mechanisms can be isolated and examined under controlled conditions. For example, the effects of pressure changes on injury/mortality can be examined by itself, with all other stresses minimized. The biological response to a range of pressure changes can be quantified, and this response should apply to any turbine in any river system that exhibits these pressure changes. Also, the relative importance of the injury mechanisms can be determined if tests of each mechanism are conducted in similar ways and results are expressed in comparable terms. Turbine designers can focus on reducing the values of those individual injury mechanisms that have been shown to cause the greatest effect in controlled laboratory conditions. If tradeoffs are required (e.g., increasing the pressure changes in order to decrease shear stresses), laboratory studies of each mechanism are needed to predict the ultimate effect on fishes.

On the other hand, field studies have the advantage of replicating the actual entrainment experience. Turbine-passed fish are exposed not just to shear stresses or pressure changes, but rather to combinations of all injury mechanisms (pressure, shear, and mechanical injury) simultaneously. There is a potential for non-additive effects among these mechanisms, i.e., the combined mortality rate may be greater than (synergistic) or less than (antagonistic) the sum of the mortalities estimated from the individual mechanisms examined separately. Effects of combined stresses are extremely difficult to study in the laboratory. Field studies have the advantage of creating realistic combinations of stresses. The primary disadvantage of field studies is their site-specificity. One field site with 10 m of head may not be able to produce turbine passage conditions that are relevant to another field site with 30 m of head. It is not possible to test levels of each of the injury mechanisms beyond those provided by the particular turbine, and these levels are relatively uncontrolled. Fish passing through one region of the turbine are exposed to a different combination of pressure, shear, and mechanical stresses than fish passing through a different region of the same turbine. Consequently, it has been difficult to develop biological criteria from field studies of turbine-passed fish that can be reliably applied to the prediction of injury/mortality at other turbines. Field studies can provide very good information about entrainment mortality at that particular site, but relatively little information that is relevant to different hydropower sites or that could be used to make turbine design tradeoffs.

There is considerable value to conducting both laboratory and field studies for developing biological criteria in support of advanced turbine designs. Laboratory studies are needed to examine each of the injury mechanisms under controlled conditions. The biological criteria resulting from these studies are not site-specific, and thus provide basic information that can be applied to a wide variety of turbines. Field studies provide the evidence that biological responses observed in the laboratory are representative of real-world conditions, where such factors as temperature, turbidity, or dissolved gas concentrations may be sub-optimal. Further, field studies reflect the simultaneous exposure of fish to multiple stresses that, when compared to laboratory tests, allow the detection of unexpected non-additive cumulative effects.

The following sections review literature that describe laboratory and field techniques that could be brought to bear on the turbine-passage problem.

3.1 Laboratory Techniques

The purpose of this section is to describe techniques and experimental apparatuses that have been used to examine injury mechanisms associated with turbine passage (strike and grinding, pressure, cavitation, shear, and turbulence). The reader is referred to Part 1 of this review for a discussion of the injury mechanisms and the conclusions of these studies.

3.1.1 Mechanical Injury (Strike and Grinding)

Although strike has always been considered one of the most obvious and major causes of injury among turbine-passed fish, there have been surprisingly few attempts to study this mechanism under controlled conditions. Most investigations of strike have focused on estimating the probabilities that fish will contact some part of the turbine machinery, especially the blades and wicket gates (von Raben 1957; Montén 1985; Solomon 1988; Nece 1991). Some of these analyses assume that any contact will cause serious injury or death, or else assume that a constant percentage of fish striking the blade will be killed. In fact, Bell and Kidder (1991) pointed out that not all fish that collide with runner blades and vanes are killed; the lethal rate of strike is variable. Laboratory tests by Turnpenny et al. (1992) found that even at rapid velocities (5.2 m/s), collision with the blunt leading edge of the runner blade (e.g., near the hub) caused little damage and no mortality among several species of fish. Collision with a narrower blade profile, as occurs near the blade tip, caused severe injury. Consequently, it is important not only to estimate the probability of contact with the turbine machinery, but also the probability of injury once that contact is made.

Turnpenny et al. (1992) examined the assumption that the consequences of a strike are the same irrespective of where the fish is struck. They constructed an experimental apparatus that allowed them to assess injury resulting from different blade leading edge profiles and collision velocities, both of which become more injurious with increasing distance from the hub. In addition, effects of collision of mechanical structures with different parts of the fish's body were examined.

A short section of the leading edge of a turbine blade was mounted to a set of springs in the test tank (Figure 4). The blade was moved along tubular rails to one side of the tank with a pneumatic ram and held in place with levers. When the lever was released, the blade was fired at either lightly anaesthetized, free-swimming fish or freshly killed fish suspended in the path of the blade. Actual velocities of the blade, which ranged from 5.2 to 7.4 m/s, were measured by a chopped light beam detector, and were precisely reproducible (Turnpenny et al. 1992). Collisions were recorded by a video camera. Because the collisions occurred very rapidly

ORNL-DWG 97M-0822

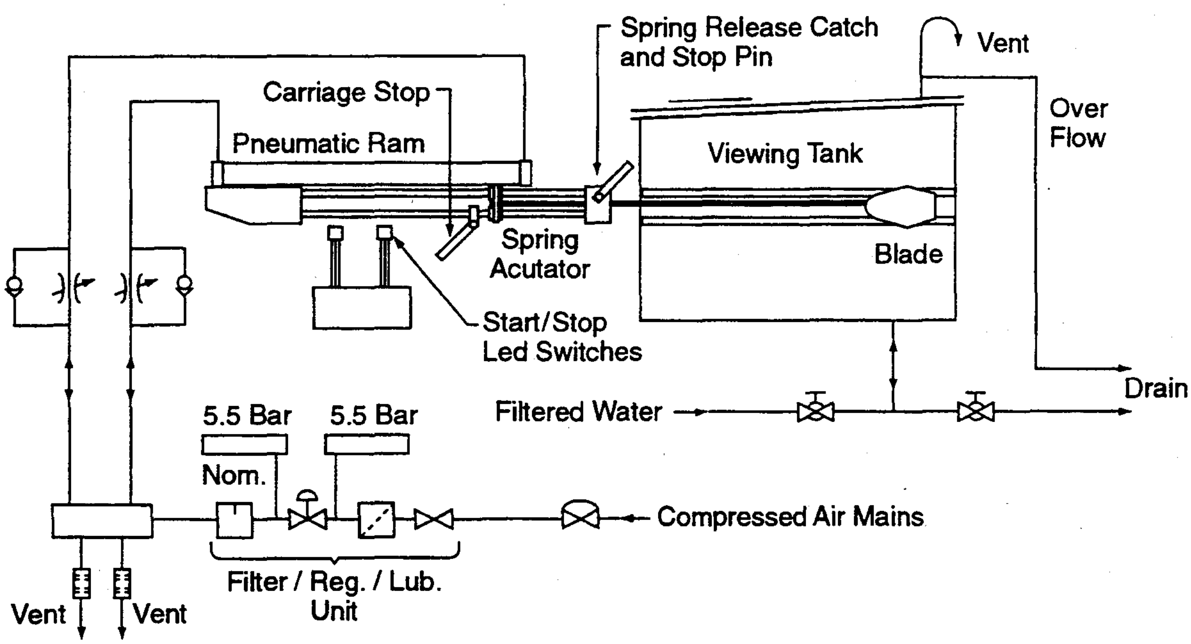


Figure 4. General arrangement of the fish/blade strike simulator used by Turnpenny et al. (1992).

(on the order of 60 milliseconds), there was no evidence that the live fish actively responded to the approaching blade, and most tests were done with freshly killed fish. Post-test analyses included measurements of the fish's standard length, mass, center of gravity (which had an important bearing on likelihood of injury), fish-to-blade angles in two planes, and the distance between the fish's center of gravity and the center of gravity of the blade section. Fish in the path of the blade that were deflected to one side by the blade or its "bow wave" (as opposed to being folded around the blade) were recorded as non-strikes.

Injuries to fish struck by the blade section included scale and mucous loss, bruising, eye damage, and internal bleeding (Turnpenny et al. 1992). It was found that small fish (of a few grams weight) were swept around the front of the blade along with the streamlines of the water. Larger fish, owing to their greater inertia, have a higher probability of colliding with the blade. The probability of collision in this laboratory experiment was expressed as the ratio of two measurements: the shortest distance between the fish's and the blade's centers of gravity and the fish's body length. Their studies affirmed the importance of fish weight when calculating strike probabilities; very small fish (<20 g) in the path of the blade virtually avoided collision, whereas larger fish (>200 g) had nearly a 100 percent chance of being struck.

Mechanical injury to turbine-passed fish can also be caused by grinding, in which fish are drawn through narrow openings or gaps between structures in the turbine passageway. There have been no studies to assess the importance of grinding as a factor in turbine-passage mortality.

3.1.2 Pressure

Studies of the effects of pressure on fish have been carried out for nearly a century, mainly with the goal of understanding the physiology of fish living at great depths in the sea. For example, Sébert et al. (1990) described a hyperbaric chamber that allows fish to be held at pressures of up to 101 atmospheres (atm) for at least one month; this apparatus was used to study the physiological adaptations of eels to vertical migrations in the sea. Of greater interest here are the relatively recent studies of rapidly varying pressures that have been done to assess the effects of explosions, pump passage, or turbine passage. For example, Rowley (1955) put rainbow trout into a small lucite chamber, increased pressure with a hand pump, and, after an exposure of less than 1 minute, released the pressure instantaneously. This time-pressure regime simulated pressure changes in a hydropower penstock, but was not similar to that experienced by turbine-passed fish. Foye and Scott (1965) exposed fish to rapid pressure increases (atmospheric to 2065 kPa instantaneously, followed by a 10-minute period of pressure decrease back to atmospheric) in a 102 cm X 30 cm cylindrical steel tank. This regime was designed to mimic pressures experienced by fish entrained during the pump cycle of a pump storage project. In order to better simulate turbine passage, Muir (1959) constructed a test apparatus that increased the hydrostatic pressure in a small (20 cm X 10 cm) cylindrical chamber to about 570 kPa (5.6 atm) in a few seconds, then reduced the pressure to 7 kPa (0.07 atm) in 0.01 seconds.

Harvey (1963) studied the effects of increased water pressures on sockeye salmon fry and smolts using a cylindrical steel chamber, 91 cm (3 ft) long and 30 cm (1 ft) in diameter. One end was fitted with a removable flange secured by bolts. Pressure was applied by means of a pump and regulated with valves and a bypass over the range of 101 to 2165 kPa (1 to 21 atmospheres). The most rapid rate of pressure increase achievable with this apparatus was about 69 kPa per second, but pressure could be returned to atmospheric instantaneously. Subatmospheric pressures were investigated with a smaller cylinder in which pressures were reduced by means of a vacuum pump. Pressures as low as 2 kPa (0.02 atmospheres) were achieved in this test chamber. Pressures were measured with a transducer and recorded on an oscillograph. Ends of the chamber were fitted with plastic ports in order to observe fish behavior. Harvey (1963) did not report the variability in actual pressures achieved in the chambers, but noted that it was not possible to control precisely the desired vacuum (subatmospheric) conditions.

Knable and Feathers (1983) pointed out that many of the early studies used compressed air to increase pressure in the test chambers. This technique could result in supersaturation of gases in the water and tissues of the test organism, which in turn could cause gas embolisms (gas bubble trauma) during subsequent decompression. They developed a large (200 cm X 70 cm) test chamber that could maintain pressures of 520 kPa for at least 24 h with a continuous exchange of water. Although the complicating effects of supersaturated gases on pressure responses were eliminated, the chamber was not designed to recreate the rapid pressure increases and subatmospheric pressures that are common to hydropower turbines.

Turnpenny et al. (1992) constructed a 140-L pressure flux vessel in which pressure could be adjusted from 10 to 400 kPa (0.1 to 3.9 atm) by means of a piston. Control of the piston was achieved with a computer-generated signal to a hydraulic actuator. A control program on the computer allowed the desired pressure time series to be defined and stored, in order to generate repeatable time-pressure patterns. Their calculations took into account the compressibility of the fish's swim bladder in determining the amount of piston movement needed to create the desired pressure change. Provided that the weight of fish (and therefore size of swim bladder) introduced to the chamber did not exceed the design limit and the pressure vessel was properly sealed, time-pressure curves were achieved within 5 percent of target values throughout the run. In addition to the main pressure chamber, which was constructed of stainless steel, an accessory plexiglass chamber connected directly to the main chamber allowed observation of the behavior of individual fish.

Montgomery Watson (1995) exposed smolt-sized rainbow trout to different levels of water pressure and dissolved gas saturation in laboratory chambers. The pressure exposure system consisted of two acrylic cylinders, each 55 cm (22 in) long and 27.5 cm (11 in) in diameter, connected to a system of hydraulic and pneumatic cylinders and their controls and water supply (detailed schematics are provided in the report). The chambers were connected to hydraulic cylinders which in turn were connected to pneumatic cylinders. A computer-controlled gas pressurization system caused the pneumatic cylinders to change the position of the hydraulic cylinders, thereby pressurizing or depressurizing the test chambers while maintaining control over dissolved gas concentrations. Pressure could be dropped from 300 kPa (100 feet of head or 3 atm) to the vapor pressure of water in 0.1 seconds.

Groups of Age 0, 9 to 10 cm-long rainbow trout were exposed to the following pressure regime in the test chambers: Initial Pressurization Phase (atmospheric pressure to 300 kPa in 30 to 60 seconds); Transient Phase (drop to the vapor pressure of water, 2 kPa, in 0.10 seconds); Low Pressure Phase (close to the vapor pressure of water for 0.25 seconds); and Recovery Phase (return to 115 to 120 kPa in 30 to 60 seconds) (Montgomery Watson 1995). This was estimated to be the worst case pressure condition for a fish passing close to a turbine blade at McNary Dam. Groups of 20 test fish in each chamber were exposed to the pressure transients (and different gas saturations) and held in the chambers for an additional 30 minutes. After the 30 minutes were up, treatment and control fish were removed from the chambers, combined, and introduced to a tank containing adult rainbow trout predators. After 25 minutes, survivors were removed from the predation tank.

Montgomery Watson (1995) also established the performance characteristics of the pressure test chamber system by running ten pressure cycles on each chamber and measuring the actual pressures achieved. An example of the repeatability of the pressure regimes created in the chambers is shown in Figure 5. Although there was some variability

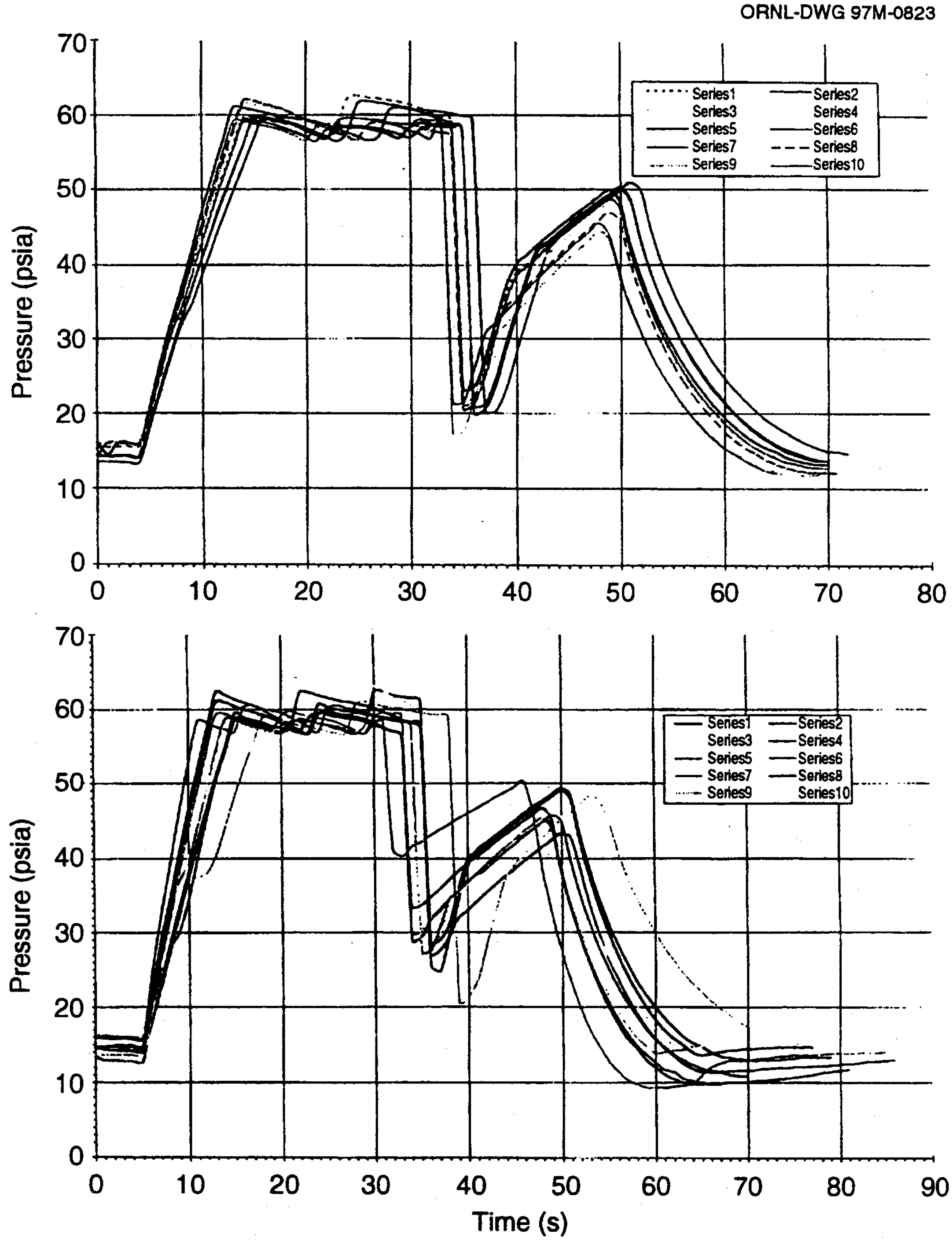


Figure 5. Example of the repeatability of the pressure vs. time regimes created in the test chambers used by Montgomery Watson (1995).

in the time-pressure histories, the absolute positive and subatmospheric pressures achieved were similar among the replicates.

In summary, nearly all of the pressure studies have been carried out by placing the fish in cylindrical chambers and exposing them to the desired time-pressure regime. A variety of response variables have been examined, ranging from swim bladder injury to direct mortality to changes in susceptibility to predation. Recent studies have been more conscious of the complicating effects of dissolved gases in the test chamber. Fish held in a static chamber may consume enough of the dissolved oxygen to be affected, whereas supersaturation of nitrogen may lead to gas bubble trauma when the chamber is decompressed. Refinements in equipment have enabled investigators to control dissolved gas concentrations and to test rapid and extreme pressure changes (similar to those experienced by turbine-passed fish) in precise, repeatable ways.

3.1.3 Cavitation

The importance of cavitation as a possible source of turbine-passage mortality was recognized early. For example, Muir (1959) noted that fish passing through a region of cavitation will be subjected not only to the stresses associated with a partial vacuum but also to pressure intensities resulting from the collapse of the vapor pockets. He exposed fish to cavitating conditions in the laboratory with a water hammer apparatus; water moving rapidly through a pipe between two tanks was abruptly stopped by the rapid closing of a check valve. A wave of reduced pressure, starting at the check valve, swept downstream through the pipe to a pipe riser containing the experimental fish. Pressure in the riser was reduced to the vapor pressure of water, as evidenced by a transducer and the formation of a vapor pocket. The development of a vacuum was followed by a rapid opening of the check valve, which increased the pressure again and caused the vapor pocket in the riser to collapse. Test fish were examined microscopically for evidence of hemorrhaging.

Ramamurthy et al. (1984) described an apparatus for generating cavitating conditions in the laboratory and studying its erosive effects on different materials. The apparatus consisted of a 61-cm-diameter circular disk in a closed, water-filled chamber. The disk was mounted on the shaft of a motor and rotated in the chamber at 1800 rpm. Equilateral triangular prisms were mounted on the surface of the disk to form the cavitating source, and the material to be tested (e.g. strips of aluminum) was also fixed on the disk in the wake region formed by the prism. As the disk spun rapidly, the prism generated cavitation bubbles which were swept toward the nearby test material. Although this rotating disk apparatus is widely accepted as a device to study the resistance of materials to cavitation, it does not appear to be adaptable to assessing cavitation damage to fish. The effects of spinning and turbulence would be harmful to the fish as well, and these would be difficult to separate from the effects of cavitation.

Turnpenny et al. (1992) used an underwater spark generator to create individual cavitation bubbles in a static water tank. The vapor bubble created by a spark in the 0.5-mm electrode gap reached its maximum size of 8-10 mm within 1.4 milliseconds, then collapsed in less than 0.1 milliseconds. The electrode gap was surrounded by a brass cage, within which freshly killed fish were held during bubble collapse experiments. Fish were mounted on a wooden splint in order to ensure a replicable geometry between the fish body surface and the spark gap. Individual fish were exposed to a series of five successive bubble implosions positioned at intervals along the head and body. Fish were photographed during the cavitation bubble implosions, and were subsequently examined for tissue damage. Although no tissue damage was observed, Turnpenny et al. (1992) cautioned that the results of these limited tests should not be interpreted to mean that cavitation is not a problem in operating turbines. Pitting damage is often seen on the runners of cavitating turbines, but such effects were not observed on brass plates exposed to collapsing bubbles in these laboratory studies. Energy levels associated with cavitation bubble collapse must be vastly higher than those that Turnpenny et al. were able to generate with their experimental apparatus.

3.1.4 Shear Stress and Turbulence

Johnson (1970a,b; 1972) reported on a series of tests to examine the injury and mortality among juvenile salmonids entering a tank of water through a submerged, high-velocity jet. The motivation for the tests was to determine whether fish would be injured in the high-velocity flows associated with slotted bulkhead downstream fish bypass systems at Columbia River Basin dams. Juvenile coho, chinook, and steelhead were introduced into a 36-cm (14-inch) supply line which narrowed to either a 10-cm or 15-cm (4-inch or 6-inch) nozzle. The nozzle was submerged in a water-filled test tank that measured 12 m long, 6 m wide, and 2 m deep (40 ft X 20 ft X 6 ft). Depending on the test, the water jet coming from the nozzle had a velocity of 17.5, 20.4, 23.6, or 28.0 m/s (57.5, 67, 77.5, or 92 ft/s). Most test fish entered the supply line from the lock in which they were held within 10 seconds, then rapidly passed through the nozzle into the tank. The jet was left in operation for three to four minutes after all fish had left the lock to ensure that they had passed through the nozzle. The pump was shut off, the tank drained, and the fish collected for post-test observation. High-speed cameras (1200 frames per second) recorded movements of the fish as they were ejected from the nozzle. Later examination of the film at slower speed (16 frames per second) provided a minimum viewing time of 5.25 seconds for each fish as it traveled in the jet.

Johnson (1970a) observed no mortality at the lowest velocity tested, 17.5 m/s. Mortality averaged 2.4, 7.2, and 31.0 percent at jet velocities of 20.4, 23.6, and 28.0 m/s, respectively. Johnson (1970b) pointed out several other possible causes for the observed mortalities, some of which he was unable to rule out completely with the experimental apparatus. Possible alternative causes for fish mortality include mechanical damage to 20- to 23-cm-long fish when forced sideways through a 10-cm-diameter nozzle, and the sudden pressure drop that occurred when fish passed through the nozzle. Although lowest pressures experienced by test fish were estimated remain above atmospheric, Johnson (1972) reported an intense plume of cavitation near the nozzle at the two highest velocities that may have injured fish which exited the jet within 1 m of the nozzle. A final complication of these studies is that the experimental apparatus didn't allow for precise control and measurement of shear forces experienced by fish. The location of fish in the jet, orientation of fish as they exited the nozzle, and location where they exited the jet into the relatively static water tank could not be controlled or replicated. Finally, fish occasionally re-entered the jet due to water circulation patterns in the tank; the shear that was experienced when fish already in the tank are drawn back into the jet and instantly accelerated from zero to nearly 28 m/s added an unquantified stress that may have been reflected in the mortality.

Groves (1972) used a modification of the water jet technique to study the effects of shear on juvenile coho, chinook, and sockeye salmon. Unlike the approach described by Johnson (1970a), test fish did not pass through the jet's nozzle. Rather, fish were flushed into the water tank through an angled tube that was positioned so that they would strike the jet within 7.6 cm (3 inches) of its emergence from the nozzle. Jet velocities ranging from 9 to 37 m/s (30 to 120 ft/s) were tested, although the exact velocity of the boundary of the jet that fish actually contacted was not known. Although the water in the center of the jet was moving at speeds approximating the calculated velocities, fish contacted on the outer margins of the stream where the water was slower. Further, the actual shear forces experienced by fish striking the jet were not calculated. High-speed photography (1,600 frames per second) allowed subsequent analysis of the path of fish entrained in the jet and the cause of injuries. Groves (1972) concluded that fish could be injured in any high energy flow situation that creates momentary (as low as 1 millisecond), localized points of sharp velocity change. He noted that such rapid, transitory events would be difficult to pinpoint in specific field conditions, and impossible for fish to detect or avoid.

Killgore et al. (1987) exposed paddlefish larvae to turbulence with an experimental apparatus that was essentially a small version of the one used by Groves (1972). A jet of water was pumped into a circular, 27-cm-diameter bucket. In the center of the bucket was an 11-cm-diameter pipe, which created a circular raceway. The jet caused water to move in a circular fashion within the bucket, at velocities of 22 to 59 cm/s. Turbulence was quantified by measuring pressure changes at four locations within the bucket. Pressures (which were equated with levels of turbulence by the authors) ranged from 1,774 to 6,421 dynes/cm^2. Paddlefish yolk-sac larvae were exposed to a particular time-turbulence regime and examined immediately afterward to assess survival.

Turnpenny et al. (1992) also tested the effects of shear using the Groves (1972) experimental approach. Water was discharged into a large flume tank (8 m long X 1.5 m wide X 1 m high; 0.6 m water depth) through a jet nozzle at velocities of 5, 10, 15, 19, and 20 m/s. The calculated relationship of shear stress (expressed as N/m^2, where 1 N/m^2 equals 10 dynes/cm^2) to flow rate of the jet is shown in Figure 6. The calculated variation in shear across the jet centerline with distance is shown in Figure 7. Fish were individually fed into the water jet through an introduction tube, entrained into the jet stream, swept to the quiet area of the tank, and were netted out. Fish were immediately examined for damage, then held for 7 days to assess long-term survival. High-speed photography of the fish's movements showed that upon entering the tank fish were immediately drawn into the center of the jet and then "pirouetted" along the tank in a circular motion. The resulting bending motion cause visible creases on the outside of the body of some fishes and crushed the internal organs of others.

Turnpenny et al. (1992) regarded their approach to studying shear as the most relevant to turbine passage because it can

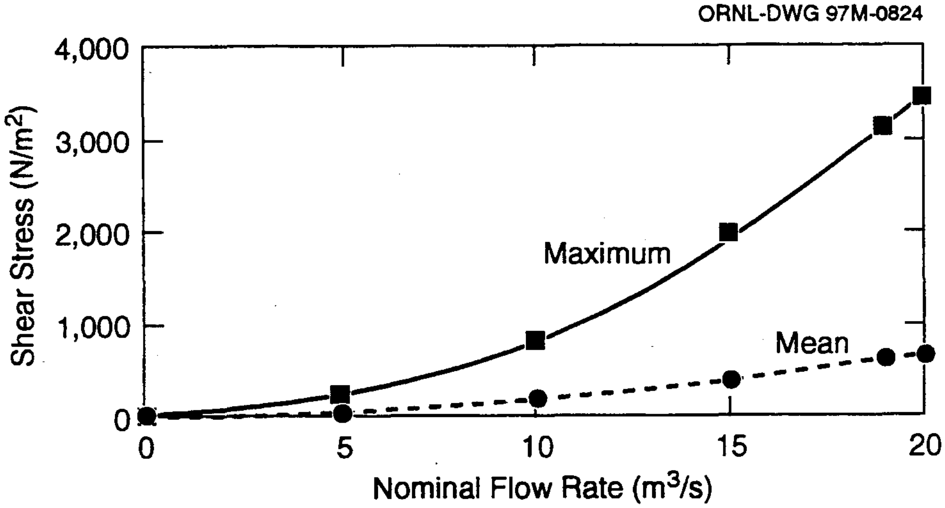


Figure 6. Calculated relationship between shear stress (N/m^2) and flow rate of the jet used in the shear stress studies of Turnpenny et al. (1992).

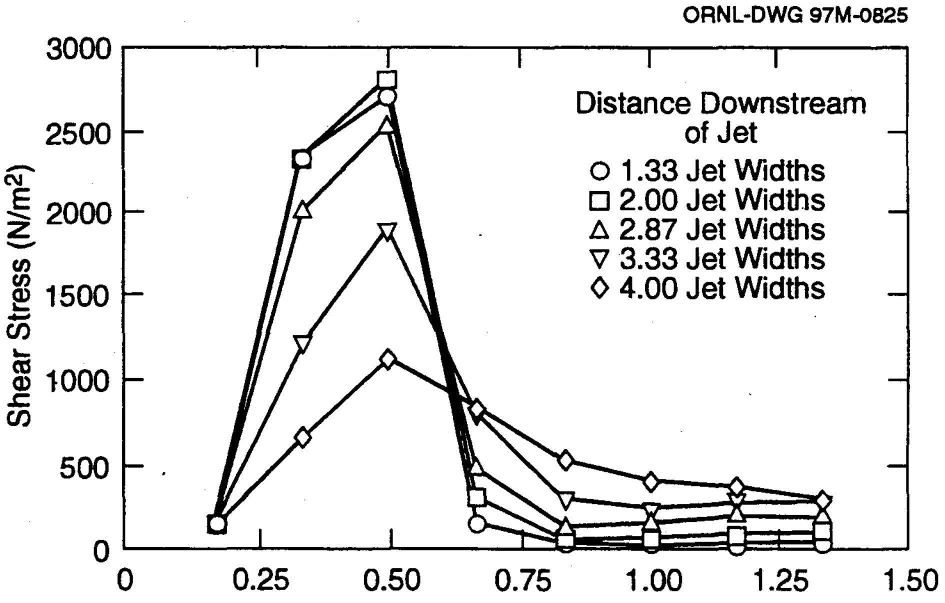


Figure 7. Calculated variation in shear across the jet centerline with distance for the Fawley nozzle used in the shear stress studies of Turnpenny et al. (1992).

produce the effects of localized shear stresses on the fish's body which lead to scale loss, eye damage, and gill damage. They felt, however, that this technique does not adequately reproduce the forces of elongation, compression, and torsion that a fish would experience within a turbine when different parts of its body enter regions of differential velocity. Such forces might lead to creases and internal organ damage seen in some of the fish. They suggested that such effects would be worth examining in future studies.

Shtaf et al. (1983) examined the effects of turbulence on fish swimming behavior in small laboratory flumes. Because turbulence was generated by placing screens and other obstructions in the flume it was not strictly predictable or reproducible. The investigators were interested in studying swimming behavior in natural waters, so water velocities in the flume were low (13 and 18 cm/s) and the resulting turbulence was not damaging. Degree of turbulence was expressed as the standard deviation of instantaneous water velocity divided by the mean water velocity. Hence, the greater the deviation from mean water velocity in the flume, the greater the degree of turbulence. This formulation is useful for comparing relative turbulence associated with different flows and structures within the same experimental flume, but does not provide an absolute expression of turbulence and shear forces to which the fish were exposed.

Morgan et al. (1976) investigated the effects of shear stresses on striped bass and white perch eggs and larvae. They were particularly interested in reproducing the rotational and deformational forces that are exerted on a fish egg exposed to adjacent flow fields of different velocities. They developed a shear stress exposure chamber which consisted of two fixed concentric plexiglas cylinders, 20.3 and 30.5 cm in diameter. A third, 25.4-cm-diameter cylinder was placed between these two water-filled cylinders and rotated at speeds ranging from 14 to 231 rpm.

The shear stresses experienced by fish in the experimental apparatus was a function of the speed of rotation of the middle cylinder (Morgan et al. 1976). In addition, flows in the water space between the small fixed cylinder and the rotating cylinder (inner annulus) were different from those in the space between the large, outer fixed cylinder and the rotating cylinder (outer annulus). In the inner annulus, the centrifugal forces are in the direction of increasing radial velocity (i.e., nearest the inner wall of the rotating cylinder). This stabilizes the flow in the inner annulus into a circularly annular pattern (Covette flow). In the outer annulus, however, faster moving flow near the wall of the rotating cylinder is pushed radially outward by centrifugal forces, resulting in turbulent mixing (Taylor instability). Shear stresses at the wall of the inner annulus were calculated; at the lowest rpm, shear was estimated to be 0.052 dynes/cm^2. The authors would not determine analytically the shear stresses in the turbulent outer annulus, but instead assumed a Reynolds number of 4,738 and a corresponding shear stress value of 0.64 dynes/cm^2. Shear forces in the outer annulus were an order of magnitude greater than those in the inner annulus at the lowest rotational speed, and the discrepancy increased with higher rpm. Fish eggs and larvae were introduced into the outer, turbulent annulus and exposed to shear stresses for various periods of time. Short-term studies used shear stresses between 76 and 404 dynes/cm^2 for 1 to 20 minutes. Longer term studies exposed eggs and larvae to shear stresses between 0.64 and 86 dynes/cm^2 for 2 or 3 days. Based on these studies, Morgan et al. (1976) developed regression equations that related mortality to shear level.

It is clear from these experiments that the potential injury mechanisms of shear stress and turbulence have proven difficult to study in the laboratory. The concept of shear and precisely how it might affect turbine-entrained fish have been difficult to describe or even to express quantitatively. As a result, the shear stress experience has not been reliably simulated in a quantitative and reproducible manner. Similarly, turbulence has not been rigorously examined. Severe turbulence in a hydroelectric turbine system is believed by some to have adverse effects, but, like shear, the mechanism has been difficult to express, quantify, or apply in controlled studies. The spinning and buffeting associated with turbulence in the draft tube and tailrace are less likely to cause injury and direct mortality than they are to disorient the fish so that it is more susceptible to indirect mortality (predation). Laboratory studies are needed to expose fish to the levels of turbulence that occur in a turbine system and to assess the consequent direct and indirect mortality.

3.2 Field Techniques

A variety of techniques are available for studying turbine passage rates and mortalities of entrained fish, including tailrace netting, Turb'N tags, Passive Integrated Transponder (PIT) tags, or hydroacoustics. These techniques are presently used to quantify the numbers of fish entering and leaving the turbine (and the consequent injury and mortality), but they do not provide any information about the behavior of fish within the turbine. For the purpose of improving turbine designs, there is a need to go beyond these applications and to develop an understanding of the precise path taken by turbine-passed fish. Flow path visualization techniques are being explored in order to define exactly those areas of the turbine that fish pass through and the mortalities associated with these areas. For injury mechanisms such as mechanical damage (blade strike, grinding, or contact with walls and other obstructions) or cavitation, some of these visual techniques could be used directly. For other injury mechanisms (pressure and shear), visual observations of the flow path of entrained fish would need to be accompanied by estimates or measurements of the levels of these stressors throughout turbine passage. Some of these techniques have been employed at hydroelectric power plants, whereas others have not but may be adaptable. The two most readily adapted techniques for visualizing the flow path of individual entrained fish are low-light-sensitive video cameras and hydroacoustics.

3.2.1 Low-Light-Sensitive Underwater Video Camera

Nestler and Davidson (1995a) used underwater video cameras to study the effects of bypass screens on water flows and smolt behavior at McNary Dam. Three different camera types were used (specifications are shown in Table 8), but no comparisons among cameras were reported. Cameras were mounted on the screens and aimed laterally to look across the surface of the screen. A 120-W incandescent light source was attached to the camera housing and aimed in the same direction as the camera. Camera depth of view was about 0.6 to 0.9 m (24 to 36 inches) for the screen surface, but when illuminated the highly reflective bodies of smolts could be detected at a distance of about 1.2 m (48 inches). During imaging, each camera was connected to a video cassette recorder and a television monitor.

Table 8. Specifications of low-light sensitive underwater video cameras used at McNary Dam by Nestler and Davidson (1995a).

Camera type	Sensitivity	Lens	Power	Size	Weight in water (kg)	Cost ($)
Underwater CCD Monochrome Television Camera OE 1359	0.03 lux on the sensor	3.7 mm, f/1/6-f/300 Auto Iris	16-24 V d.c. at 200 mA maximum	152 mm length - 53 mm diameter	0.27	10,500
DeepSea Power & Light Micro-SeaCam Underwater Video Camera	1 lux	60 degree angular field of view in water	12 VDC at 140 mA maximum	122 mm length - 36 mm diameter	0.3	5,200
Silicon-Intensified-Target (SIT) TV Camera SL-99	1,000 times greater than a standard vidicon	12.5 mm, f/1.4	12.7 VDC at 850 mA ± 50 mA	356 mm length - 95 mm diameter	1.8	10,500

Nestler and Davidson (1995a) recognized that the presence of the video camera, illumination system, and mounting hardware would produce significant hydraulic anomalies that could influence fish behavior. In addition, the illumination field required for video imaging could also attract or repel smolts. From studies designed to quantify the effects of these potential biases, they concluded that smolts did not concentrate in the wake of the camera mounting system. The fish swam around the mount without apparent response other than to avoid contact with the structure. Different illumination intensities influenced the number of fish imaged, but did not appear to alter the behavior of fish relative to impingement on the screen. Because fish behavior could not be observed with video cameras without some minimum level of illumination, a "no illumination" condition could not be examined and the biasing effects of artificial illumination on entrained fish behavior could not be completely resolved.

Moore and Scott (1988) also used a Silicon Intensifier Target underwater camera in their studies of the behavior of recently emerged trout fry. Because these fry emerge from the redds only at night, a low-light camera was needed to record their activities. The camera was housed in a special support and placed in the stream immediately downstream from the redd. The stream bed was illuminated from above the water surface with an artificial light source, the intensity of which was equivalent to full moonlight. The authors did not report the type of light source, exact illumination intensity, or the camera's viewing range. By means of the camera they were able to observe and videotape the swim-up and rapid downstream movement of trout fry under natural nighttime light levels.

Vaughn (1995) described a prototype underwater camera system that was used to inspect submerged traveling screens at the John Day Dam on the Columbia River. The monochrome cameras required a minimum scene illumination of 0.9 lux and had a fixed focus (0.1 meters to infinity). Illumination was provided by 250-watt submergible lights with variable intensity control (range of light intensities was not reported). Depending on water clarity, visibility with this video system ranged from 0 to 1.5 meters, but typically was about 0.3 meters.

Because low-light sensitive underwater cameras can directly observe (and record for later analysis) objects moving through the turbine, they have considerable value for understanding whether fish behavior significantly influences injury rates. For example, video imaging may be the most reliable technique for assessing any tendency of fish to swim away from or towards obstructions or areas of cavitation and shear stress. The movements of live fish within the turbine environment could be compared to those of dead fish or other neutrally bouyant objects to determine whether such mechanisms as blade strike have a significant behavioral component.

These low-light sensitive video camera studies all relied on external lights to illuminate a darkened area. The limited viewing range and potential effects of illumination on fish behavior are major limitations to the use of those techniques inside of a turbine. However, it may not be necessary to illuminate the turbine passageways if the entrained fish is fitted with a light-emitting tag, such as a light-emitting diode (LED), that could be detected by the camera. A single light-emitting tag could be used to estimate the fish's rate of passage through the turbine and a rough estimate of the actual flow path. Further, attaching two LED tags with different colors or different blinking rates could allow estimates of the orientation and path of the fish in three dimensions. LEDs have been incorporated into instrument packages used to sense and record depths achieved by marine diving birds (Wilson et al. 1989; Croll et al. 1992). However, these packages are still too large (9 cm X 1.5 cm; 6 to 11 g) to be attached to turbine-entrained juvenile fish. The key to the use of this technique is to develop a light-emitting tag that is small, lightweight, and can be detected at reasonable distances in turbid water and in a darkened turbine passageway.

The value of low-light video imaging technology to visualize the flow paths of turbine-passed fish is presently limited by (1) the camera's viewing range and (2) potential biases associated with the unnatural hydraulic and illumination conditions caused by the presence of the camera. At best, the cameras used by Nestler and Davidson (1995a) were only able to detect fish passing within 1.2 m (4 feet). Visualizing a long flow path taken by an individual fish would require a network of integrated, closely spaced cameras. Increasing the intensity of conventional illumination to extend to viewing range of the camera could alter the fish's behavior and bias the results. Consequently, video imaging may be most useful for studying the passage of fish through relatively small areas such as gaps between blade and hub that have been suggested as likely sites for grinding injuries. The flow fields created by the camera and its mounting bracket and light source could be eliminated by installing all equipment outside of the turbine and imaging the fish through viewing ports. Fish behavior changes caused by illumination could be reduced or eliminated by using cameras that are sensitive to wavelengths not perceived by fish or the development of a small light-emitting tag.

3.2.2 Hydroacoustic Techniques

A variety of hydroacoustic techniques have been developed to study the movements of fish near hydropower projects (Thorne and Johnson 1993). Unlike hydroacoustic equipment mounted on commercial fishing vessels to monitor the movements of schools of fish in the open sea, measurements near a hydropower plant can be made from a fixed location, e.g., the dam or a stationary floating platform near the forebay. The general approach for fixed-location acoustic studies is to place one or more transducers on a fixed structure, aim the acoustic volume toward an area of interest (e.g., horizontally out into the reservoir), and sample fish as they pass through the ensonified acoustic beam (Steig and Johnston In Press). Fish passing through the beam produce echoes that can be tracked over successive ensonifications (pulses of the acoustic beam). Three general techniques have been developed: single-beam, dual-beam, and split-beam hydroacoustics.

Single-beam hydroacoustics - The simplest echosounders transmit sound in a single beam, which permits the range, but not the direction, of targets to be determined (MacLennan and Simmonds 1992). Ransom and Steig (1995) summarized the findings of numerous evaluations of spillway and sluiceway bypass effectiveness at Columbia River basin dams. Nearly all of these evaluations used single-beam hydroacoustics techniques to obtain relative estimates of fish passage rates. Typically, the transducers were placed on a fixed structure (e.g., intake wall or trash rack) and sampled salmon smolts as they passed through the ensonified beam. The focus of these studies was the movements of smolts immediately upstream of the dam or at the intake entrance; there is no indication that these techniques were used in the deeper turbine passages.

Dual-beam hydroacoustics - Whereas single-beam techniques allows relative numbers of fish to be estimated, the dual-beam technique can be used to estimate directly the acoustic target strength, which in turn can be related to the length of individual fish or the biomass of schools of fish (Love, 1971; Johnston et al. 1993). Johnston et al. (1993) used dual-beam hydroacoustic techniques to estimate target strengths (and fish lengths) of fish entrained at two hydroelectric dams.

Split-beam hydroacoustics - This recently developed technique has the ability to estimate the absolute velocity and three-dimensional paths of individual fish passing through the beam. In addition, the individual fish's target strength can be measured, from which estimates of size or mass can be made. This technique has been employed at the entrance to hydropower dams to monitor that movement patterns of downstream-migrating fish within the hydropower reservoir.

For example, Steig and Johnston (In Press) described an application of split-beam hydroacoustic techniques to the study of fish movement patterns in the forebay of Rocky Reach Dam in Washington. An elliptical-beam transducer was mounted on each of the four corners of a barge and aimed downward and out into the forebay. Fish were detected in cells within the ensonified volume. Each cell was 5 m long (measured outward from the transducer), but had a volume that increased with distance from the transducer, owing to the elliptical shape and increasing width of the beam with distance. The split-beam technique was capable estimating the numbers of fish in each cell (and thus density), acoustic size estimate (target strength) of each fish, and the three-dimensional trajectory of each fish. Precision of the estimates was not given, and results were presented only for average density, target strength and trajectory of all fish in a given cell. Fish movement patterns in the lower reservoir and forebay indicated that fish tended to follow bulk flow near the powerhouse.

One of the prerequisites for estimating target strength (fish size) *in situ* is the ability to separate single target echoes from multiple echoes. That is, two small fish moving close together should not be interpreted as a single, large fish. Sole et al. (1995) examined these potential biases in a laboratory test tank with a Simrad EK500 split-beam echo-sounder. They concluded that (1) the single-fish discriminator software showed a bias against accepting weaker targets, and (2) multiple echoes from targets as far as 0.7 m apart were falsely accepted as single echoes. The authors cautioned that these discriminators may be unreliable for estimating target strength of pelagic organisms, unless fish are widely separated and differ little in target strength. Biases such as these will have to be corrected in order for split-beam hydroacoustics techniques to be successfully applied to visualizing the flow path of fish within a turbine.

Ransom and Steig (1994) listed the advantages and disadvantages of hydroacoustics techniques for fisheries studies. The advantages include:

1. Hydroacoustics readily provide estimates of fish entrainment rates and abundance.

2. High sampling power and relatively low manpower requirements reduce overall study costs.

3. Hydroacoustic techniques do not harm the sampled fish or alter their behavior.

4. Because large quantities of data can be easily acquired, statistical comparisons and interpretations are facilitated.

5. Net avoidance and other netting bias problems are avoided.

6. Real-time data analysis is possible.

7. Hydroacoustic techniques allow documentation of fish behavior. For example, split-beam acoustic techniques can directly estimate fish velocity and three-dimensional movements.

8. Hydroacoustics have been used extensively at power plants throughout the world for nearly 20 years.

Ransom and Steig (1994) also pointed out the disadvantages of hydroacoustics studies:

1. Direct species identification is not yet possible.

2. Specialized, costly equipment is needed.

3. Specialized training is required.

4. If very small fish are to be monitored, the technique may be susceptible to background interference. At some dams, excessive turbulence, entrained air, and electronic interference can limit the usefulness of hydroacoustics.

This last disadvantage may be the greatest problem associated with using hydroacoustics techniques to visualize the flow path of fish through the turbine. Hydroacoustics studies at hydropower plants have been oriented toward monitoring the movements of fish in the lower reservoir, forebay area, trash racks, or in the vicinity of the submerged screens (see, for example, Matousek et al. 1995; Williams et al. 1995). There do not appear to be any applications of these techniques to the interior of the turbine or draft tube, where turbulence and electronic interference are greatest. Entrained fish are most concentrated in these areas, such that the problem with discriminating multiple echoes (Sole et al. 1995) may be difficult to overcome. Finally, compared to the reservoir and forebay areas, fish move very rapidly through the turbine and draft tube. Adequate detectability requires the correct combination of ping rate and beam width, relative to the fish's velocity. The ability of split-beam hydroacoustics to estimate velocity and three-dimensional movements under these conditions may be exceeded.

3.3 Conclusions and Recommendations

Coordinated laboratory and field studies are needed to understand the relative importance of the potential injury mechanisms associated with turbine passage. Pressure changes are easy to study under controlled conditions. The rapid pressure increases and decreases experienced by an entrained fish can be reliably simulated in the laboratory, and as a result more is known about this stress than any other. At the other end of the scale, techniques for studying fluid shear stresses and turbulence are not well developed. Shear and turbulence have been difficult to recreate in laboratory experiments, and little is known about the levels of injury, direct mortality, and indirect mortality (predation and disease) that may result from exposure to these stresses in a hydroelectric turbine.

There have been substantial developments in both video and hydroacoustics techniques in recent years that might used to visualize the path taken by entrained fish in an operating turbine. This information is needed to develop a better understanding of the risk of strike and grinding, as well as the pressure vs. time, shear vs. time, and turbulence vs. time histories experienced by fish passing through existing and advanced turbines. Low-light sensitive video cameras, perhaps in conjunction with light-emitting tags attached to the fish, show promise for tracking the path of entrained fish. Split-beam hydroacoustics techniques can potentially detect and record a fish's movements in three dimensions with little potential for altering the fish's behavior. However, the ability of hydroacoustics to track fish reliably inside of a turbine, under conditions of high velocities, high turbulence, crowding of entrained fish, and electronic interference, has yet to be demonstrated.

4. Fish Behavior in Relation to Entrainment in Hydropower Turbines

The literature on fish behavior as it relates to passage of fish near or through hydropower turbines is reviewed in this section of the report. An evaluation was stimulated by the need to develop more "fish-friendly" turbine systems for hydropower facilities (Brookshier et al. 1995). One aspect of "friendliness" is compatibility of engineered systems with the normal behavior patterns of fish species and life stages in the vicinity of the generation facilities such that entrainment into turbines and injury in passage are minimized.

Turbine modelers and designers need to know how fish move into and through turbines in order to develop novel designs that are less damaging to fish. Biologists need to define whether fish can be simulated in computer and physical models as passive, neutrally buoyant particles distributed throughout the water mass entering a turbine or if they must be represented in ways that reflect specific fish distribution patterns, physical orientations, and directed swimming movements. Fish distribution patterns in a turbine intake would influence the parts of the turbine through which the fish pass (e.g., near the hub or near the blade tips). Physical orientations would affect the likelihood of being struck by a turbine blade. Capabilities of fish for directed swimming movements in the high water velocities of a turbine intake would influence the constancy of distribution patterns and orientations as fish approach the turbine runner. This report evaluates the knowledge and importance of these considerations.

Physical damage to fish that pass through hydropower turbines is a major source of mortality for many fish populations in the vicinity of hydropower projects (OTA 1995; NRC 1996). This is especially true for migratory species such as salmon for which the dam is a barrier to movement that must be traversed or the population spawning upstream perishes. Although successful technologies have been developed for passing adult salmon upstream over dams (through simulation in fish ladders of the features of the normal migratory habitat), passage of downstream-migrating juveniles has been difficult to manage and generally not very successful (NPPC 1994; Čada et al. 1994; Francfort et al. 1994).

Both guidance away from turbine intakes and injuries inflicted by the turbine system (including hydrodynamic aspects of the scroll case and draft tube) are influenced, if not determined, by the size-dependent behavior patterns of the entrained species. Most bypass systems for juvenile salmon at major hydroelectric facilities, which involve screening juveniles from deep turbine intakes, seem to have been designed to oppose normal fish behavior in dam forebays. Normal behavior is surface oriented and in the direction of flow (Williams et al. in press). The development of intake screening arose from the observations that fish pulled to unnatural depths of turbine intakes accumulated in the gatewells associated with the tops of the intakes. Recent success with surface flow bypasses (Johnson et al. 1992; Skalski et al. in press) can be attributed to those facilities' closer matches to normal migration behavior (Williams et al. in press).

Damage to fish in turbines is not restricted to species that migrate between fresh water and the ocean. Many freshwater residents undergo extensive movements over the course of the seasons. Some of these movements are necessary for successful completion of the life cycle in different portions of a river system. Dams can create obstacles to population success similar to those for ocean-going species. In other cases, local resident fishes in impoundments can be drawn into turbines accidentally as a consequence of their normal feeding and rearing processes in the vicinities of turbine intakes. Thus, it may be useful to consider a diversity of fish behaviors to minimize turbine-induced damages under a wide range of hydropower installations.

In this section we briefly introduce the sources of fish mortality from turbine passage, give a synopsis of earlier literature reviews of fish behavior near turbines with their conclusions, review relevant and current basic scientific information about fish physiology and behavior, review on-site data at dams, and finally provide generalizations and implications for improved design of turbine systems. Because the majority of *in situ* studies have been conducted with salmonids, this fish group necessarily dominates the empirical aspects of this evaluation. Academic research on the physiology and behavior of fish, in general, provide additional guidance. The primary technological focus is on fixed- or variable-blade, Kaplan-type, vertical shaft propeller turbines, the type found most commonly in the Columbia River basin and at other large hydropower installations.

4.1 Sources of Mortality in Turbines

Although the need for technologies for passing adult salmon upstream past dams on rivers such as the Columbia was obvious and led to early legislative mandates (e.g., the Federal Power Act of 1920, which provided that the Secretary of Interior may require fishways at all federally licensed hydropower projects) (OTA 1995), the need to provide downstream passage for salmon smolts was controversial (Mighetto and Ebel 1994). The need was not clearly documented until Harlan Holmes conducted a set of experiments at the newly completed Bonneville Dam on the Columbia River (H. Holmes papers on file at the University of Washington, Seattle; Bell et al. 1967). Holmes estimated that between the years 1938 and 1948 there were losses of 11 to 14% of juvenile salmon in passing through the turbines. These estimates were derived from the experimental release of several paired groups of marked juvenile chinook salmon *Oncorhynchus tshawytscha*, one group of each pair being released so the fish would pass through the turbines and the other released in the tailrace, with conclusions about turbine-caused mortality being based on differential return of adults in subsequent years.

Later studies measured losses by recovering fish released in turbine intakes in nets suspended in the tailrace (Schoeneman et al. 1961). Bell (1981) summarized studies conducted to 1980 (Kaplan-type turbines), predominantly at mainstem dams on the Columbia and Snake rivers, with a range of turbine-induced losses from 6 to 32% of juveniles. Recently, studies have been focused on new turbine technologies and attempts to isolate direct turbine-caused mortality with fish released and collected individually with "balloon tags." Vertical axis turbines at Rocky Reach Dam showed about 4% mortality with fixed blades and 7% with variable blades (RMC and Skalski 1994). Kaplan turbines at Lower Granite Dam showed 5.2% mortality directly from turbines (RMC and Skalski 1995). Mathur et al. (1996) estimated 7%

short-term (turbine passage only) mortality in Kaplan turbines of Rocky Reach Dam when test fish were released near the intake's ceiling and 5.3% when they were released near the centerline.

The early findings stimulated engineering studies designed to identify factors responsible for turbine-induced mortalities and to seek engineering solutions. Physical models of turbines and turbine facilities were used (Cramer 1965; Cramer and Oligher 1960, 1961). These studies led to generalizations that have guided turbine design and operation ever since, not only in the Columbia River basin but elsewhere (Bell 1981; Turbak et al. 1981; Lucas 1962). In general, it was concluded that fish survival follows the efficiency curve of Kaplan turbines (the most common type in Columbia River system dams) with highest survival occurring at highest efficiency; turbines with negative pressure in the draft tube have a higher kill rate than those with positive pressure, pointing to the importance of maintaining an optimum tailwater elevation; and larger fish suffer greater mortality than smaller fish. Although early physical model studies could not establish realistic effects of clearances between parts such as runners, wicket gates, and hub, much of the mortality was presumed to occur at those interfaces because of the demonstrated importance of fish size. Recent studies with marked fish in actual turbines (using balloon tags) have confirmed the importance of these interfaces (work underway by Mid-Columbia Public Utility Districts). The studies have also indicated that submerged traveling screens installed in turbine intakes to bypass fish through gatewells instead of allowing them to pass through turbines are themselves a sizable source of biological damage to downstream migrating salmon (Koski et al. 1986; Wik and Barila 1990; Peven 1993; Nestler and Davidson 1995a). Spiral flow and pressure regimes in the draft tube also present concerns. Individual injury mechanisms associated with turbine passage were considered in detail in a Corps of Engineers workshop (USACE 1995).

4.2 Behavior of Salmonids

The early studies of fish mortalities at dams also stimulated studies of the behavior of salmonids. Biologists associated with hydropower facilities sought primarily to find ways to direct juveniles away from intakes. They examined the locations of fish in dam forebays (the water just upstream of a dam) and the relationships between fish passage and the depths of intakes. Natural and artificial cues (lights, bubble curtains, electric fields, and sound) were evaluated as guidance mechanisms. Early studies established the fundamental behavior pattern of juvenile salmonids as being surface-oriented and following flow. No amount of artificial stimulus has been shown to be sufficiently effective in guiding fish movements otherwise to justify full-scale or prototype testing in the field for application at large hydroelectric projects (Ebel 1981; Mighetto and Ebel 1994; OTA 1995). Surface-flow bypasses mentioned above rely on the natural stimuli of surface orientation for effectiveness.

Basic research on behavior of juvenile salmonids was also underway during the same time, although often independent of the applied studies (Hoar 1954; McDonald 1960; Arnold 1974; Thorpe 1982; Fangstam et al. 1993). Descriptions of swimming behavior in water flow, orientation of movements, flow cues to migration, and swimming speeds in different environmental situations occupied the interests of these basic researchers.

Intensive research on salmonids, both basic and applied, has shown several important considerations for understanding fish behavior as it affects entrainment injury and mortality at turbines. These considerations are: orientation with bulk water flow (toward turbines or alternative pathways), surface orientation of salmonid downstream migrants (the most studied) and other orientations of other species, and body orientation in flow that affects the likelihood of striking a turbine blade or other structures. Basic studies of fish behavior, described in the following section, suggest other important considerations, such as buoyancy and stability, obstacle recognition and avoidance, the sensing of acceleration in relation to fish orientation and directed movements, behavior in turbulent flow, and stress responses that may modify normal behavior.

4.2.1 Orientation with Bulk Flow

That downstream-migrating juvenile salmonids or other anadromous species should follow downstream water movement seems axiomatic. However, the degree to which this relationship holds in relation to fish entering turbines or guided to other pathways has been the subject of much study.

Spill is an alternative pathway for water and fish movement that has provided evidence of the complexity of flow-following by juvenile salmonids (Williams et al. in press). Spill refers to the release of water over dam spillways rather than through turbines (Figure 8). On the Columbia River, spillways are not at the surface, generally, but their crests can be as deep as about 50 feet (15 meters) for the typical Tainter gate-equipped spillways. Spill

ORNL-DWG 96M-1484

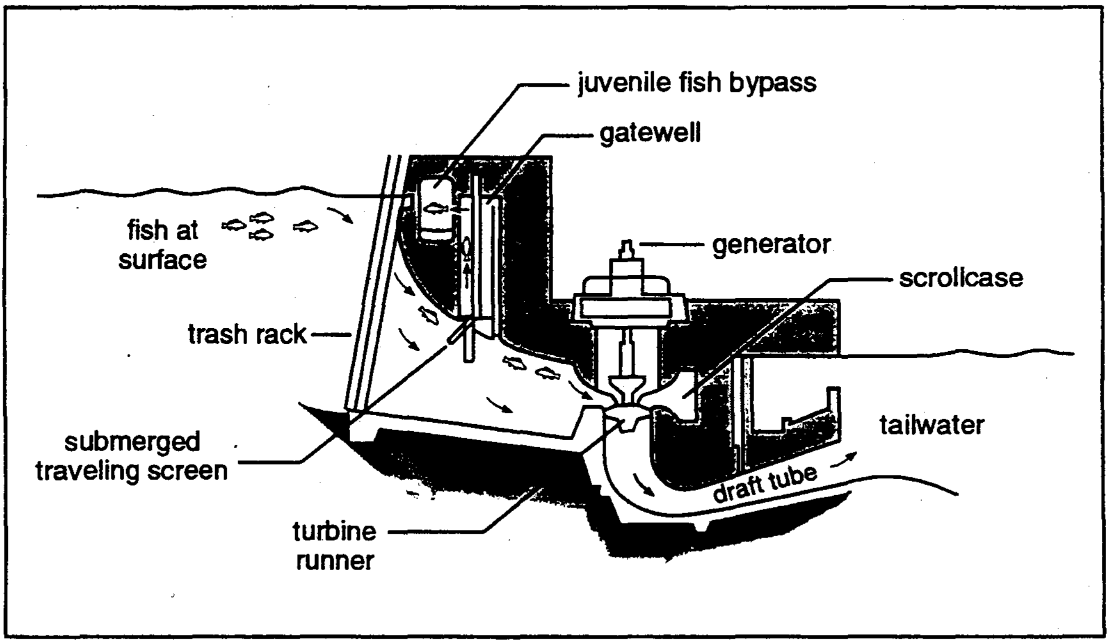


Figure 8. Generalized hydropower facility showing alternative water pathways through powerhouse turbines or spillway. Insets show cross-sections of a typical spillway and a spillway modified as a surface spillway.

volume can be small or large in relation to river discharge and turbine passage, depending on natural river discharge conditions (turbine capacity may be exceeded by total river discharge during high-runoff events) or discretionary and regulated operations that induce spill.

Because spill is recognized as being a more benign means of passing fish than through turbines [0 to 4% mortality (FPC 1994; NMFS 1995), but typically 0 to 2% for standard spill bays], extensive studies were conducted at mid-Columbia public utility district projects to define the relationships between spill volume relative to river flow and the resulting percentages of juvenile fish passed in spill (Biosonics 1983a,b, 1984; Raemhild et al. 1985). Spill volume was varied experimentally from 20 to 85% spill relative to river discharge. Non-linear response curves were found. For example, at Wanapum Dam in the spring of 1983, night-time spill of 20% of the instantaneous flow passed about 45% of the fish, while 50% spill passed 60% of the fish (Biosonics 1983b). In contrast, at Rocky Reach Dam during the spring of 1983, night-time spill amounting to 20% of the river flow was estimated to pass about 16% of the fish, spill of 50% passed about 30% of the fish, and spill of 80% passed about 55% of the fish (Biosonics 1984).

Similarly, studies were conducted at the federal Columbia River basin projects by the National Marine Fisheries Service as an aid to increasing smolt passage rate over spillways (Giorgi and Stevenson 1995). Numerous studies since 1983 at spill percentages between 37 and 66% (Kuehl 1986; Johnson and Wright 1987; Magne et al. 1987a,b; Oullette 1988; McFadden and Hedgepeth 1990) were evaluated by Giorgi and Stevenson (1995). At John Day Dam, spill effectiveness ratios (i.e., the relative number of fish following spill in relation to water flow) was 1.3 in 1987, 1.1 in summer 1988, and 1.4 in 1989. Giorgi and Stevenson (1995) concluded that the scattergram of data from 1993 showed a ratio of essentially 1. Our evaluation of these data suggests that averaging over seasons and a fairly limited range of spill percentages has obscured the underlying curvilinear nature of the response. That is, certain amounts of spill under the right conditions are likely to be more effective in passing fish than is indicated by the sheer bulk of flow. Detailed evaluation of research on spill effectiveness is beyond the scope of this review, but the point can be made that juvenile salmonids will use alternate pathways in lieu of turbine passage and not be governed by just water flow.

Spillway depth appears to influence spill effectiveness in passing fish. Raymond and Sims (1980) suggested that surface spill would be more effective than standard spill. They placed stoplogs in the spillway of John Day Dam to create a surface skimming of water for the spillway and found an enhanced number of juvenile salmon for the amount of water passed (Figure 8, right inset). Willis and Uremovich (1981) and Willis (1982) evaluated the ice and trash sluiceway at Bonneville Dam as a bypass system for juvenile salmonids, and found it passed about 40% of the fish approaching the project when there was no spill. Willis (1982) produced an estimate of spill effectiveness while studying the efficiency of the surface ice and trash sluiceway for passing fish at The Dalles Dam. At spills of about 10 to 60%, he found high fish passage (spill effectiveness) at low spill levels. Also aiding spillway passage is the fact that the spillway at The Dalles is aligned with the natural course of the river whereas the powerhouse is at right angles to river flow. Magne et al. (1987a,b) found that the ice and trash sluiceway at the second powerhouse of Bonneville Dam passed an estimated 81% of smolts passing the powerhouse in daytime and 30% at night. The efficiency of surface sluiceways in diverting fish from turbine intakes was generally in the neighborhood of 20 to 40% (Williams et al. in press). Success with surface spill and surface flow bypass systems at Wells Dam (89%; Skalski 1993) provide the rationale for a new generation of juvenile salmon bypass systems using surface flows (Johnson et al. 1992; Skalski et al. in press).

We conclude that studies with spill in conventional Columbia River spillways affirm the basic flow-following response of juvenile salmonids. However, for any specific spillway or set of spillways at a dam, the particular physical configuration will affect the percentage of fish that follow a water mass. There also tends to be a curvilinear response at any particular site of spill effectiveness in passing fish at different flows. The converse of this is also true, that is, there will be a curvilinear response for the percentage of fish that enter the turbine intakes when spill is occurring. A major factor affecting whether fish follow bulk water flow is the depth of withdrawal, with surface water having a greater likelihood of carrying fish than deep water, as we discuss below.

4.2.2 Surface orientation

There is a preponderance of evidence that juvenile salmon migrating downstream are oriented to the upper portion of the water column. Giorgi and Stevenson (1995) have reviewed much of the evidence, which includes numerous depth ranges and locations. The highly applied research on spill effectiveness at certain Columbia River dams, noted above, has reinforced this generalization. Entry into deep turbine intakes is thus a passage of last resort, rather than a preferred mode of migration.

Ice and trash sluiceways, located at the surfaces of dams, were studied in more detail recently. At Rock Island Dam, spill that was split equally between deep and shallow spill yielded 87% of the fish passing in shallow spill (Ransom et al. 1988). At Wanapum Dam, 4% of the total fish passing the dam passed through the sluiceway in 0.5% of the river discharge on a 24-hour basis (Ransom and Malone 1990). At Priest Rapids Dam in spring, a sluiceway that passed only 1.3% of the river flow passed 3% of the fish (McFadden et al. 1992). In summer, it passed 4% of the fish in 2% of the water. Spill in the sluiceway was judged to be twice as effective as spill in the typical, deeper spillway.

Studies at several dams have shown that juvenile salmon do not generally descend to significant depths unless no alternative is presented (Wagner and Ingram 1973; Dunn 1978). Field studies were reviewed by Eicher (1988). For example, in the forebay of Lower Granite Dam (Snake River), 92% of the smolts were found to be in the upper 36 feet of the water column.

Further evidence of surface orientation in the vicinity of turbine intakes comes from the fact that smolts are observed to accumulate in gatewells of unscreened turbine intakes (Long 1968; Long et al. 1970). When drawn by currents to intake depths, the fish orient to the ceilings of the intakes and seek openings (gatewells) to return to the surface.

Early studies of fish distribution in turbine intakes (e.g., Long 1968; Long et al. 1970) were conducted mostly with fyke nets suspended in the turbine intakes, which may affect fish distribution. Video imaging has indicated that fyke nets suspended in turbine intakes have a large, significant effect on almost all fish behavioral variables and some hydraulic variables (Nestler and Davidson 1995a). Thus, data obtained with fyke nets or at screens when fyke nets are operated may not represent both fish-behavioral and hydraulic features of an unobstructed intake. However, Raemhild et al. (1985) used hydroacoustic methods and found about 80% of the emigrating salmon smolts entered the turbine intake of Rocky Reach Dam on the Columbia River within 6.1 m (20 feet) of the intake ceiling, with the remainder passing in the lower 9 m (fish were somewhat less clumped near the ceiling at night, suggesting a partial breakdown of the surface orientation tendency at night).

Numerous hydroacoustics studies at each of the five mid-Columbia projects showed that smolts were concentrated in the upper portion of the water column, generally the upper one-third (several Biosonics reports). For example, Ransom et al. (1988) found that fish approaching Rock Island Dam were surface oriented. These data sets and reports should be analyzed further for information specific for fish species, life stages, and turbine intake arrangements.

High fish abundance near ceilings of intakes is the basis for current juvenile fish bypasses at most Columbia River basin dams, which use traveling screens extending from the bottoms of gatewells and into the turbine intake to enhance the numbers of fish that find the gatewell (Mighetto and Ebel 1994) (Figure 9). Fish are not all at the entrance ceiling, however, but extend into the center of flow. This is evident in the fact that fish guidance to gatewells by intake screens has been improved by extending the initial lengths further into the turbine intakes (Gessel et al. 1995). Extended length screens, still occupying only the upper portion of an intake, have been able to capture near or over 80% of the yearling chinook salmon migrants entrained in the turbine intake at McNary Dam (McComas et al. 1994) and Little Goose Dam (Gessel et al. 1995). For steelhead*Oncorhynchus mykiss*, fish guidance efficiency has exceeded 90%. The screens have altered local fish distribution, however, causing more water (and presumably fish) to flow in the lower portions of the intakes (Turner et al. 1993).

Despite vertical differences in fish distribution, juvenile salmonids often appear to be equally distributed horizontally within turbine intakes, as determined by studies at several Columbia River basin projects between 1977 and 1982 (Gessel et al. 1991). Johnson (1996), however, found statistically significant differences in horizontal distribution at Lower Granite Dam on the Snake River. It is likely that specific geometries of turbine intakes and screens, which differ among projects, can be used to estimate the percentages of fish entrained in different portions of the cross sections of the intakes, although such a complete analysis has not been done with these data.

Radiotelemetry studies of salmon smolts as they encounter dams in their downstream migration show fish near the surface and unable to orient to deep currents that would take them to the deep turbine intakes. The general pattern is for migrations of these fish to be delayed at the forebay (Giorgi et al. 1986, 1988a,b; Snelling and Schreck 1995). The transmitter-equipped juvenile salmonids move laterally back and forth along the dam or just upstream of it, apparently searching for a surface outlet. When none is found, the fish

ORNL-DWG 96M-1483

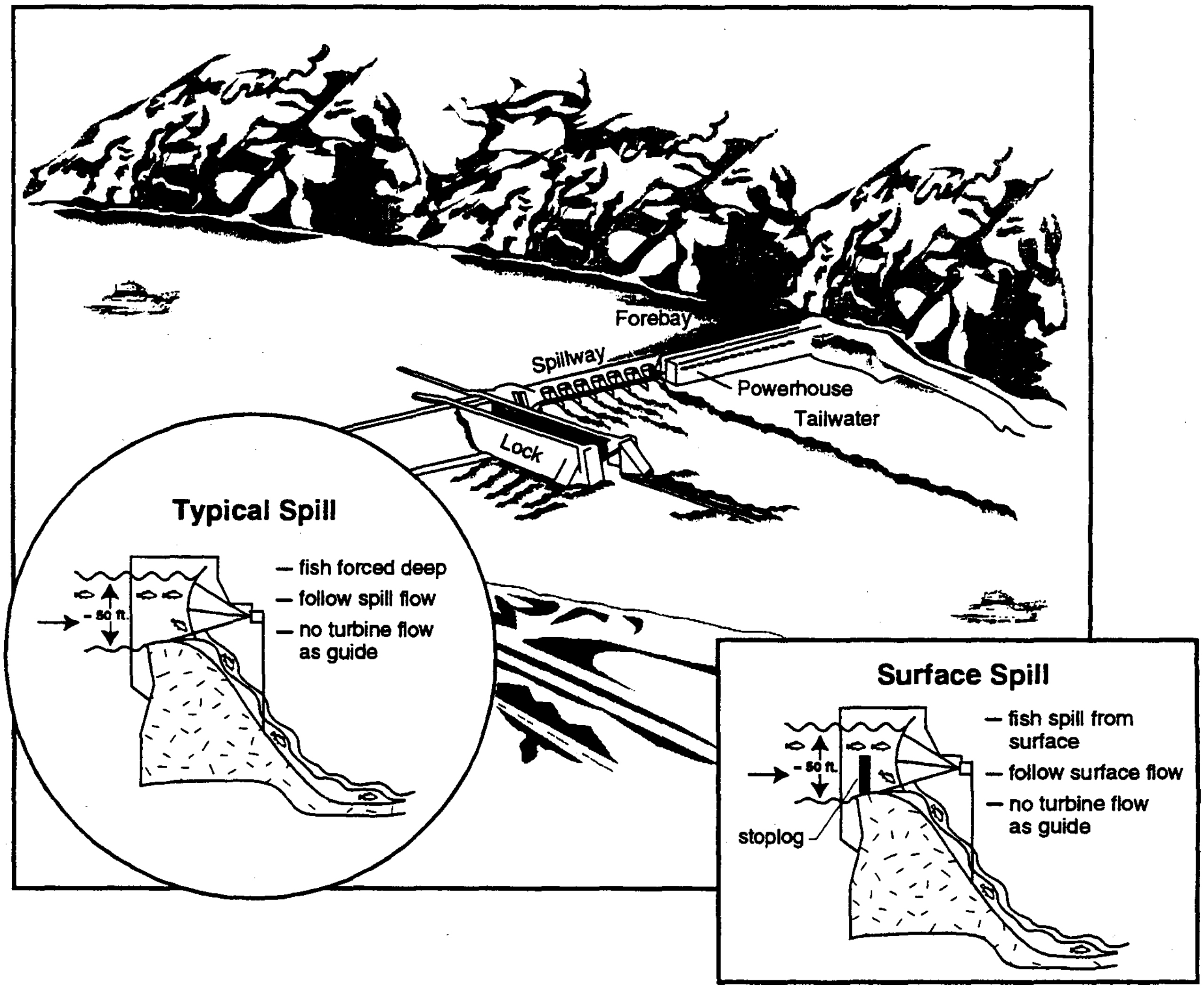


Figure 9. Generalized cross section of a Columbia River basin hydropower powerhouse, showing distribution of downstream-migrating juvenile salmon and fish-passage devices.

will descend (most often at night) to pass the dam through the turbines or turbine gatewell bypasses.

Several studies have suggested an increase in buoyancy with advancing stage of smoltification. Smoltification is the set of progressive physiological and behavioral modifications that occur in juvenile salmonids as they change from the parr stage (freshwater resident) to the smolt stage (migratory and in preparation physiologically for transition from fresh to salt water). Increased buoyancy is believed to assist a fish in attaching to currents for downstream migration with minimal energy expenditure. This feature would also tend to increase their use of surface layers in contrast to deep waters.

We conclude that the basic surface orientation of migrating juvenile salmonids has been abundantly demonstrated, although precise depth ranges vary locally. Entry to turbines at great depths is a last resort for continuing their migration. If an alternative at shallower depths is available, they will preferentially take it. Once in a turbine intake, fish orient to the upper portion of the water mass, often passing along the ceiling where traveling screens have been effective in removing them from the flow. Thus, their entry to the turbine itself will not be uniform across the water mass entering the turbine. Further report evaluation and data analyses will be needed to specify this distribution in a mathematically rigorous way for species, sizes, and intake geometries. Maximum rigor will be attained when each hydroelectric project is evaluated individually.

4.2.3 Body Orientation in Flow

Physical damages to fish in turbine systems (intake, turbine, draft tube) may depend on the fish's orientation as they enter. The simplest concept is of a fish moving passively with the water, and with no particular orientation. This "inanimate, neutrally buoyant object" model was dispelled early in studies of salmon migration in rivers. Ratter (1902) concluded that juvenile salmon in the Sacramento River, California, drifted downstream tail first, keeping their heads upstream to promote water passing through gills and for catching food. Smith (1982) used experimental observations of coho salmon *Oncorhynchus kisutch* to support the idea of fish orienting mostly upstream while drifting seaward. Recent laboratory flume studies by Nelson et al. (1994) have confirmed head-upstream swimming by chinook salmon underyearling migrants. Fish swam upstream at about one body length per second against the current as they either maintained position in the experimental flume or were swept downstream tail-first by higher velocities. Active swimming downstream was observed only in very low velocities. Sockeye salmon *Oncorhynchus nerka* smolts (yearlings or older), on the other hand, showed active downstream swimming in rivers that was not simply a matter of following currents (Brett and MacKinnon 1953; Groot 1965). Active swimming appeared to follow a compass orientation related to river and lake geography. Smolts entering a river from a lake swam actively with the currents (Groot 1982), a pattern that they may follow as they leave a reservoir and enter the flow of a turbine intake. Rainbow trout (steelhead) have been observed with infrared light to swim actively downstream at rates greater than water movement (Northcote 1962).

There have been some direct observations of fish orientation entering turbine intakes. Coho salmon yearling smolts approached an inclined plane screen installed in a penstock mostly oriented head upstream, based on visual observations and videotapes made through a viewing port of fish released into the penstock (Winchell et al. 1991). Video imaging of natural-run salmonid smolts (unidentified) in spring at McNary Dam showed an average of only about 3% (standard deviation 7.9) oriented head downstream with the current (range 0% to 33%) as they approached submerged traveling screens in turbine intakes with different camera locations and screen types (Nestler and Davidson 1995a). In summer, the percentage averaged 17.5 (SD 18; range 0-100), a significant seasonal difference. Few fish (about 8%) exhibited no control over their movements. At The Dalles Dam, however, Nestler and Davidson (1995b) found 42% of the salmonid smolts oriented head downstream as they approached the submerged traveling screens. Johnson (1996) indicated that hydroacoustic studies at Lower Granite Dam showed most smolts oriented head upstream and toward the surface. In contrast, Montén (1985) reported studies in which cuts on fish passing through turbines were tallied with the conclusion that the fish were oriented randomly as they approached the blades.

Flow instabilities in the intakes may greatly affect orientation of fish as they enter turbines. Nestler and Davidson (1995a,b) reported large flow instabilities in turbine intakes at McNary and The Dalles dams. Plotsky and Johnson (1996) reported transient vortices in intakes at Bonneville Dam that made hydroacoustic sampling impossible despite the desirability of testing the assumption that the vortices carry large numbers of smolts past screens and into turbines. The prevalence and effects of such vortices need to be established before generalizations can be made about fish orientations in turbine intakes.

Many basic studies have been conducted on Atlantic salmon *Salmo salar* in Europe and the northeast United States, with the prevailing view that migration is passive (Fried et al. 1978; McCleave 1978; Thorpe and Morgan 1978; Thorpe et al. 1981). Thorpe (1982) reasoned that there should be little advantage in a migrant expending scarce energy reserves by actively swimming. However, Arnold (1974) pointed out that migration is a complex response to currents, with a mix of passive and oriented movements. Recent experiments with Atlantic salmon have shown that active swimming is used for a considerable portion of the distance traveled even though it is a small proportion of the time (Fangstam et al. 1993). Thus, young Atlantic salmon may swim headed downstream while moving, but rest in backwaters for much of the outmigration period (Williams et al. in press).

Travel time studies in the Columbia River system, made possible with PIT-tag technology (Prentice et al. 1993), have shown marked species differences (Berggren and Filardo 1993), which may relate to migratory orientation and behavior (Williams et al. in press). Steelhead, in particular, have shown tendencies to migrate faster than the average velocity of the watermass in which they move, suggesting active downstream swimming at least part of the time.

Radiotelemetry studies by Schreck et al. (1995) in the Willamette River, Oregon showed yearling chinook salmon would exhibit directed downstream swimming in the faster reaches of the river whereas they moved more slowly (passively?) in slow reaches. When groups of fish were tagged and followed together, individuals in the "pack" exhibited numerous changes in relative longitudinal position, suggesting that individual fish migrate in spurts with periods of slower movement or rest.

Accelerating flow seems to influence the speed, and likely the orientation, of migration. Mundy et al. (1995 draft) related episodic high movement rates of yearling chinook salmon past the Prosser Dam on the Yakima River, Washington, to concurrent accelerations in flows. When the seasonal data on daily flows and daily fish movements were compared for the specific dates of fish presence, the fish appeared to be moving when flows increased. Achord et al. (1995) also noted a historical pattern of increased migration of chinook salmon yearlings on rising water flow. Our review of PIT-tag data from other studies (FPC 1994; Buettner and Brimmer 1995) suggests that this phenomenon is common.

If accelerating flow stimulates more active movement generally, it may signal a transition to head-first, downstream swimming. This hypothesis has been raised as potentially important for juvenile salmon migrations in the Columbia River basin (Williams et al. in press) but has not been tested. This phenomenon may also occur in the intakes of turbines, where the relatively quiescent waters of the reservoir are replaced by accelerating velocities in the intake and scroll case. Generally, the velocity at the upper end of a typical turbine intake on the Columbia and Snake rivers is 3-4 ft/s (about 1 m/s)(USACE 1995). The velocity gradually increases to 6-9 ft/s (about 2 m/s) as it enters the scroll case. The flow then rapidly accelerates to >20 ft/s (>3.5 m/s) through the wicket gates, and then to 50-60 ft/s (15-18 m/s) as it passes the blades and hub. The water then decelerates rapidly to 12-20 ft/s (3.6-6 m/s) as it turns to enter the draft tube. It continues to decelerate to 8-12 ft/s (2.4-3.6 m/s) in the tailrace. Because body orientation is likely important for estimating likelihood of strikes in turbines (Turnpenny et al. 1992), a possible relationship between body orientation and flow acceleration in the turbine intake warrants more detailed study. Also, extreme turbulence that may accompany these highest velocities immediately in front of the turbine runner may disorient fish, so that the "usual" behavior could be stymied and fish orientations suddenly become randomized (as suggested by the body-strike results of Montén (1985).

As indicated earlier in this report, variability among individual fish may be important. Although one fish may pass through a turbine aligned with the water flow, another may respond to changing fluid dynamics by altering its orientation. Consequently, estimates of the probabilities of injury (e.g., from blade strikes) may have wide confidence intervals. These confidence intervals may greatly exceed the average gain in survival by structural modifications to the turbine system, and thus be difficult to identify, test, and evaluate.

We conclude from this review that juvenile salmonids entering turbine intakes may be oriented in several ways, depending on the species and the migration tendencies of the fish at the time. The majority of underyearling chinook salmon (the smallest migrants) appear to move in a head-upstream manner. They likely maintain that attitude as they enter turbines. Most yearlings (the larger fish), especially steelhead, appear to swim rapidly, directed downstream in the riverine environment but oriented head upstream near bypass screens in turbine intakes. Yearling chinook salmon may show both types of orientation, but could be oriented head downstream in the accelerating flows of a turbine intake. All of these behaviors may be negated by rapid flows and turbulence at the entrance to turbine runners. Further analysis is needed of hydroacoustic and underwater television data related to submerged traveling screens as indicators of fish orientation as they enter turbines. These technologies need to be applied also at the entrances of turbine runners.

4.3 Behavior of Non-Salmonids

The relationships of the salmonid information to behavior of non-salmonids and resident fishes, including salmonids is problematical. Juvenile salmonids are attempting to move downstream, and passage through turbines is one route. Resident fishes without the migration urge likely are adapted to resist currents and water flow, the agents that would displace them from their normal habitats. However, some non-anadromous fish have extensive migrations within fresh waters that are intercepted by hydropower facilities, and thus some of their entrainment may be analogous to downstream-migrating salmon. Entrainment of non-migratory species is likely accidental and may relate to the degree to which each species uses habitats closest to the turbine intakes (FERC 1988, 1995). Entrainment probability and fish behavior for resident fishes is likely to be highly site-specific, depending on the habitats and species encountered.

The Federal Energy Regulatory Commission has begun to synthesize information obtained in entrainment monitoring studies it has required at small hydropower sites dominated by non-salmonids (FERC 1995). Its staff and contractor, Stone and Webster Environmental Technology and Services, Inc., surveyed limited-distribution reports of 45 studies east of the Mississippi River, predominantly in Michigan and Wisconsin, but also including sites in South Carolina, West Virginia, Ohio, Pennsylvania, and New York. The facilities were mostly small (less than 5 MWe), but some were up to 102 WE in electrical generating capacity. Although the emphasis of the review was on species and numbers of fish entrained and the factors affecting entrainment, some information on fish behavior in intakes was gleaned. Species included gamefishes (e.g., smallmouth bass *Micropterus dolomieui*, and walleye *Stizostedion vitreum*), panfishes (e.g., yellow perch *Perca flavescens*, and black crappie *Pomoxis nigromaculatus*), and forage fish (e.g., alewife *Alosa pseudoharengus*, white sucker *Catostomus commersoni*, gizzard shad *Dorosoma cepedianum*, and threadfin shad *Dorosoma petenense*). Most fish entrained were small, entrainment was episodic (brief periods of large numbers of fish entrained, with long intervals of low entrainment), and there was high variability in diel, seasonal, spatial, and species-specific entrainment rates.

The FERC analysis evaluated the cross-sectional distribution of fish drawn into intakes (FERC 1995). There were no consistent trends in vertical distribution (among sites or species). However, horizontal distribution was generally not uniform. About 80% of the fish occurred near the side walls and about 20% in the centers. Proximity to the shoreline was often a major factor determining relatively high fish occurrence, both among multiple intake bays and for locations in a single intake bay. This suggests an important tendency of entrained non-salmonids to follow shorelines in their normal behavior, which affects vulnerability to intakes and suggests proximity to sidewalls as consistent routes of passage through turbines.

The episodic nature of entrainment relates to both seasonality of life cycles and to seasonal cold stress (FERC 1995). Juvenile fish appear to be especially vulnerable, perhaps because of abundance and tendency to disperse, and perhaps because of poorly developed sensory abilities. They may also lack the strength or stamina to escape flows. Entrainment episodes often involve schools of juveniles, especially shad species. Even without cold stress (see below), juvenile non-salmonids may have poor orientation capabilities in currents that may suggest movement through turbines without directed avoidance behavior.

Fish guidance experiments with louvers indicate behavioral responsiveness of larger sizes of non-salmonids but poor guidance by small sizes (EPRI 1986). There was generally good guidance by fish larger than 1.2 to 2.4 in (3-6 cm) long. Guidance decreased rapidly for striped bass *Morone saxatilis* less than 1.2 in (3 cm) and for white catfish *Ameiurus catus* less than 3.6 in (9 cm). High proportions (>75%) of anadromous American shad *Alosa sapidissima* and blueback herring *Alosa aestivalis* were guided by louvers in the autumn at Holyoke Dam on the Connecticut River (Harza and RMC 1993).

Entrainment of resident fishes in bulb turbines has received more attention than other turbine types, largely because of the use of this technology in inland rivers such as the Ohio River (FERC 1988) and in tidal hydropower (Dadswell et al. 1986). Regardless of turbine type, the behavior patterns that lead to initial entrainment are germane. The results of studies of turbine-induced fish mortality in non-salmonid waters are highly varied. Spectacular damages were suffered by high numbers of large and important fish species (American shad, striped bass) in the Bay of Fundy (Dadswell et al. 1986). Other facilities, such as the Racine and Greenup/Vanceburg projects on the Ohio River have had few occurrences of entrainment damages (WAPORA, Inc. 1987; Olson et al. 1987; Olson and Kuehl 1988). Entrainment injury and mortality rates in tidal waters are clearly affected by fish size (larger ones are more susceptible to damage), species (clupeid fishes of the herring family are most sensitive), and schooling behavior (herrings that moved in and out of the tidal embayment on a daily cycle were badly affected). In freshwaters of the Ohio River, few game fish are entrained, but there were many schooling gizzard shad (clupeids) and freshwater drum *Aplodinotus grunniens*. In general, the few larger gamefish that were entrained in Ohio River facilities suffered high mortality.

The susceptibility of fishes to entrainment because of biological behavior varies seasonally and among species and life stages. Holland et al. (1984) summarized existing information on adult fish movements through dams on the upper Mississippi River. These data were further analyzed by Normandeau Associates, Inc. (1986). The movements of most gamefishes do not take them through dams and most interpool movement occurs in high flows when considerable water is spilled. Studies at the Racine project (Ohio River) showed gamefishes were entrained only occasionally. Early life stages (eggs, larvae, and pelagic juveniles) of several species are essentially planktonic and they drift with water during the spring and summer spawning periods. Water bodies with large numbers of species with these life-history patterns can be expected to show large numbers of fish entrained in turbines. Survival of these early life stages is high, however. As these fish grow, schools of juveniles occupying the open waters (especially gizzard shad and freshwater drum) remain susceptible, and entrainment damages to these ages are higher as their size increases (WAPORA, Inc. 1987). Gizzard shad schools usually occur in the top 10 feet (3 m).

There is some indication that resident fishes are more vulnerable in autumn and winter than in warm seasons (FERC 1995). Extreme cold or sudden temperature declines can make fishes comatose and they will drift into intakes. This is a common problem at steam electric generating stations, which entrain large numbers of threadfin shad on intakes in cold winters (McLean et al. 1980). A high percentage of alewife entrained annually at one hydropower facility occurred during one 1-week period in early January, and this was accompanied by a high entrainment of walleye (due either to vulnerability while feeding on moribund alewife or because of their own debility). FERC (1995) suggested that there is sufficient information about the occurrence of entrainment during periods of cold stress that these episodes could be predicted from weather data. Comatose or moribund fish are unlikely to exhibit any avoidance reactions or controlled body orientation that would cause them to differ from passive particles in transit through turbines.

We conclude that schooling behavior of juvenile fishes in habitats near turbine intakes is a major factor in susceptibility of non-salmonid and resident species of fish to entrainment. They probably exhibit little avoidance or orientation behavior once entrained except for proximity to walls of the turbine intakes that reflects nearby habitat and shoreline-oriented movements. Cold water temperatures sufficient to make fish comatose will increase vulnerability to being entrained and result in poor or no orientation and avoidance behavior during transit through turbines.

4.4 Basic Studies of Fish Behavior

Few non-salmonids have been studied in actual turbine intakes the way salmonids have been. Therefore, our discussion centers around basic features of the morphology, physiology and behavior of fishes as a group that can affect their responses to being passed through turbine systems. We emphasize features that could affect computational fluid dynamic modeling of fish movement, particularly deviations from movements projected for a neutrally buoyant particle.

4.4.1 Buoyancy and Stability

The risk of mechanical injury to fish by being struck by a turbine runner blade appears to be related to the zone of fish passage through the turbine in relation to the hub (USACE 1995). This location is, in turn, related to the position of the fish in the water column of the turbine intake, which depends partly on the buoyancy of the fish. The Corps of Engineers workshop (USACE 1995) considered the most critical uncertainties regarding runner-blade strikes to be whether or not fish remain neutrally buoyant within the turbine, whether buoyancy is species- and size-specific, and whether it is affected by pressure changes in the intake. Computational fluid dynamics modeling should take any differences from neutral buoyancy into account.

Fish are denser than the water they live in, and unless they have some mechanism for compensating for this difference, they sink (Alexander 1993). Buoyancy adaptations include hydrodynamic forces during swimming, fats and oils in specific tissues such as the liver, and gas-filled swim bladders. Densities of most fishes are reduced to within 1% of the surrounding water by these adaptations. Because tissues of different density are distributed nonuniformly in the body, the center of gravity (for sinking) is usually different from the center of buoyancy. The centers of buoyancy of fishes with swim bladders are generally slightly below the center of gravity, making the equilibrium of fish unstable; this is why dead and comatose fish float upside down. These points are important for considering whether fish can be modeled as neutrally buoyant particles for evaluations of turbine passage.

The most commonly found fish species have swim bladders, which are gas-filled floats that can match the densities of fishes to that of the water in which they swim to within about 0.5%. Use of low-density gas is an exceedingly efficient way of balancing density of bones and other dense tissues (Alexander 1993). Gas bladders occupy only about 7% of the volume of a freshwater fish and 5% of a marine one.

Although efficient for equilibrating buoyancy at a constant depth, gas bladders offer severe disadvantages for rapid changes in depth, such as occur when fish are drawn into deep turbine intakes from surface waters. Swim bladders expand when fish swim nearer the surface, where the pressure is less, and are compressed when it swims deeper. In accord with Boyle's Law, a swim bladder at a depth of 10 m is compressed to half its volume at the surface and it shrinks by half again at 20 m. Thus, the density of a fish with a swim bladder matches that of the water only at one depth, unless the quantity of gas in it is adjusted. As a fish rises a little, its density will decrease, making it tend to rise further. Conversely, if it sinks a little its density will increase and it will sink more. Most fish hover (use their pectoral fins in a back and forth motion) to make adjustments to differences in density within a fairly narrow bound. Jones (1952) found perch could not hover by fin movements alone at pressures more than 16% beyond the pressure to which they were adapted. Active swimming to desired depths, which many fish do, is required beyond this point.

Slow depth adjustment of buoyancy is made possible by gas secretion and absorption across specialized tissues of the bladder membranes, a process that has been studied for over 100 years. This equilibration process generally occurs at a rate equivalent to a few meters of depth per hour (the fastest appears to be about 2.5 m/h; Alexander 1993). Therefore, a fish with a gas bladder that is drawn rapidly (within seconds) into a turbine intake will be increasingly more dense than a neutrally buoyant particle as the depth and pressure increase. It will become more buoyant again as it passes through a draft tube and enters the tailrace at near-surface pressures. Fish drawn from mid-depths of the forebay and released at essentially surface pressures in the tailrace may be over-buoyant and float to the surface. These changes can be calculated based on Boyle's Law and a knowledge of the depth from which the fish originated.

A complicating factor in gas-bladder-induced buoyancy is the ability of some fish to evacuate gas from their bladders, usually by way of a vent to the mouth area. Salmonids have such a vent (are physostomous); the freshwater basses, for example, do not (are physoclistous). When external pressure drops rapidly, as it does in the exit of a turbine, gas in the expanding swim bladder may be released, allowing the fish to become more dense rapidly. Although such gas evacuation would not affect buoyancy in the turbine intake or turbine itself, it would affect buoyancy in the draft tube and tailwater. In principle, gas evacuation and rapid change in buoyancy would be most likely to occur in fish that have been acclimated to high pressures of deep water in the forebay of a dam. Computational fluid dynamics models that seek to understand the delivery of fish downstream of a dam may need to take such changes into account. There is no direct information available on whether such gas-bladder evacuation actually occurs in turbine passage, the pressure changes that would induce it, and the rapidity with which it would occur. Harvey (1963) suggests that the pneumatic duct connecting the bladder with the outside becomes constricted under rapid pressure drops and gas is not expelled. Indirect evidence from generally better survival of physostomous fishes in turbine passage suggests that it may be occurring.

Buoyancy mechanisms other than swim bladders may be important for fish in some turbine intakes. Dense fish without swim bladders generate upward hydrodynamic forces as they swim equal to the difference between weight and buoyancy upthrust. Sharks and sturgeons accomplish this with large pectoral fins that cannot be folded and asymmetrical tails that generate an upward thrust. Tunas have symmetrical tails but a prominent caudal peduncle and the same stout pectoral fins that provide upthrust (Magnuson 1978). Paddlefish *Polyodon spathula* have an added planing surface in the form of a large snout (which compensates for the high drag of a large mouth gape used for plankton feeding).

The freshwater pelagic (open water column) members of swim-bladderless fish, especially paddlefish (sturgeons are largely bottom dwellers), are at special risk of being entrained in turbine intakes because they must cruise constantly in the water column to keep from sinking. Once they have lost hydrodynamic control (as they probably do in a turbine intake where water may drag them along), they will sink. The point of loss of hydrodynamic control may be calculated. Like airplanes, fishes that use fins as fixed hydrofoils have a minimum speed (the stalling speed) below which the fins cannot generate the required lift. This speed can be calculated for species and individuals of different sizes from standard equations, and has been for selected examples (Alexander 1990 and textbooks on aerodynamics). Thus, the degree of hydrodynamic control, the location in the intake where this control is lost, and therefore the tendency for sinking (and resultant trajectory through a turbine) can, in principle, be estimated for these entrained fish. The location in the draft tube where there is sufficiently low turbulence for re-establishment of hydrodynamic control (and near-neutral buoyancy) may also be important. Although such an analysis need not be carried out for all fishes, the approach may aid in resolving site- and species-specific problems.

Fish that compensate for their otherwise high density by using fats, oils, or (in some cases) especially watery tissues and poorly ossified bones are of little concern for hydropower turbines. Their circum-neutral buoyancy will remain constant through turbine passage, and they can be modeled as such. Most such fishes are marine (Alexander 1993), where they may be of concern only for tidal hydropower. Sharks have especially large and oily livers as well as using hydrofoils for depth control.

We conclude from this review that models of fish trajectories cannot assume neutral buoyancy throughout the time a fish passes through a turbine. Fish without swim bladders that depend on activity to maintain themselves will likely lose control and be negatively buoyant. With numerical values depending on initial depth in the forebay, fish with swim bladders will become progressively more dense as they descend to the turbines and then positively buoyant as they are discharged to the draft tube and dam tailwater. Whether these differences will be significant for modifying fish trajectories should be established from the computational fluid dynamics modeling studies using known pressures in each part of the turbine and Boyle's Law acting on fish with gas bladders.

4.4.2 Obstacle Recognition and Avoidance

Turbines, especially wicket gates and rotating blades, are physical obstacles in the path of a moving fish. Turbine housings are solid walls, although Bell (1981) notes that there is a hydraulic "cushion" of water moving laterally after impact.. Both physical contact and shear at the surfaces of these structures can be damaging to fish. The degree to which fish are able to detect and avoid the physical obstacle in the brief time frame of passage will affect the likelihood of damage and the ability of computational fluid dynamics models to predict travel pathways (trajectories). It is also possible that changes in water flow patterns in the intakes will be perceived as an "obstacle" and the fish may initiate avoidance before the physical structure of the turbine itself is reached.

An avoidance reaction can possibly remove a fish from danger. On the other hand, a rapid change in orientation (e.g., the angle of approach to a turbine blade) can influence the damage inflicted, perhaps detrimentally. The Turbine Passage Survival Workshop (USACE 1995) identified an understanding of how fish detect velocity changes and subsequently control their vertical movements as a critical uncertainty. Aside from vision, which is likely unavailable in a dark turbine intake, fish sense obstacles through the lateral line system.

The lateral line system in fishes is a sensory pathway for detection of fluid movement for which humans have no counterpart (Bleckman 1986; Popper and Platt 1993). A system of tubes beneath the skin of the lateral musculature and head is connected to the outside water and contains sensory cells for the detection of motion in the enclosed fluid. Water displacements and pressure waves that are formed by any pulsating, vibrating, or moving object are detected by the lateral line. The lateral line is especially adapted to detecting the low-frequency pressure waves that may differ in timing from one end of a fish to the other (more typical "sound" that affects the whole body simultaneously is detected by the ear). The ear and lateral line form a continuity of perception for a broad spectrum of frequencies and forms of pressure waves. The lateral line is the organ fish use for the identification and localization of stationary and moving objects, in conjunction with or in lieu of (in darkness) sight.

Because any object moving through water (or water passing an object) creates a set of pressure waves, the aquatic environment is a collage of waves. A moving fish creates waves that are reflected from other objects and perceived by the fish's lateral line. The fish thus recognizes that an object is present and apparently develops an understanding of the shape, position, and motion of an object encountered repeatedly (for blinded fish can be trained to recognize specific object stimuli such as different-sized glass disks as cues for punishment or reward). Other moving objects (or stationary objects in moving water) create their own waves, which are received by a fish's lateral line system. The lateral line has been documented to be an important sensory component of prey recognition, feeding, predator recognition, predator avoidance, avoidance of physical structures, and shoaling (schooling) behavior. It is the most likely sensory system for fish to use in identifying and reacting to structural features of a turbine system. It now seems clear that the lateral line is primarily used in hydrodynamic interactions at very short distances, on the order of the body length of the receiver (Kalmijn 1989). The system responds to a range of about 10 to 200 Hz.

Turbine blades and wicket gates would perhaps be most analogous to a predator, for which the lateral line system of the prey gives warning of imminent capture, allowing quick movement sufficient to move the target safely away from the predator. The ability of a fish to detect and avoid obstacles in a turbine sufficient to affect likelihood and geometry of strikes is questionable, considering the short distance for reception and the rapid rate at which fish encounter the obstacles (because of both rapid water flow and movement of the runner blades). An ability to make avoidance reactions also would depend on the degree of hydrodynamic control being maintained by the fish at the moment. On the other hand, any rapid detection and avoidance responses on the part of a fish as it encounters a wicket gate or runner blade could alter the ability of the fish to pass around the object, thus causing it to deviate from the theoretical flow lines expected in CFD models. A more blunt object would project more prominent waves, thus enhancing a fish's ability to detect it. Turnpenny et al. (1992) showed less damage by the blunt faces of the thicker portions of turbine blades near the hub than the slimmer blade tips. Establishment of sensation as a cause for fewer strikes must await studies of live fish to compare with those of freshly killed fish, as used by Turnpenny et al. (1992).

We conclude that the lateral line has great sensitivity over relatively short distances; it can induce burst swimming and changes in fish orientation, and these may affect fish orientation in a fluid dynamics model. These effects may occur near the walls of turbine intakes at a distance from the runner. It is unlikely, however, that lateral-line sensing of obstacles in turbines themselves occurs fast enough to affect fish orientation markedly in the very rapid passage times.

4.4.3 Sensing acceleration

Fish moving with a mass of water and out of sight and lateral-line sensing of walls or other boundaries might be viewed as unaware of their net displacement. In a perfectly steady flow this may be true. However, if the water accelerates or slows, the fish is able to sense this change in rate of movement (linear acceleration) by means of the inner ear. Sensing acceleration or deceleration may be important as cues for body orientation and mode of swimming, as noted above (where accelerating flows tended to cause more rapid fish passage and possibly downstream swimming). Increased turbulence would be recognizable as angular accelerations, and perhaps stimulate changes in body orientation, also.

The inner ear of vertebrates is involved with both auditory (hearing) and postural (body orientation) senses (Popper and Platt 1993). Although the semicircular canals and the utricle of the inner ears have been believed to be the structures that sense acceleration, the current view is that all of the component organs of the inner ear provide major inputs to both postural control and hearing. Portions (the semicircular canal organs) tend to respond to angular accelerations whereas other portions (the otolithic organs and the nonotolithic macula neglecta) respond to linear accelerations. Otolith organs are liquid-filled pouches that each contain a dense mass of some crystalline forms of calcium minerals (called otoliths--earstones--, which are commonly used in aging fishes because the minerals are deposited concentrically as fish age). Sensory cells detect movements of the otoliths within the pouches in response to changes in acceleration. Much is known about the anatomy and function of these organs (Popper and Platt 1993), which undoubtedly come into play as fish follow their trajectory through a turbine system.

There is little firm evidence on which to form conclusions about the effects of sensing accelerations, other than what was discussed earlier. The degree to which fish change orientation in response to changes in linear and angular acceleration in a turbine system is not known but could be of great significance to computational fluid dynamics models of fish trajectories.

4.4.4 Behavior in Turbulent Flow

Once a fish has left the turbine and initial part of a draft tube, it enters a zone of high turbulence in the lower draft tube and tailrace. If the goal of a fish-friendly turbine system is to deliver fish into a normal migration environment downstream of the dam, then reorientation of fish in the turbulent tailrace will be necessary. Disorientation and physiological stress there may be a major cause of mortality through predation (Long et al. 1968). Few studies have been conducted of fish behavior in high turbulence. Passive movement of positively or negatively buoyant objects may be the best model (see above), especially in the most turbulent zones. However, Shtaf et al. (1983) attempted to define experimentally the influence of lesser amounts of turbulence on fish behavior and showed several types of behavioral responses in the roach *Rutilus rutilus* and minnow *Phoxinus phoxinus*. The existing experimental work is embryonic, at best, and it is now of little practical use for turbine system designs or modeling. Nonetheless, the work suggests experimental techniques and approaches that may be usefully explored to establish whether fish in the turbulent draft tube and tailrace modify their trajectories based on turbulence.

Work is currently underway to develop theoretical concepts of fish migration in rivers that take into account a probable use of turbulent flows to assist downstream movement beyond passive attachment to bulk flow (Williams et al. in press). The notion is that migrating juvenile salmon probably use features of unsteady flow in rivers such as turbulent bursts, vortices, and waves to find regions of relatively high velocity to speed their migration. This use would imply a sensory ability to detect these features and behavior to establish a beneficial orientation in them. Turbulence in a draft tube and tailrace is likely much greater than in a natural river except at waterfalls. Because the outlet of a turbine imparts a "whirl" component (USACE 1995), fish may sense this whirl as a natural vortex and orient to it in ways that move them rapidly toward the periphery. The periphery, however, is a draft tube wall, which may impart abrasions on impact.

We conclude that the use of unsteady fluid flow in migrations and turbine intakes is speculative at this point, but may lead to focused research of value to design of turbine systems that better match the natural behavior of juvenile salmonids.

4.4.5 Stress

Stressed fish may not behave normally, which could affect their performance in turbine systems. In the context of turbine-effect studies, stress has been used in a general sense to describe disorientation, loss of equilibrium, stunning, abnormal swimming behavior and energy depletion, usually as a *result* of turbine passage (USACE 1995). In other contexts, stress is related to specific physiological changes in enzyme systems and measures of blood chemistry (Adams 1990). Examples of sensitive indicators of stress are the capacities of fish to osmoregulate, mount an immune response, resist disease, respond physiologically to another stressful factor, swim, avoid predators, and learn (Schreck 1990). Numerous stress-induced physiological events alter the capacity of fish to perform various physiological and behavioral operations or functions. The degree of pre-existing stress in fish that enter a turbine intake may alter many of the behavioral features discussed in the preceding sections.

Juvenile salmonids that pass through turbines in the Columbia River, for example, are often under some degree of stress (NRC 1996; Williams et al. in press). For example, gas bubble trauma affects juvenile migrants at times when large amounts of water are spilled at dams and atmospheric gases become supersaturated (Bouck 1980; Weitkamp and Katz 1980). Bubble formation in tissues likely affects buoyancy to some degree and also the changes in buoyancy that might be expected during turbine passage. Various infectious diseases are present in migrating salmonids. High water temperatures in reservoirs result in migrants being exposed to temperatures considerably above their physiological optima and often close to lethal levels. Recovery from the physical trauma of turbine passage at upstream dams is not likely to be complete when fish reach the next dam in the series of eight from the middle Snake River to the mouth of the Columbia River.

The episodic occurrence and seasonal timing of entrainment of many non-salmonids in turbines leads to the conclusion that cold stress is a significant factor, as discussed above. A comatose or moribund fish is unlikely to exhibit avoidance or orientation behavior in a turbine intake that would affect turbine-induced mortalities. Whether cold stress makes fish more or less vulnerable to physical damages from turbine passage is not known.

The importance of preexisting stress levels for fish performance in turbine passage (especially as it affects trajectories) is not well known (Schreck et al. 1984; Bjornn 1992), except for strong inferences about effects of cold stress. Attempts to relate trajectories and injuries to most preexisting stresses have generally been inconclusive in numerous hydroacoustic studies in the mid-Columbia River (several studies by Parametrix, Inc. for the Grant County Public Utility District). Suggestions have been made, however, that testing of fish behavior in turbines should include background information on preexisting stress levels, and perhaps experiments should use fish in both test and control lots that have been given known amounts of prior stress (USACE 1995). We agree with these suggestions, for it is important for modeling of fish trajectories to know whether the behaviors modeled and responses seen are representative or skewed by virtue of a preexisting stress.

4.5 Measurement Concerns

Although it is desirable to have more accurate information on fish behavior and orientation in turbine intakes, especially as fish approach the turbine runner, there are important limitations for making observations. Realistic expectations of further research are necessary.

Direct observation in physical models is hampered by elements of scale. Although the turbine system can be scaled to a smaller size, the fish cannot. The types of behaviors examined in this report are often not only species-specific, but also size-specific within a species. Use of very small fish (e.g., fry or aquarium species) as surrogates for larger ones compromises the need to observe relevant behavior.

Video observation and recording of fish positions in actual turbine systems seems feasible based on experiences viewing juvenile salmonids at traveling screens at fish bypass systems at Columbia River Basin dams (Nestler and Davidson 1995a,b). The technique has obvious limitations in turbid water, but would be useful in clear-water sites where representative fish species are entrained. However, positioning cameras in the extremely high velocities near the turbine runners without disrupting the fish and water flows that are of interest may prove to be infeasible. Nestler and Davidson (1995a,b) relate placement difficulties with even the slower velocities at the bypass screens.

Hydroacoustics has provided valuable data in turbine intakes at a distance from the runner, but turbine "noise" affects data analysis increasingly as hydrophones are placed near or directed toward the turbine (FWS 1992). The background noise affects the detection of small fish most strongly, and these are the sizes often of concern. Experimentation with different sound frequencies may be necessary before hydroacoustic detection can be used in close proximity to the turbine runners.

Forensic analysis of fish that have been passed through turbines experimentally (subsequent recovery often facilitated by use of balloon tags) may be improved to the point where location and orientation can be inferred more accurately. Balloon tag studies at Rocky Reach Dam on the Columbia River were able to resolve a difference of 1.7% in mortality of smolts passing through turbines with fixed versus variable blades, leading engineers to conclude that the additional injury rate was induced by a small gap between the hub and the blade of the variable pitch turbine (RMC and Skalski 1993). However, many sources of physical damage in turbines result in similar pathologies. The limits of inference may be too severe for meaningful engineering redesign of turbines.

Without implying too much pessimism, we conclude that the practical limits of observation and measurement of fish and flows in the proximity of turbine runners using existing technologies may inhibit development of much information that is germane to developing a more fish-friendly turbine.

4.6 Conclusions and Recommendations

1. Studies with spill in conventional Columbia River spillways affirm the basic flow-following response of juvenile salmonids. There will be a curvilinear response for the percentage of fish entering the turbine intakes when spill is occurring. A major factor affecting whether fish follow bulk water flow is the depth of withdrawal, with surface water having a greater likelihood of carrying fish than deep water.

   Recommendation: The first priority for a fish-friendly turbine *system* in migratory salmonid waters should be one that bypasses as many downstream-migrating fish as possible along these fish's natural surface-oriented migration pathway away from deep turbine intakes.

2. The basic surface orientation of migrating juvenile salmonids has been abundantly demonstrated. Once in a turbine intake, fish orient to the upper portion of the watermass, often passing along the ceiling where traveling screens have been somewhat effective in removing them from the flow. Horizontal distribution is more uniform, but probably is affected by vortices and other flow instabilities characteristic of a site. Thus, juvenile salmonid entry to the turbine itself will not be uniform across the cross-section of the watermass entering the turbine.

Recommendation: Further report evaluation and data collection and analyses are needed to specify fish cross-sectional distribution in a mathematically rigorous way for species, sizes, and intake geometries in order to quantitatively specify fish trajectories through turbines.

3. Fish entering turbine intakes may be oriented in several ways, depending on the species and the migration tendencies of the fish at the time. Underyearling chinook salmon (the smallest migrants) appear to move in a head-upstream manner. They likely maintain that attitude as they enter turbines. Yearlings (the larger fish), especially steelhead, appear to swim rapidly, directed downstream. Yearling chinook salmon may show both types of orientation, but could be oriented head downstream in the accelerating flows of a turbine intake.

Recommendation: Further analysis is needed using hydroacoustic and underwater television data, both new and as related to submerged traveling screens, as indicators of species- and size-specific fish orientation as they enter turbines.

4. Schools of juvenile non-salmonid fishes that reside in the open waters of large rivers or tidal estuaries are most vulnerable to entrainment in turbine intakes. Their entrainment is accidental and not related to flow-following behavior. Particularly susceptible freshwater fishes are juvenile gizzard shad and freshwater drum. Few adult gamefishes, which are more oriented to bottoms and shorelines, are vulnerable. Horizontal distribution of entrainment is often not uniform for these species. Susceptible freshwater fishes are generally forage species with high reproductive potential. There has been no special effort to study the orientation of these fishes in turbines.

Recommendation: Considerably more justification would be needed for commitment of major expenses for fish-friendly turbines in freshwaters occupied by non-migratory species.

5. A high percentage of non-salmonid entrainment in hydropower turbines, as in steam electric power station intakes, is of forage species that are made comatose by rapid temperature declines or prolonged cold weather in autumn and winter. Fish in these conditions are not likely to exhibit avoidance or orientation behaviors that would cause them to differ from passive particles during transit through turbines.

Recommendation: Simulation of many non-salmonids as passive objects seems appropriate.

6. Models of fish trajectories cannot assume neutral buoyancy throughout the time a fish passes through a turbine. Fish without swim bladders that depend on activity to maintain themselves will likely lose control and be

negatively buoyant. With numerical values depending on source depth in the forebay, fish with swim bladders will become progressively. more dense as they descend to the turbines (the swim bladder is compressed as water pressures increase) and then positively buoyant as they are discharged to the draft tube and dam tailwater.

> ***Recommendation:*** The significance of differences from neutral buoyancy and of changes in buoyancy during fish trajectories through a turbine should be established from modeling studies of fish with a range of constant and changing densities.

7. Lateral-line sensing of obstacles occurs rapidly and can affect fish orientation . However, it is unclear whether sensations in turbines will affect fish orientation markedly in the very rapid passage times.

> ***Recommendation:*** Further study of reaction times is needed. Models can tentatively assume that orientation of fish as they enter the scroll case will be retained as they transit the turbine itself (or at least that the fish will not be able to control its orientation in a turbulent environment), under the assumption that reaction times are too long for the rapid flow rates.

8. The use of unsteady fluid flow by fish in migrations is speculative at this point, but may lead to focused research of value to the design of turbine systems, especially draft tubes and tailwaters, that better match the natural migratory behavior of juvenile salmonids.

> ***Recommendation:*** Research on the orientation in and use of unsteady flows by migrating juvenile salmonids is needed.

9. The importance of pre-existing stress levels for fish performance (especially as they affect trajectories) in turbine passage is not known. It is important for modeling of fish trajectories to know whether the behaviors modeled and responses seen are representative or skewed by virtue of a pre-existing stress.

> ***Recommendation:*** Testing of fish behavior in turbines should include background information on pre-existing stress levels, and experiments should use fish in both test and control lots that have been given known amounts of prior stress.

10. Practical limits of observation and measurement of fish and flows in the proximity of turbine runners may inhibit development of much information that is germane to developing a more fish-friendly turbine.

> ***Recommendation:*** Innovative means for obtaining information on fish behavior near turbine runners should be pursued, but there should be realistic expectations about the feasibility of this research.

5. Literature Cited

Achord, S., D.J. Kamikawa, B.P. Sandford and G.M. Matthews. 1995. Monitoring the migrations of wild Snake River spring and summer chinook salmon smolts, 1993. DOE/BP-18800-2, U. S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Adams, S.M. 1990. Biological indicators of stress in fish. American Fisheries Society Symposium 8, Bethesda, Maryland.

ARL (Alden Research Laboratory, Inc.). 1996. Development of a more fish tolerant turbine runner. Technical Memorandum #2: Development of Biological Design Criteria. Draft. ARL, Inc., Holden, MA. 32 p. + figures.

Alexander, R.M. 1990. Size, speed, and buoyancy adaptations in aquatic animals. American Zoologist 30:189-.

Alexander, R.M. 1993. Buoyancy. Pages 75-97 in D. H. Evans, editor. The Physiology of Fishes. CRC Press, Boca Raton, Florida.

Arnold, G.P. 1974. Rheotropism in fishes. Biological Review 49: 515-576.

Barton, B.A., C.B. Shreck, and L.A. Sigismondi. 1986. Multiple acute disturbances evoke cumulative physiological stress responses in juvenile chinook salmon. Transactions of the American Fisheries Society 115:245-251.

Bell, M.C., 1981. Updated compendium on the success of passage of small fish through turbines. U. S. Army Corps of Engineers, Contract No. D-35-026-CIVEN-66-C16 and Contract No. DACW-68-76-C-0254.

Bell, M.C., A.C. DeLacy, and G.J. Paulik. 1967. A compendium on the success of passage of small fish through turbines. Section I: 1-201 in Bell, M.C., 1981. Updated compendium on the success of passage of small fish through turbines. U. S. Army Corps of Engineers, Contract No. D-35-026-CIVEN-66-C16 and Contract No. DACW-68-76-C-0254.

Bell, M.C. and J.C. Kidder. 1991. General discussion. Section I in Revised Compendium on the Success of Passage of Small Fish Through Turbines. M.C. Bell (ed). U.S. Army Corps of Engineers, North Pacific Division, Portland, OR. 83 p.

Berggren, T.J., and M.J. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. North American Journal of Fisheries Management 13:48-63.

Biosonics, Inc. 1983a. Hydroacoustic assessment of downstream migrating salmon and steelhead at Rock Island Dam in 1983. Public Utility District No.1 of Chelan County, Wenatchee, Washington.

Biosonics, Inc. 1983b. Hydroacoustic assessment of downstream migrating salmon and steelhead at Wanapum and Priest Rapids dams in 1983. Public Utility District. No. 2 of Grant County, Ephrata, Washington.

Biosonics, Inc. 1984. Hydroacoustic assessment of downstream migrating salmon and steelhead at Rocky Reach Dam in 1983. Public Utility District No. 1 of Chelan County, Wenatchee, Washington.

Bjornn, T.C. 1992. Survival of chinook salmon smolts as related to stress at dams and smolt quality. U. S. Fish and Wildlife Service, Idaho Cooperative Fishery Research Unit, University of Idaho, Moscow, Idaho.

Bleckmann, H. 1986. Role of the Lateral Line in Fish Behavior. Pages 177-204 *in* T. J. Pitcher, editor. The Behavior of Teleost Fishes. The Johns Hopkins University Press, Baltimore.

Bouck, G.R. 1980. Etiology of gas bubble disease. Transactions of the American Fisheries Society 109:703-707.

Brett, J.R., and D. MacKinnon. 1953. Preliminary experiments using lights and bubbles to deflect migrating young spring salmon. Journal of the Fisheries Research Board of Canada 10:548-559.

Brookshier, P.A., J.V. Flynn, R.R. Loose. 1995. 21st Century Advanced Hydropower Turbine System. Pages 2003-2008 *in* J. J. Cassidy, editor. Waterpower '95. Proceedings of the International Conference on Hydropower. American Society of Civil Engineers, New York.

Buettner, E.W., and A.F. Brimmer. 1995. Smolt monitoring at the head of Lower Granite Reservoir and Lower Granite Dam. DOE/BP-11631-10, U. S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Čada, G.F., J.S. Suffern, K.D. Kumar, and J.A. Solomon. 1980. Investigations of entrainment mortality among larval and juvenile fishes using a power plant simulator. p. 111-122 In: Issues Associated with Impact Assessment. Proceedings of the Fifth National Workshop on Entrainment and Impingement. L.D. Jensen (ed.). EA Communications, Sparks, MD.

Čada, G.F. and M.J. Sale. 1993. Status of fish passage facilities at nonfederal hydropower projects. Fisheries 18(7):4-12.

Čada, G.F., M.D. Deacon, S.V. Mitz, and M.S. Bevelhimer. 1994. Review of information pertaining to the effects of water velocity on the survival of juvenile salmon and steelhead in the Columbia River basin. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Čada, G.F. and J.E. Francfort. 1995. Examining the benefits and costs of fish passage and protection measures. Hydro Review 14(1):47-55.

Čada, G.F. In Press. Fish passage mitigation of impacts from hydroelectric power projects in the United States. Proceedings of the International Conference on Fish Migration & Fish Bypass-Channels. Vienna, Austria, September 24-26, 1996.

Chanson, H. 1989. Flow downstream of an aerator - aerator spacing. Journal of Hydraulic Research 27(4):519-536.

Cramer, F.K. 1965. Fish passage through hydraulic turbines. Processed Report. U. S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Cramer, F.K., and R.C. Oligher. 1960. Fish passage through turbines, tests at Cushman No. 2 hydroelectric plant. Progress Report No. 2. U. S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Cramer, F.K., and R.C. Oligher. 1961. Fish passage through turbines, further tests at Cushman No. 2 hydroelectric plant. Progress Report No. 4. U. S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Croll, D.A., A.J. Gaston, A.E. Burger, and D. Konnoff. 1992. Foraging behavior and physiological adaptation for diving in thick-billed murres. Ecology 73(1):344-356.

Dadswell, M.J., R.A. Rulifson and G.R. Daborn. 1986. Potential impact of large-scale tidal power developments in the upper Bay of Fundy on fisheries resources of the northwest Atlantic. Fisheries (Bethesda) 11:26-35.

Dadswell, M.J. and R.A. Rulifson. 1994. Macrotidal estuaries: A region of collision between migratory marine animals and tidal power development. Biological Journal of the Linnean Society 51(1-2):93-113.

Daily, J. 1986. Lessons from a career in hydraulics. Journal of Hydraulic Engineering 112(9):780-793.

Dunn, C.A. 1978. Evaluation of downstream fish passage through multi-level outlet pipes at Wynoochie Dam. Washington Department of Fisheries, Olympia, Washington.

Ebel, W.J. 1981. Effects of environmental degradation on the freshwater stage of anadromous fish. Pages 147-180 *in* 50 Years of Cooperation and Commitment (1931-1981). NOAA Technical Memo, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, Seattle, Washington.

Eicher, G.E. 1988. Fish collection, transportation and release in relation to protection at power plants. Pages 1-13 to 1-23 *in* W. C. Micheletti. Fish Protection at Steam and Hydroelectric Power Plants. EPRI CS/EA/AP-5663 SR, Electric Power Research Institute, Palo Alto, California.

EPRI (Electric Power Research Institute). 1986. Assessment of downstream migrant fish protection technologies for hydroelectric application. Report No. 2694-1. Electric Power Research Institute, Palo Alto, California.

EPRI (Electric Power Research Institute). 1987. Turbine-related fish mortality: review and evaluation of studies. EPRI AP-5480. Project 2694-4. Final Report. Palo Alto, CA.

Fangstam, H., I. Berglund, M. Sjoberg, and H. Lundqvist. 1993. Effects of size and early sexual maturity on downstream migration during smolting in Baltic salmon (*Salmo salar*). Journal of Fish Biology 43: 517-529.

Feathers, M.G. and A.E. Knable. 1983. Effects of depressurization upon largemouth bass. North American Journal of Fisheries Management 3:86-90.

FERC (Federal Energy Regulatory Commission). 1988. Hydroelectric Development in the Upper Ohio River Basin. FERC Docket No. EL85-19-114. Final Environmental Impact Statement. Washington, DC.

FERC (Federal Energy Regulatory Commission). 1995. Preliminary assessment of fish entrainment at hydropower projects. A report on studies and protective measures. Paper No. DPR-10, Office of Hydropower Licensing, Federal Energy Regulatory Commission, Washington, DC.

Ferguson, J.W. 1991. Relative survival of juvenile chinook salmon through Bonneville Dam on the Columbia River. p. 308-317 In: Waterpower '91. Proceedings of the International Conference on Hydropower. D.D. Darling (ed.). American Society of Civil Engineers, New York, NY.

Foye, R.E. and M. Scott. 1965. Effects of pressure on survival of six species of fish. Transactions of the American Fisheries Society 94:88-91.

FPC (Fish Passage Center). 1994. Fish Passage Center Annual Report 1993. DOE/BP-38906-3, U. S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Francfort, J.E., G.F. Čada, D.D. Dauble, R.T. Hunt, D.W. Jones, B.N. Rinehart, G.L. Sommers, and R.J. Costello. 1994. Environmental mitigation at hydroelectric projects. Volume II. Benefits and costs of fish passage and protection. DOE/ID-10360 (V2), Idaho National Engineering Laboratory, Idaho Falls, Idaho.

Fried, S.M., J.D. McCleave, and G.W. LaBar. 1978. Seaward migration of hatchery reared Atlantic salmon, *Salmo salar*, smolts in the Penobscot River estuary: riverine movements. Journal of the Fisheries Research Board of Canada 35:76-87.

FWS (U. S. Fish and Wildlife Service, Wisconsin Department of Natural Resources, and Michigan Department of Natural Resources). 1992. Joint agency fish entrainment/turbine mortality study plan guidelines. Vol. 2. Entrainment and turbine mortality studies, Appendix III: Fish entrainment and turbine mortality study plan guidelines. U. S. Fish and Wildlife Service, Washington, DC.

Gessel, M.H., J.G. Williams, C.A. Brege, R.A. Krcma, and D.R. Chambers. 1991. Juvenile salmonid guidance at the Bonneville Dam second powerhouse, Columbia River, 1983-1989. North American Journal of Fisheries Management 11:400-412.

Gessel, M.H., B.P. Sandford, and D.B. Dey 1995. Studies to evaluate the effectiveness of extended-length screens at Little Goose Dam, 1994. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington.

Giorgi, A.E., and J.R. Stevenson. 1995. A review of biological investigations describing smolt passage behavior at Portland District Corps of Engineers projects: Implications to surface collection systems. Don Chapman Consultants, Boise, Idaho.

Giorgi, A.E., L.C. Stuehrenberg, D.R. Miller, and C.W. Sims. 1986. Smolt passage behavior and flow-net relationship in the forebay of John Day Dam. DOE/BP-39644-1, U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Giorgi, A.E., L. Stuehrenberg, and J. Wilson. 1988a. Juvenile radio-tag study: Lower Granite Dam 1985-86. DOE/BP-21237-2, U. S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Giorgi, A.E., G.A. Swan, W.S. Zaugg, T. Coley, and T.Y. Barila. 1988b. Susceptibility of chinook salmon smolts to bypass systems at hydroelectric dams. North American Journal of Fisheries Management 8:25-29.

Gordon, N.D., T.A. McMahon, and B.L. Finlayson. 1992. Stream hydrology: An introduction for ecologists. John Wiley & Sons, New York, NY. 526 p.

Groot, C. 1965. On the orientation of young sockeye salmon (*Oncorhynchus nerka*) during their seaward migration out of lakes. Behaviour (Suppl.) 14: 1-198.

Groot, C. 1982. Modifications on a theme - A perspective on migratory behavior of Pacific salmon. Pages 1-21 *in* E. L. Brannon and E. O. Salo, editors. Proceedings of the salmon and trout migratory behavior symposium. School of Fisheries, University of Washington, Seattle.

Groves, A.B. 1972. Effects of hydraulic shearing actions on juvenile salmon (Summary report). Northwest Fisheries Center, National Marine Fisheries Service, Seattle, WA. 7 p.

Hamilton, W.S. 1983a. Preventing cavitation damage to hydraulic structures. Part one. Water Power and Dam Construction. November, 1983. p. 40-43.

Hamilton, W.S. 1983b. Preventing cavitation damage to hydraulic structures. Part two. Water Power and Dam Construction. December, 1983. p. 48-53.

Hamilton, W.S. 1984. Preventing cavitation damage to hydraulic structures. Part three. Water Power and Dam Construction. January, 1984. p. 42-45.

Harvey, H.H. 1963. Pressure in the early life history of sockeye salmon. Ph.D. Thesis. University of British Columbia, Vancouver, B.C. 267 p.

Harvey, H.H. and W.S. Hoar. Unpublished manuscript. The sounding response of sockeye salmon. International Pacific Salmon Fisheries Commission.

Harza and RMC (Harza Engineering Company and RMC Environmental Services). 1993. Response of juvenile clupeids to louvers in the Holyoke Canal, Fall 1992. Prepared for Northeast Utilities Service Company, Berlin, Connecticut.

Hoar, W.S. 1954. The behavior of juvenile Pacific salmon, with particular reference to the sockeye (*Oncorhynchus nerka*). Journal of the Fisheries Research Board of Canada 11: 69-96.

Hogan, J. 1941. The effects of high vacuum on fish. Transactions of the American Fisheries Society 70:469-474.

Holland, L., D. Huff, S. Littlejohn, and R. Jacobson. 1984. Analysis of existing information on adult fish movements through dams on the upper Mississippi River. U. S. Fish and Wildlife Service, National Fishery Research Laboratory, LaCrosse, Wisconsin.

Hubbs, C.L. and A.B. Rechnitzer. 1952. Report on experiments designed to determine effects of underwater explosions on fish life. California Fish and Game 38:333-366.

Johnson, R.L. 1970a. Fingerling fish mortalities at 57.5 fps. Report No. 22. August 1970. U.S. Army Corps of Engineers, North Pacific Division, Portland, OR. 14 p.

Johnson, R.L. 1970b. Fingerling fish research effect of mortality of 67 fps velocity. Report No. 23. December 1970. U.S. Army Corps of Engineers, North Pacific Division, Portland, OR. 6 p.

Johnson, R.L. 1972. Fingerling fish research, high-velocity flow through four-inch nozzle. Report No. 24. April 1972. U.S. Army Corps of Engineers, North Pacific Division, Portland, OR. 3 p.

Johnson, R.L. 1996. Behavioral hydroacoustic evaluations of fish passage at Lower Granite Dam with the prototype SBC. Abstracts of the 1996 Annual Program Review, Anadromous Fish Evaluation Program, US Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Johnson, L., and R. Wright. 1987. Hydroacoustic evaluation of the spill program for fish passage at John Day Dam in 1987. Associated Fish Biologists, Inc., Seattle, Washington.

Johnson, G., C. Sullivan, and M. Erho. 1992. Hydroacoustic studies for developing a smolt bypass system at Wells Dam. Fisheries Research 14:221-237.

Johnston, S.V., B.H. Ransom, and J.R. Bohr. 1993. Comparison of hydroacoustic and net catch estimates of fish entrainment at Tower and Kleber Dams, Black River, Michigan. p. 308-317 In: Waterpower '93. Proceedings of the International Conference on Hydropower. W.D. Hall (ed.). American Society of Civil Engineers, New York, NY.

Jones, F.R.H. 1951. The swimbladder and the vertical movements of teleostean fishes. I. Physical factors. Journal of Experimental Biology 28:553-566.

Jones, F.R.H. 1952. The swimbladder and the vertical movements of teleostean fishes. II. The restriction to rapid and slow movements. Journal of Experimental Biology 29:94-109.

Kalmijn, A.J. 1989. Functional evolution of lateral line and inner ear systems. Page 187 *in* S. Coombs, P. Gorner, and H. Munz, editors. The Mechanosensory Lateral Line: Neurobiology and Evolution. Springer-Verlag, New York.

Killgore, K.J., A.C. Miller, and K.C. Conley. 1987. Effects of turbulence on yolk-sac larvae of paddlefish. Transactions of the American Fisheries Society 116:670-673.

Knable, A.E. and M.G. Feathers. 1983. Device for examining the effects of pressure changes on fish. Progressive Fish-Culturist 45(1):16-18.

Koski, C.H., S.W. Petit, J.B. Athern, and A.L. Heindl. 1986. Fish transportation oversight technical team annual report - FY 1985. Transport operations on the Snake and Columbia rivers. National Marine Fisheries Service, Seattle, Washington.

Kuehl, S. 1986. Hydroacoustic evaluation of juvenile salmonid fish passage at John Day Dam in summer, 1986. Biosonics, Inc., Seattle, Washington.

Lagler, K.F., J.E. Bardach, and R.R. Miller. 1962. Ichthyology. John Wiley & Sons, Inc., New York. 545 p.

Long, C.W. 1968. Diel movement and vertical distribution of juvenile anadromous fish in turbine intakes. Fishery Bulletin, U. S. 66:599-609.

Long, C.W., R.F. Krcma, and F.J. Ossiander. 1968. Research on fingerling mortality in Kaplan turbines - 1968. Progress Report. Bureau of Commercial Fisheries, Seattle, Washington. 7 p.

Long, C. W., R.F. Krcma, W. Marquett, and R. Duncan. 1970. Further research on a fingerling bypass for low head dams. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, Seattle, Washington.

Love, R.H. 1971. Measurements of fish target strength: A review. Fishery Bulletin 69(4):703-715.

Lucas, K.C. 1962. The mortality of fish passing through hydraulic turbines as related to cavitation and performance characteristics, pressure change, negative pressure, and other factors. p. 307-335 In: F. Numachi, editor. Cavitation and Hydraulic Machinery. Proceedings of IAHR (International Association for Hydraulic Research) Symposium, Sendai, Japan.

MacLennan, D.N. and E.J. Simmonds. 1992. Fisheries acoustics. Chapman and Hall, London.

Magne, R.A., D.R. Bryson, and W.T. Nagy. 1987a. Hydroacoustic monitoring of downstream migrant juvenile salmon passage at John Day Dam in 1984-1985. U. S. Army Corps of Engineers, Portland, Oregon.

Magne, R.A., W.T. Nagy, and W.C. Maslen. 1987b. Hydroacoustic monitoring of downstream migrant juvenile salmonids at John Day Dam in 1983. U. S. Army Corps of Engineers, Portland, Oregon.

Magnuson, J. J. 1978. Locomotion by scombrid fishes: hydromechanics, morphology and behavior. Pages 239-313 in W. S. Hoar and D. J. Randall, editors. Fish Physiology, Vol. 7. Academic Press, New York.

Mathur, D., P.G. Heisey, E.T. Euston, J.R. Skalski, and S. Hays. 1996. Turbine passage survival estimation for chinook salmon smolts (*Oncorhynchus tshawytscha*) at a large dam on the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 53:542-549.

Matousek, J.A., S.G. Metzger, A.W. Wells, D.S. Battige, and R.W. Williams. 1995. Turbine entrainment at six hydroelectric projects located on the AuSable River, Michigan. p. 281-290 In: Waterpower '95. Proceedings of the International Conference on Hydropower. J.J. Cassidy (ed.). American Society of Civil Engineers, New York, NY.

McCleave, J.D. 1978. Rhythmic aspects of estuarine migration of hatchery-reared Atlantic salmon (*Salmo salar*) smolts. Journal of Fish Biology 12: 559-570.

McComas, R.L., B.P. Sandford, and D.B. Dey. 1994. Studies to evaluate the effectiveness of extended-length screens at McNary Dam, 1993. Northwest Fisheries Science Center, National Marine Fisheries Service, Seattle, Washington.

McDonald, J. 1960. The behavior of Pacific salmon fry during their downstream migration to freshwater and saltwater nursery areas. Journal of the Fisheries Research Board of Canada 17:655-676.

McEwen, D. and G. Scobie. 1992. Estimation of the hydraulic conditions relating to fish passage through turbines. NPC001. National Engineering Laboratory, East Kilbride, Glasgow. 155 p.

McFadden, B.D., and J. Hedgepeth. 1990. Hydroacoustic evaluation of juvenile fish passage at John Day Dam in summer, 1989. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington.

McFadden, B.D., B.H. Ransom, and B. Schnebly. 1992. Hydroacoustic evaluation of the effectiveness of the sluiceway at Priest Rapids Dam in passing juvenile salmon and steelhead trout during spring and summer 1992. Public Utility District No. 2 of Grant County, Ephrata, Washington.

McLean, R.B., P.T. Singley, J.S. Griffith, and M.V. McGee. 1980. Threadfin shad impingement: Effect of cold stress. NUREG/CR-1044, ORNL-NUREG/TM-340, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Mesa, M.G. 1994. Effects of multiple acute stressors on the predator avoidance ability and physiology of juvenile chinook salmon. Transactions of the American Fisheries Society 123:786-793.

Mesa, M.G., T.P. Poe, D.M. Gadomski, and J.H. Petersen. 1994. Are all prey created equal? A review and synthesis of differential predation on prey in substandard condition. Journal of Fish Biology 45 (Supplement A):81-96.

Mighetto, L., and W. J. Ebel. 1994. Saving the salmon: A history of the U. S. Army Corps of Engineers' efforts to protect anadromous fish on the Columbia and Snake rivers. Historical Research Associates, Inc. for the U. S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Montén, E. 1985. Fish and turbines: Fish injuries during passage through power station turbines. Vattenfall, Stockholm, Sweden. 111 p.

Montgomery Watson. 1995. Allowable gas supersaturation for fish passing hydroelectric dams. Project Number 93-8. Draft Final Report for Bonneville Power Administration, U.S. Department of Energy, Portland, OR. 107 p. + appendices.

Moore, A. and A. Scott. 1988. Observations of recently emerged sea trout, *Salmo trutta* L., fry in a chalk stream, using a low-light underwater camera. Journal of Fish Biology 33:959-960.

Morgan, R.P., II, R.E. Ulanowicz, V.J. Rasin, Jr., L.A. Noe, and G.B. Gray. 1976. Effects of shear on eggs and larvae of striped bass, *Morone saxatilis*, and white perch, *M. americana*. Transactions of the American Fisheries Society 105(1):149-154.

Muir, J.F. 1959. Passage of young fish through turbines. Journal of the Power Division. Proceedings of the American Society of Civil Engineers 85(PO 1):23-46.

Mundy, P.R., B. Watson, and R. Tuck. draft 1995. Migratory behavior of juvenile spring chinook salmon (*Oncorhynchus tshawytscha*) in relation to water flow in the Yakima River, Washington.

Nece, R.E. 1991. Calculations for determining strike and pressure gradient. Section II in Revised Compendium on the Success of Passage of Small Fish Through Turbines. M.C. Bell (ed). U.S. Army Corps of Engineers, North Pacific Division, Portland, OR. 83 p.

Nelson, W.R., L.K. Freidenburg, and D.W. Rondorf. 1994. Swimming performance of subyearling chinook salmon. Pages 39- 62 *In* D. W. Rondorf and W. H. Miller, editors. Identification of the spawning, rearing and migratory requirements of fall chinook salmon in the Columbia River basin. DOE/BP-21708-2, Bonneville Power Administration, Portland, Oregon.

Nestler, J.M., and R.A. Davidson. 1995a. Imaging smolt behavior on bypass screens and a vertical barrier screen at McNary Dam in 1992. Technical Report EL-95-21, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi.

Nestler, J.M., and R.A. Davidson. 1995b. Imaging smolt behavior on an extended-length submerged bar screen and an extended-length submerged traveling screen at The Dalles Dam in 1993. Technical Report EL-95-13, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi.

NMFS (National Marine Fisheries Service). 1995. Proposed recovery plan for Snake River salmon. US Department of Commerce, National Oceanic and Atmospheric Administration, Washington, DC.

Normandeau Associates, Inc. 1986. Analysis of fish movements in the vicinity of Lock and Dam 15 of the upper Mississippi River. Bedford, Massachusetts.

Northcote, T.G. 1962. Migratory behaviour of juvenile rainbow trout, *Salmo gairdneri*, in outlet and inlet streams of Loon Lake, British Columbia. Journal of the Fisheries Research Board of Canada 19:201-270.

NPPC (Northwest Power Planning Council). 1994. Columbia River basin fish and wildlife program. Portland, Oregon.

NRC (National Research Council). 1996. Upstream--Salmon and Society in the Pacific Northwest. National Academy Press, Washington, DC.

Olson, F.W., and E.S. Kuehl. 1988. Fisheries resource studies, Vanceburg Hydroelectric Generating Station No. 1 (FERC Project No. 2614). Volume 2. Survival of sauger passing through bulb turbines and tainter gates at Greenup Dam, Ohio River. CH2M Hill and Biosonics, Report for the City of Vanceburg, Kentucky.

Olson, F.W., J.F. Palmisano, G.E. Johnson, and W.R. Ross. 1987. Fish population and entrainment studies for the Vanceburg Hydroelectric Generating Station No. 1. CH2M Hill and Biosonics, Report for the City of Vanceburg, Kentucky.

OTA (Office of Technology Assessment). 1995. Fish passage technologies: Protection at hydropower facilities. OTA-ENV-641, Washington, DC: U. S. Government Printing Office.

Oullette, D.A. 1988. Hydroacoustic evaluation of juvenile fish passage at John Day Dam in summer, 1988. Biosonics, Inc., Seattle, Washington.

Peven, C.M. 1993. Fish Guidance System Developmental Testing at Rock Island Dam Powerhouse No. 1, Spring and Summer 1993. Chelan County Public Utility district, Wenatchee, Washington.

Plotsky, G., and P. Johnson. 1996. Smolt passage studies at Bonneville Dam. Abstracts of the 1996 Annual Program Review, Anadromous Fish Evaluation Program, US Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Popper, A.N., and C. Platt. 1993. Inner Ear and Lateral Line. Pages 99-136 *in* D. H. Evans, editor. The Physiology of Fishes. CRC Press, Boca Raton, Florida.

Prentice, E.F., T.A. Flag, and C.S. McCutcheon. 1990. PIT-tag monitoring systems for hydroelectric dams and fish hatcheries. American Fisheries Society Symposium 7:323-334.

Raemhild, G.A., R. Nason, and S. Hayes. 1985. Hydroacoustic studies of downstream migrating salmonids at hydropower dams: two case studies. Pages 244-251 *in* Proceedings of the Symposium on Small Hydropower and Fisheries. Edited by F.W. Olson, R.G. White, and R.H. Hamre. American Fisheries Society, Bethesda, Maryland.

Ramamurthy, A.S., Y.S.L. Ranganath, and L.B. Carballada. 1984. Pressure and source size effects on cavitation damage. Journal of Hydraulic Engineering 110(10):1490-1494.

Ransom, B.H., G.A. Raemhild, and T.W. Steig. 1988. Hydroacoustic evaluation of deep and shallow spill as a bypass mechanism for downstream migrating salmon and steelhead at Rock Island Dam. Pages 1-70 to 1-84 *in* W. C. Micheletti, editor. Fish Protection at Steam and Hydroelectric Power Plants. EPRI CS/EA/AP-5663-SR, Electric Power Research Institute, Palo Alto, California.

Ransom, B.H., and K.M. Malone 1990. Hydroacoustic evaluation of the sluiceway at Wanapum Dam in passing juvenile salmon and steelhead trout during spring 1990. Hydroacoustic Technology Inc. Report to Grant County P.U.D. No. 2, Ephrata, Washington.

Ransom, B.H. and T.W. Steig. 1994. Using hydroacoustics to monitor fish at hydropower dams. Lake and Reservoir Management 9(1):163-169.

Ransom, B.H. and T.W. Steig. 1995. Comparison of the effectiveness of surface flow and deep spill for bypassing Pacific salmon smolts (*Oncorhynchus* spp.) at Columbia River basin hydropower dams. p. 271-280 In: Waterpower '95. Proceedings of the International Conference on Hydropower. J.J. Cassidy (ed.). American Society of Civil Engineers, New York, NY.

Ratter, C. 1902. Natural history of the quinnat salmon: a report of investigations in the Sacramento River 1896-1901. Bulletin of the U. S. Fisheries Commission 22:65-142.

Raymond, H.L., and C.W. Sims. 1980. Assessment of smolt migration and passage enhancement studies for 1979. Processed report. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, Seattle, Washington.

RMC (RMC Environmental Services, Inc.), and J.R. Skalski. 1994. Survival of yearling fall chinook salmon smolts (*Oncorhynchus tshawytscha*) in passage through a fixed-blade Kaplan turbine at Rocky Reach Dam, Washington. Processed Report. Public Utility District No. 1 of Chelan County, Wenatchee, Washington.

RMC (RMC Environmental Services, Inc.), and J.R. Skalski. 1995. Survival of yearling fall chinook salmon smolts (*Onchorhynchus tshawytscha*) in passage through a Kaplan turbine at Rocky Reach Hydroelectric Dam, Washington. Processed Final Report. Public Utility District No. 1 of Chelan County, Wenatchee, Washington.

Rodrigue, P.R. 1986. Cavitation pitting mitigation in hydraulic turbines. Volume 2: cavitation review and assessment. EPRI AP-4719, Electric Power Research Institute, Palo Alto, CA.

Rowley, W.E., Jr. 1955. Hydrostatic pressure tests on rainbow trout. California Fish and Game 41:243-244.

Sale, M.J., G.F. Čada, L.H. Chang, S.W. Christensen, S.F. Railsback, J.E. Francfort, B.N. Rinehart, and G.L. Sommers. 1991. Environmental mitigation at hydroelectric projects. Volume 1. Current practices for instream flow needs, dissolved oxygen, and fish passage. DOE/ID-10360. U.S. Department of Energy, Idaho Field Office, Idaho Falls, ID.

Schoeneman, D.E., R.T. Pressey, and C.O. Junge. 1961. Mortalities of downstream migrating salmon at McNary Dam. Transactions of the American fisheries Society 90:58-72.

Schreck, C.B., H.W. Li, A.G. Maule, S. Bradford, B. Barton, and L. Sigismondi. 1984. Columbia River Salmonid Smolt Outmigration: McNary Dam Passage and Enhanced Smolt Quality. U. S. Fish and Wildlife Service, Oregon Cooperative Fishery Research Unit, Oregon State University, Corvallis, Oregon.

Schreck, C.B. 1990. Physiological, behavioral, and performance indicators of stress. Pages 29-37 *In* S. M. Adams, editor. Biological Indicators of Stress in Fish. Symposium 8, American Fisheries Society, Bethesda, Maryland.

Schreck, C.B., J.C. Snelling, R.E. Ewing, C.S. Bradford, L.E. Davis, and C.H. Slater. 1995. Migratory characteristics of juvenile spring chinook salmon in the Willamette River. DOE/BP-92818-5, U. S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Sébert, P., L. Barthélémy, and B. Simon. 1990. Laboratory system enabling long-term exposure (≥ 30 d) to hydrostatic pressures (≤ 101 atm) of fishes or other animals breathing water. Marine Biology 104:165-168.

Shtaf, L.G., D.S. Pavlov, M.A. Skorobogatov, and A. S. Barekyan. 1983. The influence of flow turbulence on fish behavior. Journal of Ichthyology 23(2):129-140.

Skalski, J.R. 1993. Summary of 3-Year Bypass Efficiency Study at Wells Dam. Public Utility District No. 1 of Douglas County, East Wenatchee, Washington.

Skalski, J., G. Johnson, C. Sullivan, E. Kudera, and M. Erho. In press. Statistical evaluation of turbine bypass efficiency at Wells Dam on the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences.

Smith, L.S. 1982. Decreased swimming performance as a necessary component of the smolt migration in salmon in the Columbia River. Aquaculture 28:153-161.

Snelling, J.C., and C.B. Schreck. 1995. Movement, distribution, and behavior of juvenile salmonids passing through Columbia and Snake River dams. Project 82-003. DOE/BP-9196-4, U. S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Solomon, D.J. 1988. Fish passage through tidal energy barrages. Contractors Report No. ETSU TID 4056, Energy Technical Support Unit, Harwell, England. 76 p.

Sole, M., M. Barange, and I. Hampton. 1995. Evidence of bias in estimates of target strength obtained with a split-beam echo-sounder. International Council for the Exploration of the Sea (ICES) Journal of Marine Science 52:139-144.

Steig, T.W. and S.V. Johnston. In Press. Monitoring fish movement patterns in a reservoir using horizontally scanning split-beam techniques. International Council for the Exploration of the Sea (ICES) Journal of Marine Science.

Thorne, R.E. and G.E. Johnson. 1993. A review of hydroacoustic studies for estimation of salmonid downriver migration past hydroelectric facilities on the Columbia and Snake Rivers in the 1980s. Reviews in Fisheries Science 1(1):27-56.

Thorpe, J.E., and R.I.G. Morgan. 1978. Periodicity in Atlantic salmon *Salmo salar L.* smolt migration. Journal of Fish Biology 12: 541-548.

Thorpe, J.E., L.G. Ross, G. Struthers, and W. Watts. 1981. Tracking Atlantic salmon smolts, *Salmo salar L.*, through Loch Voil, Scotland. Journal of Fish Biology 19: 519-537.

Thorpe, J.E. 1982. Downstream movements of juvenile salmonids: a forward speculative view. Pages 387-395 *in* J. D. McCleave, G. P. Arnold, J. J. Dodson, and W. H. Neill, editors. Mechanisms of Migration in Fishes. New York and London: Plenum Press.

Traxler, S.L., B.R. Murphy, and T.L. Linton. 1993. Subsediment seismic explosions do not injure caged fishes in a freshwater reservoir. Journal of Freshwater Ecology 8(1):73-75.

Tsvetkov, V.I., D.S. Pavlov, and V.K. Nezdoliy. 1972. Changes in hydrostatic pressure lethal to the young of some freshwater fish. Journal of Ichthyology 12:307-318.

Turbak, S.C., D.R. Reichle, and C.R. Shriner. 1981. Analysis of environmental issues related to small-scale hydroelectric development. IV. Fish mortality resulting from turbine passage. ORNL/TM-7521, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Turner, A.R., Jr., J.W. Ferguson, T.T. Barila, and M.F. Lindgren. 1993. Development and refinement of turbine intake screen technology on the Columbia River. Pages 123-128 *in* K. Bates, editor. Proceedings of the Symposium on Fish Passage and Technology. Bioengineering Section, American Fisheries Society, Bethesda, Maryland.

Turnpenny, A.W.H., M.H. Davis, J.M. Fleming, and J.K. Davies. 1992. Experimental studies relating to the passage of fish and shrimps through tidal power turbines. Marine and Freshwater Biology Unit, National Power, Fawley, Southhampton, Hampshire, England.

USACE (U.S. Army Corps of Engineers). 1991. Revised compendium on the success of passage of small fish through turbines. North Pacific Division , Portland, Oregon.

USACE (U.S. Army Corps of Engineers). 1995. Proceedings: 1995 turbine passage survival workshop. U.S. Army Corps of Engineers, Portland District, Portland, Oregon. 212 p. + appendices.

Vaughn, R.A. 1995. John Day Dam - underwater video inspection. p. 2077-2084 In: Waterpower '95. Proceedings of the International Conference on Hydropower. J.J. Cassidy (ed.). American Society of Civil Engineers, New York, NY.

Vogel, S. 1981. Life in moving fluids. The physical biology of flow. Princeton University Press, Princeton, New Jersey. 352 p.

Voith Hydro. 1996. First Project Status Report - Advanced Hydropower Turbine System Program: Phase I. Presentation at Voith Hydro, York, PA on March 6, 1996.

von Raben, K. 1957. Regarding the problem of mutilations of fishes by hydraulic turbines. Die Wasserwirtshaft 4:97-100. Fisheries Research Board of Canada Translation Series No. 448.

Wagner, E., and P. Ingram. 1973. Evaluation of fish facilities and passage at Foster and Green Peter dams on the South Santium River drainage in Oregon. Fish Commission of Oregon, Portland.

WAPORA, Inc. 1987. Fish passage studies at the Racine and New Martinsville hydroelectric projects. 4 volumes. Cincinnati, Ohio.

Weitkamp, D.E., and M. Katz. 1980. A review of dissolved gas supersaturation literature. Transactions of the American Fisheries Society 109:659-702.

Wik, S.J., and T.Y. Barila. 1990. Evaluation of extended-length screening concept - Lower Granite Dam. Seventh Progress Report: Fish Passage Development and Evaluation Program 1984-1990. U. S. Army Corps of Engineers, North Pacific Division, Environmental Resources Division: 329-337.

Williams, R.W., J.O. Barnes, E.R. Guilfoos, T.E. Rourke, and B.H. Shiel. 1995. Comparison of full tailrace netting and hydroacoustic monitoring for estimating entrainment at two hydroelectric stations in Wisconsin. p. 340-347 In: Waterpower '95. Proceedings of the International Conference on Hydropower. J.J. Cassidy (ed.). American Society of Civil Engineers, New York, NY.

Williams, R. N., L. D. Calvin, C. C. Coutant, M. W. Erho, Jr., J. A. Lichatowich, W. J. Liss, W. E. McConnaha, P. R. Mundy, J. A. Stanford, R. R. Whitney, D. L. Bottom, and C. A. Frissel. in press. Return to the River. Restoration of Salmonid Fishes in the Columbia River Ecosystem. Northwest Power Planning Council, Portland, Oregon.

Willis, C.F. 1982. Indexing of juvenile salmonids migrating past The Dalles Dam, 1982. Report to U.S. Army Corps of Engineers. Contract No. DACW57-78-C-0056. Oregon Department of Fish and Wildlife, Portland, Oregon.

Willis, C.F., and B.L. Uremovich 1981. Evaluation of the ice and trash sluiceway at Bonneville Dam as a bypass system for juvenile salmonids, 1981. Progress Report to National Marine Fisheries Service. Contract No. 81-ABC-00173. Oregon Department of Fish and Wildlife, Portland, Oregon.

Wilson, R.P., A.E. Burger, B.L.H. Wilson, M.P.T. Wilson, and C. Noeldeke. 1989. An inexpensive depth gauge for marine animals. Marine Biology 103(2):275-283.

Winchell, F.C., E.P. Taft, and A.C. Solonsky. 1991. Evaluation of the Eicher Screen at Elwha Dam: Spring 1990 test results. EPRI GS/EN-7036, Electric Power Research Institute, Palo Alto, California.