ELECTRIC POWER RESEARCH INSTITUTE

Fish Passage Through Turbines: Application of Conventional Hydropower Data to Hydrokinetic Technologies

2011 TECHNICAL REPORT

Fish Passage Through Turbines: Application of Conventional Hydropower Data to Hydrokinetic Technologies

EPRI Project Manager
P. Jacobson

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue
Palo Alto, CA 94304-1338
USA

PO Box 10412
Palo Alto, CA 94303-0813
USA

800.313.3774
650.855.2121

askepri@epri.com

www.epri.com

1024638
Final Report, October 2011

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THIS REPORT WAS PREPARED AS AN ACCOUNT OF WORK SPONSORED BY AN AGENCY OF THE UNITED STATES GOVERNMENT. NEITHER THE UNITED STATES GOVERNMENT NOR ANY AGENCY THEREOF, NOR ANY OF THEIR EMPLOYEES, MAKES ANY WARRANTY, EXPRESS OR IMPLIED, OR ASSUMES ANY LEGAL LIABILITY OR RESPONSIBILITY FOR THE ACCURACY, COMPLETENESS, OR USEFULNESS OF ANY INFORMATION, APPARATUS, PRODUCT, OR PROCESS DISCLOSED, OR REPRESENTS THAT ITS USE WOULD NOT INFRINGE PRIVATELY OWNED RIGHTS. REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY THE UNITED STATES GOVERNMENT OR ANY AGENCY THEREOF. THE VIEWS AND OPINIONS OF AUTHORS EXPRESSED HEREIN DO NOT NECESSARILY STATE OR REFLECT THOSE OF THE UNITED STATES GOVERNMENT OR ANY AGENCY THEREOF.

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Alden Research Laboratory, Inc.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2011 Electric Power Research Institute, Inc. All rights reserved.

Acknowledgments

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Alden Research Laboratory, Inc.
30 Shrewsbury Street
Holden, MA 01520-1843

Principal Investigators
S. Amaral
G. Hecker
N. Pioppi

This report describes research sponsored by EPRI.

This material is based upon work supported by the Department of Energy Water Power Program under Award Number DE-EE0002659.

Constructive comments by Jocelyn Brown-Saracino and her colleagues, U.S. Department of Energy, and by Glenn Cada, Oak Ridge National Laboratory strengthened this report. We also thank Doug Dixon of EPRI for his leadership of this project during its formative stage.

This publication is a corporate document that should be cited in the literature in the following manner:

Fish Passage Through Turbines: Applicability of Conventional Hydropower Data to Hydrokinetic Technologies. EPRI, Palo Alto, CA: 2011. 1024638.

Report Summary

This report reviews information on impacts of conventional hydropower turbines that can be used to evaluate potential impacts of hydrokinetic turbines on fish. The report discusses design and operational differences between conventional and hydrokinetic turbines as well as differences in the magnitude or potential for fish injury and mortality. This report will be valuable to industry, resource agencies, non-governmental environmental organizations, and universities involved in research, management, and protection of aquatic ecosystems.

Background

Hydrokinetic generation is an emerging technology for producing electricity from flowing water. This form of generation differs from conventional and pumped storage hydropower generation in that it does not employ dams or other structures to impound water and create hydraulic head. Rather, hydrokinetic turbines are placed in natural, free-flowing water courses and man-made channels. Because hydrokinetic generation is a new form of power generation, relatively little information is available regarding potential impacts on fish individuals and populations. A substantial body of information exists, however, pertaining to the effects of turbine passage at conventional hydropower projects. Useful information can be obtained from the literature on turbine passage at conventional hydropower projects, despite important differences between conventional and hydrokinetic power generation.

Objectives and Approach

This report reviews existing information on injury mechanisms associated with fish passage through conventional hydro turbines and the relevance and applicability of this information to fish passage through hydrokinetic turbines. Available information includes probability of blade strike, blade strike survival rates, and criteria for shear levels and pressure regimes that can damage fish.

Results

Fish passing through the blade sweep of a hydrokinetic turbine experience a much less harsh physical environment than do fish entrained through conventional hydro turbines. The design and operation of conventional turbines results in high flow velocities,

abrupt changes in flow direction, relatively high runner rotational and blade speeds, rapid and significant changes in pressure, and the need for various structures throughout the turbine passageway that can be impacted by fish (e.g., walls, stay vanes, wicket gates, flow straighteners). Most, if not all, of these conditions do not occur or are not significant factors for hydrokinetic turbines. Furthermore, compared to conventional hydro turbines, hydrokinetic turbines typically produce relatively minor changes in shear, turbulence, and pressure levels from ambient conditions in the surrounding environment. Injuries and mortality from mechanical injuries will be less as well, mainly due to low rotational speeds and strike velocities, and an absence of structures that can lead to grinding or abrasion injuries. While information pertaining to conventional hydro turbines is useful for assessing the potential for adverse effects of passage through the swept area of hydrokinetic turbines, additional information is needed to rigorously assess the nature and magnitude of effects on individuals and populations, and to refine criteria for design of more fish-friendly hydrokinetic turbines.

EPRI Perspective

This report will provide hydrokinetic device and project developers, fisheries resource managers, and regulators with improved understanding of the potential for hydrokinetic turbines to adversely affect individual fish and fish populations. The information contained in this report can also be used by researchers and potential research funders to identify areas for future, productive research.

Keywords

Fish
Hydrokinetic
Hydropower

Table of Contents

List of Figures

List of Tables

Section 1: Introduction

A lack of information on potential environmental impacts and the subsequent need to gather extensive field data have hindered project developers from obtaining necessary permits for the installation of pilot and full-scale hydrokinetic projects in a timely and cost-effective manner. Environmental issues that appear to be of greatest importance to state and federal resources agencies typically include issues associated with potential impacts to fish populations, including habitat alteration, disruptions in migrations and movements, and injury and mortality to fish that encounter turbines. In particular, there is considerable concern for fish and other aquatic organisms to interact with hydrokinetic turbines in a manner that could lead to alterations in normal behavioral patterns (e.g., migrations, spawning, feeding) and/or significant levels of injury and mortality (i.e., injuries resulting from entrainment through the water volume swept by the blades of one or more turbines). To develop information and data that can be used to assess the probability of such impacts occurring for any given project, the Electric Power Research Institute was awarded a grant by the U.S. Department of Energy (DOE) to complete the following studies:

- Review of existing information on injury mechanisms associated with fish passage through conventional hydro turbines and the relevance and applicability of this information to fish passage through hydrokinetic turbines.
- Development of theoretical models for the probability of blade strike and mortality for various hydrokinetic turbine designs.
- Flume testing with three turbine designs and several species and size classes of fish to estimate injury and survival rates and describe fish behavior in the vicinity of operating turbines.

EPRI contracted Alden Research Laboratory, Inc. (Alden) to conduct the first two efforts (i.e., desktop studies) and Alden and the U.S. Geological Survey's Conte Anadromous Fish Research Laboratory (CAFRL) to conduct flume testing. This report presents the results of the review of conventional hydropower data on fish passage through turbines and its relevance to hydrokinetic technologies. There are separate reports for flume testing and theoretical modeling at Alden (EPRI 2011a) and flume testing at the CAFRL (EPRI 2011b). The primary goal of the EPRI studies is to provide developers and resource and regulatory agencies with data and information that will lead to a better understanding of the potential impacts of hydrokinetic turbines on local and migratory fish populations. Achieving this goal will assist with licensing of proposed projects in the U.S. where hydrokinetic turbines have been or are being considered for installation.

Impacts to aquatic organisms by hydrokinetic turbines will depend primarily on turbine design and operational parameters and the environment in which the turbines are deployed (e.g., river, tidal, or ocean) and the ability of aquatic organisms to detect and subsequently avoid these devices. Potential direct impacts include fish injury and mortality due to blade strike and/or hydraulic conditions that can damage or disorient fish (Coutant and Čada 2005; EPRI 2006; Čada et al. 2007; DOE 2009). Indirect impacts are related to disruptions in volitional or natural movements and migrations or access to feeding, spawning, and nursery habitats in the vicinity of turbine installations (DOE 2009). The size and number of turbines installed may influence the magnitude of direct and indirect impacts. The potential for injury and mortality of fish that pass through operating hydrokinetic turbines is an obvious concern, particularly if installations are located in rivers with diadromous fish populations (i.e., species that undergo obligatory upstream and downstream migrations that occur during specific times of the year). The potential for fish injury and mortality may also be an important issue for tidal and ocean turbines located in biologically productive areas (i.e., areas where the probability of large numbers of fish encountering or passing through turbines is high).

A large amount of information and data related to fish passing through conventional hydro turbines has been compiled in recent years, mainly through the U.S. Department of Energy's (DOE) former Advanced Hydro Turbine Systems Program (Čada 2001; http://hydropower.inel.gov/turbines). Various mechanisms that lead to turbine passage injury and mortality have been extensively evaluated in the lab and field and some of these data should be applicable to fish passage through or near hydrokinetic turbines. Available information includes probability of blade strike, blade strike survival rates, and criteria for shear levels and pressure regimes that can damage fish. Previous assessments that have examined potential environmental impacts of hydrokinetic turbines have recognized that information and data from studies of fish passing through conventional hydro turbines may be useful in determining the risk of injury and mortality for fish encountering hydrokinetic turbines (Coutant and Čada 2005; EPRI 2006; Čada et al. 2007; DOE 2009). These assessments have generally concluded that fish passing through hydrokinetic turbines should suffer less damage, if any, because known injury mechanisms typically are not as severe or as prevalent compared to conventional hydropower turbines. However, despite what appear to be logical conclusions, previous reviews of the existing data have not been sufficient or rigorous enough to alleviate many concerns regarding the ability of fish to safely interact with hydrokinetic turbines.

Although the available data for conventional hydro turbines may be applicable to hydrokinetic turbines, the following operational differences should be noted:

- Hydrokinetic devices operate in an open environment with water flowing both through and around the devices, whereas conventional hydro turbines incorporate an intake and/or penstock that conveys all the flow through the runner. The open environment around hydrokinetic turbines offers the opportunity for aquatic organisms to detect and avoid the devices.

- Hydrokinetic devices operate with essentially no head differential (other than that created by a device itself), which provides low shear levels and small pressure changes from upstream to downstream. Conversely, conventional hydro turbines typically operate under head differentials of anywhere from 10 ft to 1,000 ft, resulting in potentially high levels of shear and considerable pressure differences and pressure change rates.
- Hydrokinetic turbines generally operate at considerably lower rotational speeds and blade velocities, which will contribute to lower probabilities of blade strike and mortality from strike.

The goal of the review of turbine passage studies associated with conventional hydropower was to synthesize the available information in order to draw inferences as to how known injury mechanisms may or may not lead to injury and mortality of fish interacting with hydrokinetic devices. The information gathered has been categorized by injury mechanism type (e.g., shear and turbulence, pressure, and mechanical) and is discussed in terms of design and operational differences between conventional hydro and hydrokinetic turbines, as well as differences in the magnitude or potential for fish injury and mortality.

Section 2: Review and Application of Conventional Hydropower Data to Hydrokinetic Turbines

An extensive amount of research has been conducted during the past 60 years in attempts to determine injury and survival rates for fish passing through conventional hydro turbines and to identify and quantify injury mechanisms (e.g., flow shear and turbulence, pressure changes, grinding and abrasion in gaps, blade strike, and cavitation). Much of this research has been conducted with anadromous salmonids to address smolt losses at hydro projects in the Pacific Northwest. Numerous studies were also conducted at hydro projects throughout the Midwest and Northeast in the 1990's to estimate turbine passage survival for diadromous and riverine fishes. These studies were conducted as part of FERC relicensing efforts and were used to assess the need for downstream fish passage and protection facilities. Also in the 1990's, the DOE established the Advanced Hydro Turbine Systems Program (AHTS) in an attempt to develop improved turbine technologies that reduced damage to entrained fish. In addition to the development of two "fish-friendly" turbine designs for conventional hydropower projects (the Alden turbine and the Minimum Gap Runner Kaplan), this program sponsored many studies that examined fish injury mechanisms and produced data that have formed the basis for the development of bio-criteria for current and future advancements in turbine design and operation. More recent studies funded by the Electric Power Research Institute (EPRI) have continued to investigate means to increase turbine passage survival. This research has included blade strike experiments that have provided data and guidelines for reducing fish mortality by re-designing the leading edge of turbine blades.

The primary injury mechanisms for fish passing through conventional hydro turbines that have been identified and investigated during previous research efforts are:

- High shear and turbulence levels
- Rapid and excessive pressure reductions
- Cavitation
- Grinding and abrasion between moving and stationary components
- Leading edge blade strike

Data and information that have been gathered on these injury mechanisms have been used in the development of advanced conventional hydro turbine designs that cause less damage to fish (Čada 2001). This information should have considerable applicability to assessment of the potential effects of hydrokinetic turbines on fish. For example, the effects of operational parameters (e.g., runner speed) on blade strike probability and mortality have been used to assess damage to fish passing through conventional hydro turbines (Ploskey and Carlson 2004; Deng et al. 2005; Hecker and Allen 2005) and, in a similar manner, can be adapted to assess direct strike mortality rates associated with hydrokinetic turbines. Also, shear and pressure bio-criteria can be compared to theoretical and numerical model data for hydrokinetic turbines to determine if thresholds for damage to fish are exceeded, and to determine in what areas of the turbine this damage may occur. A detailed review of previous research on the various injury mechanisms associated with fish passage through conventional hydro turbines and its relevance to hydrokinetic technologies is provided below.

Shear and Turbulence

Shear and turbulence are hydraulic conditions that occur with flow of water through intakes, turbines, and draft tubes. When exposed to shear and turbulence, a fish experiences differential forces across its body (Killgore et al. 2001) which can cause rotation and deformation and lead to injury and mortality (Morgan et al. 1976). The intensity and amount of shear and turbulence encountered by a fish during turbine passage will depend on project design and operation. Shear and turbulence have been identified as potential sources of injury and mortality for fish passing through hydroelectric turbines (Solomon 1988; Čada et al. 1997). Both parameters describe changes in water velocity over a specified distance (e.g., the length of a fish). Shear describes the change in water velocity with respect to distance that results from adjacent water masses moving with different velocities. The impact caused by shear, or shear stress, is expressed as a force per unit area acting upon a surface. Conditions that produce high levels of shear exist throughout conventional hydroelectric turbines, but fish typically encounter them when passing between flow masses of differing velocities or near solid surfaces. Shear forces are expected to be greatest along solid boundaries or at the leading edge of turbine blades (USACE 1995, Čada et al. 1997).

Turbulence occurs when fluid masses within a moving water body make small and intense changes in direction other than that of the bulk flow direction (Vogel 1981) and can also result from the breakdown of shear zones (Turnpenny et al. 1992). Due to high velocities and boundary effects of structures, flow passing through a turbine can be highly turbulent (Neitzel et al. 2000). The effect of turbulence on fish depends on the turbulence scale (size) and intensity (magnitude of velocity variations compared to the average flow velocity). Small-scale turbulence can be found throughout a conventional turbine passageway, particularly in the wake of the runner blades (Turnpenny et al. 2000), whereas large-scale turbulence tends to be highest within the turbine draft tube (Čada et al. 1997). Small-scale turbulence has been found to result in body compression and distortion in fish; large-scale turbulence often creates vortices which spin fish and cause disorientation (Čada et al. 1997).

More detailed descriptions of the physical characteristic that define hydraulic shear and turbulence and their occurrence at hydro projects are provided by Čada et al. (1997) and Odeh et al. (2002).

Review of Shear Studies

Studies conducted to assess the effects of shear on turbine-passed fish have focused on determining thresholds at which injury and mortality are likely to occur. Studies have also been conducted to quantify shear levels to which fish may be exposed when passing through turbines. However, the ability to correlate injury and mortality with shear levels experienced by individual fish that are collected after turbine passage has been problematic (Deng et al. 2005). Also, this type of field assessment can be complicated by the presence of other mechanisms that can result in similar injuries (e.g., blade strike).

Velocities and magnitudes of shear stress experienced by fish passing through turbines are expected to be greater than those experienced by fish in their natural environments. Measurements of velocity within a turbine have been reported to vary from zero near solid boundaries to as high as 120 ft/s away from boundary effects, with the magnitude of change across shear zones estimated to be approximately 30/s (USACE 1995). Early estimates of shear stress values for bulb turbine draft tubes ranged from 500 - 5,400 N/m^2, with stress levels below 1,000 N/m^2 in over 90% of the passage zone (McEwen and Scobie 1992).

Based on the estimates by McEwen and Scobie (1992), Turnpenny et al. (1992) exposed salmonids to a high-velocity water jet in a static water tank that created shear stress values of a similar magnitude. Results from post-exposure evaluations showed no injuries or mortalities to fish from shear stress values at or below 774 N/m^2. Results also suggested that fish orientation at initial exposure influenced injury rates and that mortality was proportional to jet velocity. Common injuries observed in fish exposed to higher values included eye damage or loss, torn gill covers, loss of mucous layer leading to osmotic imbalance, and deformation. In a review of this and other studies using the same experimental design, Čada et al. (1997) concluded that the extent of damage to fish from shear stress varied by species, size, and life-stage. Reviewers also pointed out that the experimental design restricted testing to small-scale effects; the demonstration of larger-scale effects would require additional study (Čada et al. 1997).

Although these studies succeeded in creating damaging shear effects, the exact levels of shear to which fish were exposed were not fully quantified in either study. In addition, fish experienced a different shear regime depending on their distance from the jet nozzle. To address these issues, subsequent studies have employed computer modeling techniques to predict shear forces throughout a turbine pathway, including shear surrounding runner blades and other structural components (e.g., wicket gates and stay vanes). In a follow-up to their previous research, Turnpenny et al. (2000) applied Computational Fluid Dynamic (CFD) techniques to identify the risk of injury from shear effects in small low-head (< 30 m) Francis and Kaplan turbines. The CFD model indicated that shear stress levels were of minor importance in both turbine types based on low probabilities of occurrence. Combining the computer modeling data with a modified formula for estimating injury due to blade strike, investigators predicted that less than 2% of salmonids passing through low-head turbines would suffer potentially fatal injuries from shear stress (Turnpenny et al. 2000). Field tests performed at representative sites were able to validate these predictions, although investigators based their comparisons on the assumption that observed eye injuries were the result of shear and not another type of injury mechanism (e.g., blade strike).

More recent studies have evaluated the responses and/or tolerance levels of fish to shear stresses associated with hydro turbines for the purpose of establishing biological criteria that will aid in the design of more advanced fish-friendly turbines. In a comprehensive study performed at the Pacific Northwest National Laboratory (PNNL), investigators modeled and quantified the shear environment within a turbine passage using CFD techniques and then designed a test facility based on their model to assess the biological responses of several salmonid species and American shad to comparable levels of shear (Neitzel et al. 2000, 2004; Guensch et al. 2002). During the biological tests, juvenile salmonids (Chinook, rainbow trout, steelhead) and American shad were exposed to a shear environment at the edge of a high-velocity water jet, with the interactions recorded by a high-speed video system. Experimental conditions were selected to address the assumptions that the magnitude of shear effects would depend on the relative velocity of fish to fluid, the shape of the fish, and the orientation of the fish to flow. Test fish were subjected to strain (shear) rates from 168 to 1,185/s (corresponding to velocity differences of about 3 to 21 m/s over a distance of about 1.8 cm).

Neitzel et al. (2004) reported that injuries classified as "significant major" were not observed for any of the species tested at or below a strain rate of 517/s (velocity of 9.1 m/s over a distance of 1.8 cm). The study results indicated American shad were the most susceptible to shear-related injuries, whereas steelhead and rainbow trout were least susceptible. Shear-related injuries also varied based on initial fish orientation, with fish released headfirst suffering more damage than those released tail first. (Note: The design of the experimental apparatus was such that fish moving headfirst down the introduction tube were struck from behind by the jet. Thus, a "headfirst" release resulted in shear forces that opened the operculum and lifted scales in a direction from the back of the fish forward toward the head.) Typical headfirst injuries included torn operculi, injured gill arches, and missing eyes. Neitzel et al. (2000) concluded that their results, as well as those from other studies, supported the general conclusion that single exposures to shear strain rates of 850/s (15 m/s over 1.8 cm) and higher would be harmful to juvenile fish (Neitzel et al. 2000) and that injury or mortality to the tested fish is unlikely to occur at strain rates less than about 500/s.

Guensch et al. (2002) and Deng et al. (2005) presented the results for an analysis of the high-speed video from the above study that was taken during the exposure of each fish to the high-velocity jet (Neitzel et al. 2000), concentrating primarily on tests conducted with Chinook salmon. Using a quantitative approach to the analysis, values of specific parameters (fish velocity, acceleration, jerk, impulse, and force) were calculated from observations of the release and injury mechanisms recorded. Most injuries were observed to occur upon the initial contact of a fish with the jet and not after a fish fully entered the flow. At strain rates of 688 and 852/s, which correspond to velocity gradients of 12.5 and 15.2 m/s over 1.8 cm, damage to the operculum was the most frequently observed injury. Injuries to the eye, isthmus, and the gill arches were equally common at the highest strain rate (1,185/s) and corresponding velocity gradient (21.3 m/s over a distance of 1.8 cm). Underyearling (Age 0) fish appeared less susceptible to injury than larger yearling (Age 0) fish, especially at lower jet velocities, but the smaller fish were more susceptible to disorientation following shear exposure. In general, Guensch et al. (2002) found that all parameters examined from a fish's bulk motion (velocity, jerk, and force) were positively correlated to injury levels.

Neitzel et al. (2004) used a logistic regression model to further explain the effect of strain rate on injury or mortality for various test groups. This approach was used to estimate strain rates at which 10% of a population suffered injury and/or mortality (i.e., LC-10). Calculations of LC-10 values demonstrated that juvenile salmonids sustained minor injury when exposed to a shear zone having a strain rate equal to or less than about 500/s. Also, the LC-10 values were lower for fish entering the shear zone head first compared to entering tail first. Overall, authors of these PNNL studies asserted that their results succeeded in defining the relationship between fish injury and shear forces (strain rates) present at hydroelectric projects (i.e., associated with turbines, spillways, and gates) and provided useful bio-criteria for improving fish passage and survival with future turbine designs.

As part of the Advanced Hydropower Turbine Systems Program sponsored by the U.S. Department of Energy (DOE), Alden Research Laboratory, Inc. (Alden) and Concepts NREC conducted a multi-phase research program to design, construct, and test a new turbine to minimize fish injury at hydropower projects (Cook et al. 2003). Based on an evaluation of previous turbine mortality studies, Alden developed biological criteria to aid in their turbine design, including the maximum allowable shear (Cook et al. 1997). The initial criterion used for minimizing shear-related injuries was a maximum strain rate of 180/s. However, this criterion was later modified based on the research discussed above and CFD modeling that was performed to determine if biological criteria for eliminating injuries associated with shear (as well as turbulence and pressure) were being met (Cook et al. 2003; Lin et al. 2004). Although the CFD simulations indicated the presence of strain rates greater than the subsequently established design criterion (i.e., a maximum strain rate of 500/s), these zones were relatively small and considered unlikely to cause significant injury or mortality to turbine-passed fish. Biological testing conducted with a pilot-scale Alden turbine and six species of fish indicated that observed injuries and mortalities were likely due to blade strike and not other mechanisms (i.e., damaging levels of flow shear, turbulence, and pressure) (Cook et al. 2003).

Building upon a growing body of work, investigators began to take a more comprehensive look at the effects of shear on fish within hydroelectric turbines. Using a multi-discipline approach, Čada et al. (2006) combined measurements of hydraulic conditions inside turbines, results from laboratory testing of associated shear stresses on fish, CFD modeling, and field evaluations of injury and mortality in an attempt to define and mitigate the impact of shear on turbine-passed fish at a dam on the Columbia River. The authors of this study used the previously determined minimum strain rate (517/s; Neitzel et al. 2004) at which injuries became more prevalent for juvenile salmonids to calculate the maximum shear force value (1.6 kPa). Using this value as an injury/mortality threshold, CFD modeling was performed under multiple sets of conditions existing within a Kaplan turbine at the Wanapum Dam on the Columbia River. After verifying the CFD model's accuracy by using velocity measurements taken during the aforementioned PNNL lab study (Neitzel et al. 2000, 2004), Čada et al. (2006) estimated that areas of potentially lethal shear stress within the turbine existed in areas in or near the stay vanes and wicket gates, runner, and draft tube. However, areas with potentially damaging shear levels were shown to comprise less than 2% of the volume of flow through the turbine under typical operating conditions. Using the assumption that mortality from shear would be proportional to the flow-weighted volumes estimated by CFD, the authors concluded that less than 0.6% of turbine-passed fish at Wanapum would suffer mortality due to shear stresses associated with the turbine flow rates at which field tests were conducted. While mortality rates estimated from a field study at Wanapum (NAI et al. 2006) were higher than those predicted from the shear stress data, the authors provided several reasons for these differences, including the likelihood that other injury mechanisms (strike, pressure, cavitation, etc.) may have contributed to the higher values of the empirical data and that the effects of each injury mechanism change with turbine flow rate.

An advanced hydropower turbine (AHT) designed to improve the survival of turbine-passed fish was installed at Unit 8 of the Wanapum Dam and several studies were conducted to compare its biological performance to that of the project's existing Kaplan units. The AHT was designed to reduce velocity gradients (shear) and flow recirculation using new features such as shaped stay vanes and a modified draft tube. Dauble et al. (2007) summarized the results of studies that were performed for the Wanapum turbines to determine if fish survival associated with the AHT design would meet performance goals. These studies included evaluations of mechanical, pressure, and shear and turbulence injury mechanisms. To examine the various forces experienced by fish passing through each turbine design, an autonomous sensor device (the Sensor Fish) was released into each turbine intake concurrently with tagged live fish. Pressure and acceleration measurements collected by the sensor fish were analyzed in tandem with CFD simulations to predict the location, frequency, and severity of shear exposure events during passage. The results of this analysis indicated there were fewer severe shear events for the AHT (1.1%) than the conventional turbines (3.4%) at Wanapum. Sensor fish data were also correlated with lab observations of shear-type injury to estimate shear injury rates for each turbine.

Overall, predicted probabilities of major shear injury were 3.1% for the AHT and 4.4% for the conventional turbine, whereas field observations with tagged fish of injuries believed to be caused by shear stresses were 1.1% for the AHT and 0.9% for the conventional Kaplan unit.

In addition to studies that have investigated shear-related injury associated with hydro turbine passage, several studies have examined shear effects on ichthyoplankton with respect to other human-induced impacts (e.g., entrainment through cooling water intakes and barge propellers and wash). Morgan et al. (1976) examined the effects of shear on fish eggs and larvae using an experimental apparatus that included two concentric plexiglass cylinders (20.3 and 30.5 cm diameter) permanently fixed to a plexiglass base with a third rotating cylinder (25.4 cm diameter) placed between them. The movement of the middle cylinder was used to create shear fields in the inner and outer chambers of the apparatus. White perch and striped bass larvae and fertilized eggs were introduced into the test chamber to evaluate the effects of shear on each species and life stage. Exposures to shear lasted from 1 to 20 minutes. The apparatus was operated at a speed (rpm) that produced shear levels of 76 to 404 dynes/cm^2. Mortality consisted of disruption of the yolk-protein material or total disintegration for eggs and lack of mobility or acute tissue destruction for larvae. The results were reported as shear rates that produced 50% mortality of test specimens within various time intervals. This level of mortality occurred at shear rates of 415 to 785 dynes/cm^2 for one minute of exposure and 125 to 300 dynes/cm^2 after four minutes of exposure. The lowest thresholds for 50% mortality were experienced by white perch larvae and the highest by striped bass larvae. Striped bass eggs were also shown to be less prone to injury and mortality than white perch eggs.

Killgore et al. (2001) evaluated survival of early life stages of fish after entrainment through a scale-model towboat propeller in a circulating water channel. Shovelnose sturgeon larvae, lake sturgeon larvae, paddlefish eggs and larvae, and blue sucker larvae were injected 38 cm upstream of the 46 cm-diameter propeller. They were then collected in downstream nets and observed for immediate and delayed mortality (up to 180 minutes after entrainment). The propeller was operated at several different speeds to achieve shear stresses of 634, 1613, 3058, and 4743 dynes/cm^2. Mortalities observed under these conditions were then compared to control mortality without the propeller activated. At shear forces of 4743 dynes/cm^2, observed mortality was as high as 86.0% and was significantly greater than control mortality for most species. However, mortality rates were not significantly different from the control mortality at shear stresses below 1613 dynes/cm^2.

Review of Turbulence Studies

The effects of turbulence on turbine-passed fish have been less studied and are more difficult to assess than other injury mechanisms associated with turbine passage. Turbulence is characterized by fluctuations in velocity magnitude and direction associated with moving water. Because shear forces are present in turbulent flow, it is often difficult to differentiate the effects of shear and turbulence. Shear stress in turbulent flows often causes eddies, while turbulent flows result in shear forces and shear stress from the interaction of water moving at different velocities and in different directions (Odeh et al. 2002). Turbulence can be quantified in terms of shear stress, but is also a function of intensity and scale. In general, the physical effects of shear and turbulence on an organism are probably similar. Injuries associated with turbulence may be less severe and less likely to lead to direct mortality; however, turbulence could be a primary source of disorientation, particularly for fish exiting draft tubes, leading to indirect mortality (i.e., increased susceptibility to predation) (Čada et al. 1997).

In an effort to quantify ichthyoplankton mortality rates associated with turbulence created by barges, Killgore et al. (1987) investigated the survival of paddlefish yolk-sac larvae exposed to turbulence of different frequencies and intensities. The results of this study indicated that the intensity of turbulence, expressed in terms of pressure and velocity, was more harmful to paddlefish larvae than the frequency of exposure. Low turbulence levels (1,770-1,900 dynes/cm^2; 22-23 cm/s) resulted in short-term mortality rates equal to or less than 13%. High turbulence levels (6,220-6,420 dynes/cm^2; 57-59 cm/s) produced short-term mortality rates equal to or greater than 80%.

Potential for Shear and Turbulence to Injure Fish Passing Through Hydrokinetic Turbines

Based on the review of available information and data, shear and turbulence levels that are damaging to fish are unlikely to occur with most hydrokinetic turbines. At conventional hydro projects, high levels of shear typically occur near boundaries, where there are changes in flow paths, such as along solid surfaces (walls, turbine blades, wicket gates), and in narrow passages or gaps between turbine components (USACE 1995, Čada et al. 1997). Intense turbulence is typically associated with draft tubes and small regions in the runner. Because hydrokinetic turbines generally lack structures leading to and from the rotors or blades (e.g., stay vanes, wicket gates, draft tubes) where high levels of shear and turbulence occur, and they operate with much lower velocities with little change in flow direction, the potential for injury due to excessive shear and turbulence will be negligible or absent for many hydrokinetic turbine designs. As with conventional hydro turbines, damaging shear levels may occur in close proximity to hydrokinetic turbine blades or rotors, but such occurrences probably will be constrained to regions that are small relative to the available passage space through a blade sweep. Although the volume of areas with damaging shear varies with turbine design and operation, there is evidence that less than 2% of flow paths through advanced conventional turbines have shear levels sufficiently high to cause damage to fish (Čada et al. 2006; Cook et al. 2003; Lin et al. 2004). In support of these conclusions, a recent report describing potential environmental impacts of marine and hydrokinetic technologies (DOE 2009) did not identify shear or turbulence as potential mechanisms for fish injury.

Research on shear forces capable of damaging fish suggest that shear strain rates less than about 500/s will not result in injury or mortality. This criterion is based primarily on data from tests with juvenile salmonids and American shad, but is likely to be protective of many other species as well. Computer modeling can be utilized to determine the location and extent of regions of high strain rates, but evidence from models conducted with conventional turbines demonstrates that damaging shear is unlikely to impact fish passing through hydrokinetic turbines (Cook et al. 2003; Čada et al. 2006; Dauble et al. 2007). Also, the absence of confined flow paths downstream of hydrokinetic turbines (i.e., no draft tubes) and relatively uniform flow direction from upstream to downstream should not produce turbulence of a scale and magnitude that could injure fish. Small-scale turbulence may occur in the vicinity of blades or rotors and other turbine components, but is unlikely to occupy a sufficient volume relative to the entire passage volume through a turbine to cause damage to fish at a rate that would lead to a noticeable or measurable impact. Also, velocities are considerably higher in conventional turbines because they operate under static head and the flow path from the intake through the turbine becomes constricted. Conversely, velocities approaching and passing through hydrokinetic turbines are the same or similar in magnitude to ambient currents.

Shear and Turbulence Bio-Criteria for Hydrokinetic Turbines

Despite the unlikelihood that damaging levels of shear and turbulence will occur with hydrokinetic turbines, consideration of biological design criteria during pre-development analyses of performance can still ensure minimal impacts to aquatic organisms. Based on the existing data and information, the potential for shear-related injury and mortality could be eliminated if hydrokinetic turbines are designed and operated so as to minimize the occurrence of strain rates greater than 500/s. Laboratory studies have identified exposure strain rates in the range of 495/s up to 833/s as the minimum strain rate at which fish begin to exhibit injuries and mortality, depending on species and life stage (Turnpenny et al. 1992, Neitzel 2000; Neitzel et al. 2004, Deng et al. 2005), although values may be lower for fish larvae and eggs (Morgan et al. 1976, Killgore et al. 1987, Killgore et al. 2001). In addition, studies comparing CFD modeling data with empirical data to identify areas of high shear and turbulence forces within turbines have found that when the frequency and/or volume of areas with damaging strain rates are minimized, fish injury and mortality rates are low (Cook et al. 2003, Čada et al. 2006). Disorientation and increased stress are also likely to be reduced due to the more “fish-friendly” hydraulic conditions associated with hydrokinetic turbines, which will lead to less potential for indirect mortality (e.g., predation, disease) as well.

Pressure and Cavitation

Low pressure, rapid change in pressure, and cavitation have all been identified as mechanisms that can lead to injury and mortality of fish passing through conventional hydro turbines (Solomon 1988; Turnpenny 2000; Čada et al. 1997). The potential for pressure-related injury and mortality depends on the magnitude of pressure reduction and how rapidly it occurs, how quickly fish can adjust to changing pressure conditions, and the acclimation pressure of fish when they enter a turbine intake. Cavitation (the formation of water vapor bubbles that collapse suddenly and cause high pressure spikes) can also lead to injury and mortality. However, cavitation is often limited to small regions around runner blades when turbines are operated off their design point. The potential for damaging low pressure regimes and cavitation to occur with hydrokinetic turbines is low because hydrokinetic turbines are not operated under the higher heads associated with conventional turbines. Similar to conventional turbines, hydrokinetic turbines are designed and operated in a manner that minimizes cavitation.

Review of Pressure Studies

Rapid reductions in pressure are considered a potential injury mechanism for fish passing through conventional hydro turbines and are represented by the force per unit area acting upon a specific point (Čada et al. 1997). Pressures associated with conventional hydro turbines have been measured from a high of 460 kPa to a low of 2 kPa (Montgomery Watson 1995). Following entrainment into a turbine intake, a surface-oriented fish is subjected to an increase in pressure upstream of the runner, with the duration varying from seconds to minutes depending on the resistance of the fish to passage (Dadswell et al. 1986, Abernethy et al. 2001). When passing through the runner into the draft tube, fish experience a rapid decrease in pressure, often in a matter of seconds or less, that often falls below atmospheric levels (Čada 1990, Abernethy et al. 2001). Upon exiting a draft tube, fish are exposed to near atmospheric pressure as they surface in the tailrace (Čada 1990, Abernethy et al. 2001).

During passage through a conventional turbine, fish encounter a wide range of pressures and may have some control (both temporally and spatially) over their exposure and have the ability to make quick physiological adjustments. The capacity of fish to adjust to changes in pressure is primarily dependent on their type of buoyancy control, including whether they have a swim bladder (also referred to as an air or gas bladder). Only ray-finned fish have swim bladders, which includes all species commonly entrained at hydro projects in North America. Species with swim bladders are classified as either physostomous or physoclistous based on how they regulate swim bladder volume. Physostomous fish, such as salmon and trout species, have a pneumatic duct connecting the swim bladder and esophagus which allows for rapid intake and venting of gas. Physoclistous fish, such as freshwater bass and sunfish species, lack a pneumatic duct, resulting in slower adjustments to bladder volume via gas diffusion through the swim bladder wall. As a result, physoclistous fish have limited ability to compensate for the rapid pressure changes that typically occur during turbine passage compared to physostomous fish and are more susceptible to pressure-induced damage. In addition to the means of controlling swim bladder volume, acclimation pressure of fish prior to entering a hydro intake and passing through a turbine may influence the potential for pressure-related injury or formation of embolisms.

Initial laboratory evaluations demonstrated species-specific responses by exposing fish to various pressures and rates of pressure change under laboratory conditions. Salmonids (physostomous) exposed to gradual and rapid increases in pressure up to as high as 2,064 kPa followed by decompression to atmospheric pressures showed little or no mortality (Harvey 1963, Rowley 1955, Foye and Scott 1965). Conversely, salmonids exposed to low pressures showed higher mortality rates than controls at pressures below 84.6 kPa (Harvey 1963). In addition, increases in decompression rates resulted in higher mortalities for both physostomous and physoclistous fish (Tsvetkov et al. 1972). Turnpenny et al. (1992) tested marine fishes under pressure scenarios that mimicked passage through a low-head turbine at a tidal barrage and found that physostomous fish showed much less external damage and a higher tolerance to the scenarios tested than physoclistous fish. When laboratory tests examined pre-exposure acclimation pressure as a variable, fish mortality was shown to be directly related to the magnitude of depressurization (Feathers and Knable 1983).

In a comprehensive review of these studies, Čada et al. (1997) concluded that pressure increases similar to those experienced in hydro turbines (i.e., as fish move deeper when approaching a turbine) were unlikely to cause injury or mortality to fish. However, it was concluded that exposures to sub-atmospheric pressures within turbines were more damaging, particularly to physoclistous fish. Specifically, the highest mortalities were observed when the rate of pressure decrease and the difference between the fish's acclimation and exposure pressure were greatest (Čada et al. 1997). To demonstrate this, Čada et al. (1997) compared mortality rates to the ratio of exposure and acclimation pressure reported in the studies reviewed (see Figure 2-1). The results of this comparison suggested that pressure-related mortality was likely to be minimized when minimum exposure pressures remained above 60% of acclimation pressure. Although this was a more conservative estimate compared to a criterion of 30% previously suggested by ARL (1996), this lower minimum value was based on data for salmonids (physostomous fish; USACE 1991) and would be less protective for physoclistous fish.

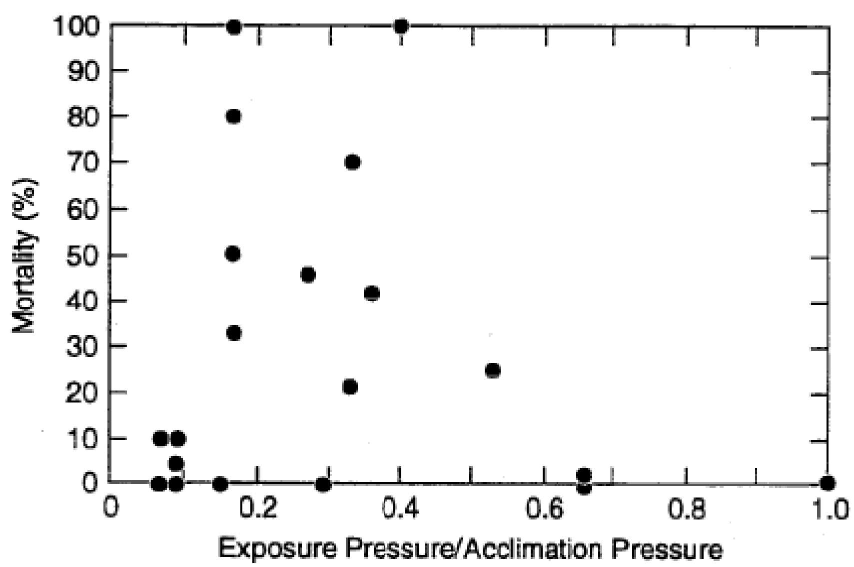

Figure 2-1
Fish mortality as a function of the ratio of exposure pressure to acclimation pressure (Source: Čada et al. 1997)

More recent investigations have examined the direct effects of pressure stresses on fish under operating conditions representative of conventional hydro projects. As part of the former DOE Advanced Hydropower Turbine System program (AHTS), the Pacific Northwest National Laboratory (PNNL) completed a multi-year laboratory study to quantify the response of fish to rapid pressure changes in a closed laboratory system following acclimation at different depths and gas saturation levels (Abernethy et al. 2001, 2002, 2003) (Figure 2-2). Three species (bluegill, Chinook salmon, and rainbow trout) were exposed to pressure regimes associated with two turbine designs (vertical Kaplan and horizontal bulb units), while maximum and minimum pressure conditions were tested only with the Kaplan design. Results summarized by Becker et al. (2003) supported the conclusion that pressure changes (independent of turbine design) resulted in greater rates of injury and mortality due to swim-bladder rupture for physoclistous fish (bluegill) than for physostomous fish (salmonids). Rates of injury and mortality to both depth- and surface-acclimated salmonids were deemed negligible even at pressure values less than 30% of acclimation pressure. Comparatively, bluegill experienced significant rates of injury and mortality at pressure values below 60% of acclimation pressure, particularly for fish acclimated at depth. Dissolved gas saturation levels were not found to significantly contribute to passage-related injuries or mortalities. From these results, authors suggested that pressures at or above 50 kPa (about 50% of atmospheric pressure or 7 psia) and rates of pressure change at or below 3,500 kPa/s could be expected to provide safe passage for salmonids and would result in limited mortality for physoclistous species such as bluegill (Becker et al. 2003). Also, to eliminate substantial injuries to physoclistous species, it was concluded a higher minimum pressure (greater than or equal to 60% of the fish's acclimation pressure) would likely be necessary.

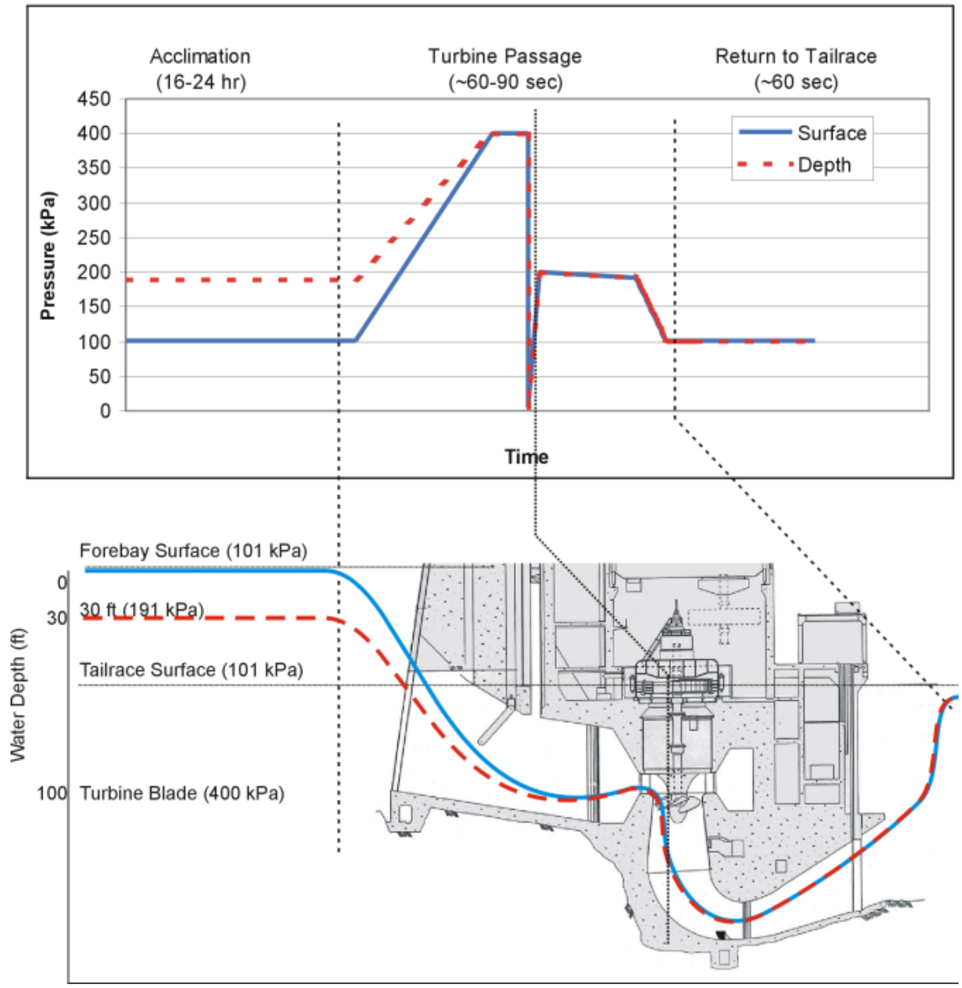

Figure 2-2
Pressure exposure simulation of turbine passage for surface- and depth-acclimated fish (Source: Abernethy et al. 2001)

Studies employing CFD modeling have allowed investigators to define a given turbine's pressure regime under various operating conditions, including the identification of any areas where damaging pressures may occur. Based on these models, investigators can predict the occurrence of pressure-induced mortality and also verify the predictions by collecting empirical data. As a follow up to an earlier study, Turnpenny et al. (2000) utilized these techniques to refine a method of predicting injury rates resulting from damaging pressures for small, low-head Francis and Kaplan turbines. The authors were able to show that the main risk areas of pressure related injury were located in the turbine runner and the draft tube. Despite this, results of field tests indicated that pressure-related injuries only accounted for 6.3% of the total injuries observed (Turnpenny et al. 2000). Overall, the authors concluded that their predictive model provided a good representation of risk from pressure effects in smaller low head turbines.

In a CFD study of the flow conditions through the pilot-scale Alden turbine, Lin et al. (2004) defined the internal pressure regimes resulting from operation at the best efficiency point (BEP) and off-BEP conditions. The results of this analysis were used to explain observations of similar fish survival rates despite different operating conditions evaluated during a previous pilot-scale biological evaluation of fish passage through the turbine. The Alden turbine had been previously designed to meet established bio-criteria for minimum pressure levels and rates of pressure change (≥69 kPa and < 552 kPa/s; Cook et al. 1997). Although the CFD results showed evidence of low pressure zones near the turbine's trailing blade edge at all conditions evaluated, these zones were relatively small in volume and consistent with the more current minimum bio-criteria value (≥50 kPa) recommended by Abernethy et al. (2002). Pressure change rates higher than recommended bio-criteria maximum levels (≤3,500 kPa/sec) were also found near the blade trailing edges for all operating conditions examined, but these rates were also shown to occupy relatively small volumes compared to the entire passage volume of the turbine. After comparing these CFD results with the survival rates observed during the pilot-scale biological evaluation, the authors concluded the established bio-criteria values for minimum pressures and rates of pressure change were reasonable and indicated pressure-related injuries were likely not occurring for fish passing through the Alden turbine.

To further clarify the role of acclimation pressure in effecting pressure-related injuries and mortalities to turbine-passed fish, Carlson and Abernethy (2005) studied the impacts of simulated turbine passage pressure on juvenile salmonids that achieved neutral buoyancy while acclimating to absolute pressures higher than atmospheric levels. This scenario was designed to mimic the acclimation pressures corresponding to the depths at which salmonids had been observed during downstream migration. Prior studies had not allowed salmonids to achieve neutral buoyancy while being acclimated at depth (Abernethy et al. 2001, 2002, and 2003). The results, while lacking statistical significance, indicated that neutrally buoyant juvenile salmonids acclimated at depth pressure levels might be at greater risk for injury and mortality than fish acclimated to near-surface pressures. In a more recent study, Brown et al. (2007) demonstrated that acclimation pressure was a statistically significant predictor for risk of injury or death, but only when fish were exposed to significantly lower simulated turbine minimum pressures in the range of 8–19 kPa.

Review of Cavitation Studies

Cavitation refers to the vaporization and subsequent rapid condensation of water. This process occurs when the localized pressure in water falls to or below the vapor pressure of water at the ambient temperature, resulting in the formation of gas bubbles. These gas bubbles grow in the region of reduced vapor pressure and then collapse suddenly upon reaching areas with higher pressure. The almost instantaneous collapse of bubbles causes high pressure shock waves and noise, the intensity and frequency of which may vary according to bubble size, surrounding water pressure, dissolved gas content, and the presence of air bubbles (Čada et al. 1997).

Within conventional hydro turbines, and depending on air content and water temperature, conditions leading to cavitation may occur on the downstream side of blades, in high-velocity regions, and areas where there are abrupt flow direction changes, or surface roughness (USACE 1995; Čada et al. 1997).

Because cavitation forces are sufficient to cause material damage to turbine components, fish likely would be unable to withstand the same forces produced by collapsing cavitation bubbles, resulting in injury and mortality (Lucas 1962). Turnpenny et al. (1992) performed laboratory experiments to identify the direction that a shock wave traveled following the collapse of a cavitation bubble adjacent to a fish. The collapse behavior of cavitation bubbles next to a fish was compared to that of cavitation next to a solid surface. The results demonstrated that both scenarios resulted in the bubble collapsing asymmetrically, with the implosion directed towards the nearby surface (fish and solid object). While neither the force associated with the collapse nor fish mortality rates were quantified, the authors agreed with previous assumptions that fish would experience cavitation damage within a turbine in this manner. Turnpenny (1992) also noted that cavitation damage within a turbine could be more severe than in his experimental protocol due to the presence of higher energy levels in turbines.

During a 1995 Turbine Passage Survival Workshop held by the U.S. Army Corps of Engineers (USACE 1995), participants agreed that operating turbines at the best efficiency point would likely minimize the occurrence of conditions that lead to cavitation, and therefore should minimize the potential for any subsequent damage to turbine-passed fish resulting from cavitation effects. It was also suggested that the geometry of a turbine runner could be altered to reduce areas of low pressure, high velocity, abrupt changes in flow direction, and surface roughness (Cook et al. 1997), and thereby reduce the potential for cavitation. Due to the pressure conditions necessary for cavitation to occur (water vapor pressure of about 2 kPa), areas of risk within a turbine passageway for both pressure- and cavitation-related damage were expected to be in similar locations. As a result of this relationship, fish damage resulting from cavitation could be minimized in a manner similar to that used to meet the minimum pressure criteria.

Based on the conclusions reached for mitigating pressure effects, Čada et al. (1997) asserted that maintaining water pressures at levels equal to or greater than 60% of ambient fish acclimation pressures within a turbine would also prevent cavitation and any resulting damage to fish. Achieving an average minimum turbine pressure of about 50 kPa (as discussed previously) would be sufficient to suppress cavitation that occurs at a pressure of about 2 kPa. Support for this conclusion has been demonstrated in evaluations of pressure effects related to fish behavior and turbine design criteria (Abernethy et al. 2002, Lin et al. 2004). Even though CFD modeling indicates the formation of low pressure zones near the trailing edge of turbine blades at levels close to vapor pressure, the frequency and volume of these low-pressure zones typically have been shown to be minimal and are very small compared to the overall volume of the turbine passageway.

Potential for Pressure and Cavitation to Injure Fish Passing Through Hydrokinetic Turbines

Because hydrokinetic turbines do not operate under a differential head (water level), pressure changes associated with flow passing through hydrokinetic turbines will be minor and will not be sufficient to cause damage to fish (i.e., the ratio of minimum pressure to acclimation pressure will meet established criteria for preventing fish injury and mortality). Recent reviews of potential environmental effects associated with the operation of hydrokinetic turbines have also reached a similar conclusion (EPRI 2006; DOE 2009).

The typical pressure regimes of flow passing through hydrokinetic turbines are unlikely to cause fish injury and mortality. In addition, regions where cavitation is most likely to occur are relatively small and comprise only a fraction of the total passage volume in a turbine. Regardless, low levels of cavitation associated with local low pressure regions (i.e., below vapor pressure) on the downstream side of rotors and blades may still be present in hydrokinetic turbines and should be addressed in the assessment of potential impacts to fish. Because cavitation can damage equipment and often occurs when turbines are operated under low efficiency conditions, the potential for cavitation and subsequent risks to fish can be minimized or eliminated through blade design and efficient turbine operation that includes a low rpm.

Pressure and Cavitation Bio-Criteria for Hydrokinetic Turbines

Pressure changes associated with hydrokinetic turbines are unlikely to cause injury or mortality to fish that pass through a blade sweep. However, using CFD modeling, turbine developers should confirm that minimum pressures do not fall below 60% of the pressure to which most fish are acclimated or below a minimum absolute pressure of about 50 kPa (7 psia). The 60% criterion for the ratio of minimum exposure pressure to fish acclimation pressure should be easy to achieve for hydrokinetic turbines given that the difference in pressure levels upstream and downstream of a blade sweep will be negligible. Unlike conventional hydro turbines that may pass fish acclimated to surface depths, fish that pass through hydrokinetic turbines should be acclimated to the pressure at the depth of the turbines (i.e., they will not be pulled from shallower depths through an intake structure in the manner that surface-oriented fish are when they pass through conventional hydro turbines). Also, other than localized regions comprising a small percentage of the passage volume, fish will not be exposed to a rapid pressure decrease on the downstream of hydrokinetic turbines following passage through a blade sweep. In addition to meeting the bio-criteria for pressure, potential damage to fish associated with cavitation can be minimized through proper blade design and by operating hydrokinetic turbines at their best efficiency point. Minimizing the probability of occurrence and size of potential cavitation regions should result in negligible impacts to fish associated with this injury mechanism.

Mechanical (Strike and Grinding)

Among the mechanisms that result in direct injury and mortality to fish that pass through conventional hydro turbines, those classified as mechanical in nature are often identified as having the predominant impact. Mechanical effects are related to the structural components of a turbine and are caused by one or more of the following: strike, grinding, and abrasion. A strike is defined as a collision between a fish and either the leading edge of a blade or another structure such as fixed guides, stay vanes, or flow straighteners (Čada et al. 1997). Grinding injuries are a result of fish being drawn into narrow openings or gaps between stationary and/or moving components, including between runner blades and the turbine hub, blade tips and the outer ring, at the top and bottom of wicket gates, or between stay vanes and wicket gates. Abrasion damage is caused by fish rubbing against a moving or stationary surface (USACE 1995).

Review of Blade Strike Studies

For many hydro projects, blade strike may be the primary source of injury and mortality for fish passing through turbines. Many physical and biological factors play a role in determining the probability of a fish being struck by a blade. Due to the difficulty in making direct observations within turbines, blade strike effects were initially defined by calculating strike probability and assuming most, if not all, strikes resulted in mortality. Early theoretical models developed for estimating blade strike probability incorporated information on flow velocity, blade and guide vane angles, blade rotational speed, and fish length (Von Raben 1957; Monten 1985; Solomon 1988). Other predictive models relied on additional biological variables such as fish stiffness and the probability of tissue trauma from a strike of a given force (related to species and age). Although important, these theoretical approaches were based on assumptions that can vary considerably with site-specific conditions. As a result, estimates of strike probability and injury/mortality could exhibit considerable error unless applied to sites with similar design and operation features to those used to develop the predictive models (Čada et al. 1997).

Turnpenny et al. (1992) examined the approach and collision between fish and different blade profiles to establish how fish size, orientation, and position relative to the blade affected the outcome of a strike. These tests were conducted to simulate strike speeds (and blade thicknesses) near the hub and at the blade tip. Results showed that strikes from narrow blade profiles at higher speeds caused severe damage, such as mucous loss, bruising, eye damage, internal bleeding, and broken spines. Conversely, strikes from wider (thicker) blade leading edges at slower speeds caused little damage and no mortality. Turnpenny et al. (1992) also observed that the inertia and orientation of a fish relative to the blade affected strike-related injury and mortality. Fish weighing less than 20 g were swept aside by the blade unless their center of gravity was directly in the blade's path, whereas fish weighing up to 200 g had a 75% chance of being struck when their center of gravity was aligned with the blade's path. Using the results from these tests, Turnpenny et al. (1992) developed equations for low-head, axial-flow tidal turbines based on the theoretical techniques developed by Von

Raben. Calculations of blade strike probabilities accounted for fish length, fish location, fish orientation, fish swimming speed, flow velocity, open space between blades, blade leading edge thickness, and blade speed. In a later study, Turnpenny et al. (2000) modified these statistical methods to predict injury rates for smaller turbines. As would be expected, results showed that rates of strike injury were highly dependent on fish size, turbine type, the runner diameter and rotational rate (rpm), the number of blades, and operating load. In addition, the ratio between strike and mortality was shown to be dependent on fish length.

An examination of the initial studies of blade strike indicated that injury and mortality rates for fish struck by a blade were generally a function of the morphometric characteristics of a given species, turbine design, the spatial aspects of fish passing through a turbine, and the velocity of the fish relative to the velocity of a blade (USACE 1995). It was also concluded that turbine designers could change the probability of strike by altering the number and length of blades, the area per blade channel, the thickness and bluntness of blade leading edges, and the blade tilt.

As part of the former DOE Advanced Hydropower Turbine Systems program, Alden and Concepts NREC conducted a multi-phase research program to design and test a new fish-friendly conventional hydro turbine (Cook et al. 2003). Based on an evaluation of data relevant to injury and mortality of fish passing through turbines, Alden developed the following strike-related biological criteria to guide the selection of fish-friendly features for the new turbine design: (1) peripheral runner (blade tip) speed less than 40 ft/s; (2) minimum number of blades and minimized total leading-edge length of blades; and (3) maximum flow passage size and small clearances between the runner and fixed turbine housing components.

The biological performance of the Alden turbine was evaluated during a pilot-scale laboratory study. Tests were conducted with multiple fish species and sizes, two operating heads (40 and 80 ft), several turbine operating efficiencies, and with and without wicket gates (Hecker et al. 2002; Amaral et al. 2003; Cook et al. 2003). Results of tests conducted with rainbow trout indicated that fish release depth, turbine efficiency, and the presence of wicket gates had no statistically significant influence on survival and injury rates. As was expected, and typical of any turbine design, passage survival decreased with increasing fish size (i.e., strike probability and mortality increases with fish length). Using the pilot-scale test data and a standard turbine blade strike probability model, estimates of strike were calculated for a full-scale prototype unit at the heads evaluated during the laboratory study (40 and 80 ft). High survival rates (> 96%) were predicted for fish up to 200 mm in length for both operating heads. The biological evaluation of the Alden turbine demonstrated that the fish-friendly features incorporated into the design contributed to low injury and mortality rates and that blade strike was the primary mechanism of damage to fish.

To further assess fish survival through a prototype Alden turbine in a real world application, Hecker and Allen (2005) used an established strike probability model and available strike mortality data to account for the effects of fish length and the relative velocity of turbine inflow to blade speed (i.e., strike velocity). Both of these parameters influence strike injury and mortality rates and strongly influence the proportion of struck fish that are killed. The resulting predictive model was used to estimate turbine passage survival rates for the Alden turbine and a Kaplan with a minimum gap runner (MGR), both designed for the same site conditions (approximate turbine discharge of 1,500 cfs and head of 92 ft). Using this approach, 100-mm fish passing through the Alden turbine were estimated to have mortality about one fifth that of the same size fish passing through the MGR Kaplan. The primary reasons for the Alden turbine having considerably less fish mortality were lower inflow-to-blade velocity (i.e., strike velocity), lower rotational speed, more tangential absolute flow velocity, and half the number of blades (three for the Alden turbine versus six for the MGR Kaplan). The primary conclusion from this study was that strike-induced mortality would be reduced in turbines with larger diameters (i.e. lower rpm), fewer blades, and lower inflow-to-blade velocities.

Ploskey and Carlson (2004) were able to verify a predictive blade strike probability model by estimating blade strike and injury at two turbines at Bonneville Dam and comparing the results to direct turbine survival data collected during a field study (NAI et al. 2000). The field study examined fish passage survival for specific passage routes through a turbine's runner that were based on the release depth of fish in the turbine intake. The results of the field study demonstrated that fish injury and mortality rates were higher when fish passed closer to the blade tips (thinner and faster leading edge) compared to passing near the runner hub (thicker and slower leading edge). Ploskey and Carlson (2004) used deterministic and stochastic versions of a previously developed predictive model (Turnpenny et al. 2000) which calculated strike probability estimates as a function of fish length and the turbine geometry. Overall, Ploskey and Carlson (2004) concluded that the location along the length of a turbine blade from the hub to the tip where a fish passes and the orientation of the fish when encountering a leading edge were significant factors in the successful application of theoretical blade-strike models.

In a similar study, Deng et al. (2005) evaluated the validity of estimating strike probability to establish a turbine's biological performance. To do this, modifications were made to the predictive model developed by Turnpenny et al. (2000) to account for the potential effects of wicket gate geometry and water velocity on turbine passage survival. Using the modified model, deterministic and stochastic predictions that considered how fish orient to an approaching blade were compared with biological field data collected during field studies (NAI et al. 2000). In addition, the study authors compared their predictions with observations of neutrally-buoyant beads interacting with runner blades in a scaled physical model. Results from bead testing showed that a bead's release location affected its route of passage. Beads released at the top of the wicket gates passed close to the runner hub, whereas those released near the middle and bottom of the wicket gates passed close to the mid blade and blade tips, respectively.

Stochastic predictions of turbine passage survival were similar to two sets of empirical data, and the orientation of fish as they encounter a blade's leading edge was a significant factor in determining strike probability and mortality. It was concluded that fish orientation can affect the results of predictive models and should be studied further to improve their reliability.

With the knowledge that blade strike does not always result in mortality (Turnpenny et al. 1992), a multi-year study was initiated by EPRI to evaluate the importance of leading edge blade thickness, shape, and impact velocity on fish survival (Hecker et al. 2007; Amaral et al. 2008; EPRI 2008, 2011). The goal of this study was to determine the optimum blade geometry (including thickness) for maximizing survival of fish struck by turbine blades. The researchers used CFD modeling and laboratory testing with fish to develop leading edge blade design criteria. Results from the CFD analysis indicated that a semi-circular shaped blade created the highest differential forces (leading edge pressures) and thus had the greatest potential to deflect a fish prior to impact. In the first year of laboratory testing, rainbow trout of various lengths (about 100 to 250 mm) were exposed to semi-circular blades of differing thicknesses (9.5, 25.4, 50.8, 101.6, and 152.4 mm) traveling at speeds up to about 30 ft/sec. The ratio of fish length to blade thickness (L/t) was used to standardize the results. During the second year, the scope of testing was expanded to include two additional species (white sturgeon and American eel) and higher strike speeds (up to 40 ft/s).

Rainbow trout had high strike survival rates (> 90%) at strike velocities up to about 40 ft/s when the L/t ratio was about 1 or less (i.e., fish length was equivalent to or greater than the leading edge blade thickness) (Figure 2-3). Conversely, increases in L/t ratios above 1 at strike velocities of about 24 ft/s resulted in dramatic decreases in survival (Figure 2-3). These results demonstrated that strike survival was influenced by strike velocity, fish length, and blade thickness. White sturgeon and American eel exhibited higher blade strike survival rates than rainbow trout at equivalent L/t ratios, as well as high survival rates at L/t ratios and strike speeds greater than those tested with rainbow trout. Investigators concluded that unique physical features of sturgeon and eel made them less susceptible to strike-related injury (Amaral et al. 2008; EPRI 2008). The results of this study provide valuable information with respect to making turbine blades less injurious to fish.

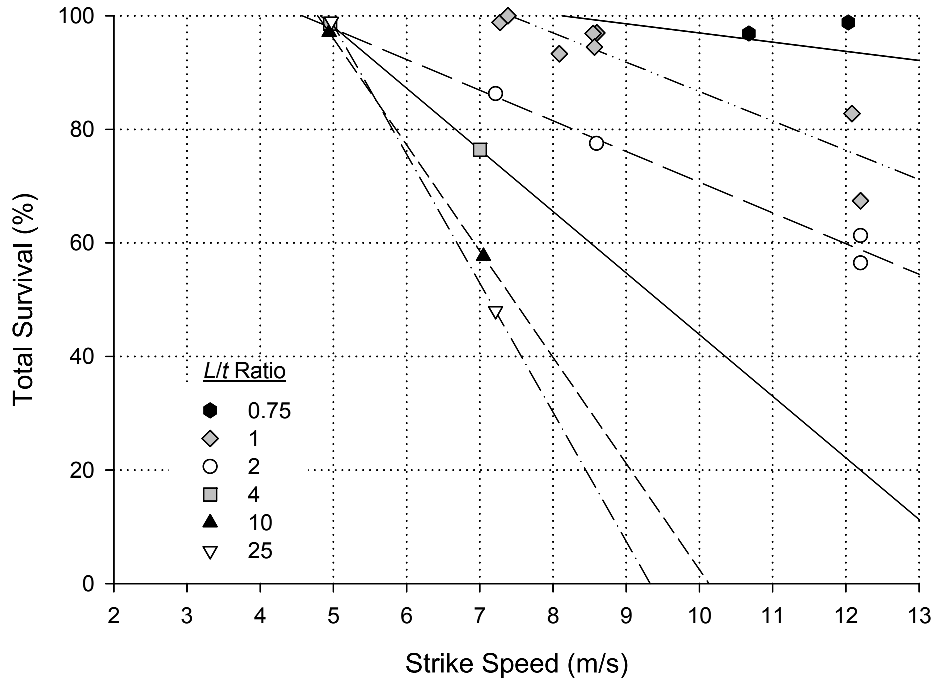

Figure 2-3
Blade strike survival rates of rainbow trout tested at various fish length to leading edge thickness ratios (L/t) over a range of strike velocities (Source: EPRI 2011)

Review of Grinding and Abrasion Studies

Due to limited information and data, the extent to which fish passing through conventional hydro turbines are injured and killed from grinding and/or abrasion is not completely known. Clearly, there is potential for fish to be caught between moving and stationary turbine components or to pass through gaps or contact rough surfaces resulting in injury, but these injury mechanisms have not been quantified to any reasonable extent for conventional hydro turbines. Despite the lack of data, efforts have been made to improve the fish-friendliness of conventional hydro turbines by reducing the potential for grinding and abrasion. In particular, a minimum gap runner (MGR) design for Kaplan turbines was developed through the former DOE Advanced Hydro Turbines Systems program by a team of researchers led by Voith Hydro (Franke et al. 1997). The MGR design greatly reduced the gap between the blade tips and outer ring and between the blades and the hub. Modifications were also made to stay vanes and wicket gates to reduce gaps associated with these components. The design of hydrokinetic turbines should also incorporate features that will prevent or reduce grinding and abrasion of fish, e.g., reduce the gaps between the rotor blade tips and duct. However, because hydrokinetic turbines have an open flow path and inherently fewer components that could lead to grinding and abrasion injuries, the reduction of these injury mechanisms should be secondary to more prevalent sources of potential injury (e.g., blade strike).

Potential for Mechanical Injury to Fish Passing Through Hydrokinetic Turbines

Mechanical mechanisms of fish injury and mortality associated with hydrokinetic turbines will be similar to those experienced by fish passing through conventional hydro turbines. However, the potential for grinding and abrasion is likely to be minimal (or possibly absent for some hydrokinetic turbine designs) given that there are fewer locations where these types of injuries could occur during passage through hydrokinetic turbines. Specifically, there are typically no structures upstream and downstream of hydrokinetic rotors that can result in abrasion, and there are few gaps between turbine components where grinding may occur. Some hydrokinetic turbines have stators that direct flow to the turbine blades and which may create opportunities for grinding or pinching in the space between the stators and rotors.

Because opportunities for abrasion and grinding are limited, the primary source of mechanical-related fish injury and mortality associated with hydrokinetic turbines will be blade strike. Fish striking fixed turbine components, such as stators or an outer ring (ducted units), should not result in injury because of relatively low approach velocities (typically less than 10 ft/s). Most species and life stages will have sufficient swimming capabilities to avoid collision with stationary structures at the velocities approaching hydrokinetic turbines, and existing blade strike data demonstrate that collisions at these velocities will not result in injury. Even if such collisions occur, the low strike velocities will not result in injury or mortality based on data from turbine blade strike studies conducted at strike velocities between about 15 and 40 ft/s (Hecker et al. 2007; Amaral et al. 2008; EPRI 2008). Therefore, strike by moving turbine blades may be the primary potential source of mechanical injury for fish passing through hydrokinetic turbines. Mortality from strike could occur if the relative velocity of fish to blades (i.e., strike velocity) and the ratio of fish length to leading edge blade thickness are sufficiently high to cause physical harm (Hecker et al. 2007; Amaral 2008; EPRI 2008). However, even if strike velocities are sufficiently high to injure fish, the probabilities that fish will encounter a turbine may be very low and, for those that do approach a turbine, active avoidance of turbine passage and moving blades may be high, resulting in little or no strike-related mortality.

Mechanical Bio-Criteria for Hydrokinetic Turbines

To minimize the potential for fish injury and mortality associated with mechanical components, device developers should consider the following in the design of hydrokinetic turbines:

- Minimize the number and size of gaps between stationary and moving components.
- Minimize the size of gaps between stationary components.
- Maximize the size of gaps between trailing edge of stators and turbine blades.
- Minimize the number of blades.

- Maximize the thickness of the blade leading edges and approximate a semi-circular leading edge shape.
- Minimize blade speed. Blade speeds and approach velocities that result in strike velocities of about 15 ft/s and less will result in minimal or no injury to all species and life stages (except possibly early larval fish); injury and mortality at higher speeds will depend on the ratio of fish length to the leading edge blade thickness.

The actual effects of each of these turbine design features on levels of fish injury and mortality may be difficult to isolate and quantify for some hydrokinetic turbine designs. However, strike probability and mortality models can be used to estimate and compare the biological performance of various design alternatives with respect to the potential for blade strike. Also, adherence to the above criteria may not be necessary if it can be determined that encounter probabilities will be low and/or active avoidance of a turbine and moving blades will be high. Similarly, if strike velocities will be about 15 ft/s or less (criteria for no strike-related mortality), attention to other fish-friendly features would not be required (e.g., gap sizes and blade thickness).

Section 3: Summary and Conclusions

Several previous studies have identified potential environmental impacts associated with the installation and operation of hydrokinetic turbines in riverine, tidal, and marine areas with sufficient water velocities for power production (Coutant and Čada 2005; EPRI 2006; Čada et al. 2007; DOE 2009). In particular, these studies have listed many of the injury mechanisms that have been shown to cause damage to fish passing through conventional hydro turbines (e.g., blade strike and damaging shear and pressure conditions). Because the goal of these studies was to identify and describe potential impacts, detailed assessments of the relative importance or likelihood of various injury mechanisms for fish exposed to hydrokinetic turbines was typically not provided. However, general conclusions from some of these studies suggested that fish should suffer less injury and mortality passing through hydrokinetic turbines due to less severe conditions associated with specific design and operational features known to contribute to injury of entrained fish. Some of these studies also recommended that a more detailed analysis of fish injury and mortality data from research examining the environmental impacts of other energy sources be conducted, with specific references to extensive research on fish passage through conventional hydro turbines. The review of existing information provided in this report focuses on conventional hydro studies and provides a more thorough assessment of its relevance to hydrokinetic power generation.

There are many factors that need to be considered and understood in order to determine the potential impacts of hydrokinetic turbines on fish populations in riverine and tidal environments. The potential for injury and mortality of fish passing through the blade sweep of hydrokinetic turbines appears to be one of the most prevalent concerns raised by resource agencies and other interveners during the FERC licensing process for pilot projects. This report addresses this concern by examining information and data describing the injury mechanisms for fish passing through conventional hydro turbines and how that information may be relevant to assessing impacts of hydrokinetic projects. However, the hydraulic, mechanical, physical environment experienced by fish entrained through conventional hydro turbines is typically much harsher than what is experienced by fish passing through the blade sweep of a hydrokinetic turbine. This is mainly due to conventional turbines being operated under static head, whereas hydrokinetic units extract energy from ambient current velocities, typically without using any structures to create head or constrain flow through the turbines. The design and operation of conventional turbines results in high flow velocities, abrupt changes in flow direction, relatively high turbine rotational and blade speeds, rapid and significant changes in pressure, and the need for various structures throughout the turbine passageway that can be impacted by fish (e.g., walls, stay vanes, wicket gates, flow straighteners). Most, if not all, of these conditions do not occur or are not a component of hydrokinetic turbines and, therefore, they generally are not experienced by fish that approach and pass through the blade sweep of a hydrokinetic turbine. Also, when compared to conventional hydro turbines, the operation of hydrokinetic turbines typically produces relatively minor changes in shear, turbulence, and pressure levels from ambient conditions in the surrounding environment. Injuries and mortality from mechanical injuries will be less as well, mainly due to low rotational speeds and strike velocities, and an absence of structures that can lead to grinding or abrasion injuries. A comparison of the design and operational features associated with conventional hydro and hydrokinetic turbines presented in Table 3-1 demonstrates why rates of injury and mortality will be lower with exposure to hydrokinetic turbines.

Table 3-1
Comparison of design and operational features associated with conventional hydro and hydrokinetic turbines

Parameter	Conventional Hydro	Hydrokinetic
Flow path	Turbines Spill and sluice gates Spillway Fish bypasses	Turbines Free-flowing area around turbines
Infrastructure	Dam (spillway and gates) Intake structure with trash rack Penstocks and scroll cases Stay vanes and wicket gates Draft tube Fish passage facilities	Piers and/or anchors
Power (mid-size unit)	10 MW	100 kW
Head maintained for power production	10 - 1,000 ft	None
Number of blades	Kaplan: 4 - 6 Francis: 14 - 18	Horizontal axis: 2 - 16 Cross-flow: 3 or 4
Pressure change	Head dependent; > 1 atmosphere (about 100 kPa) or more	Small pressure change from upstream to downstream
Approach velocity	> 6 m/s	1 to 4 m/s
Rotational speed	60 to 600 rpm	Horizontal-axis propeller: < 100 rpm Cross-flow: 50 to 150 rpm
Number of exposures to runner	1	Multiple, depending on number of turbines in project

As presented in this report, extensive research has been conducted on injury mechanisms associated with fish passage through conventional hydro turbines. Bio-criteria developed from these studies for determining the ability of fish to safely pass through a turbine are relevant to hydrokinetic turbines and indicate that injury and mortality rates will be lower for fish passing through hydrokinetic turbines. However, more information is needed to define what fish experience when passing through hydrokinetic turbines in order to fully demonstrate that injury and mortality will not occur or will be negligible for fish passing through a turbine's blade sweeps. For any given hydrokinetic turbine design, information on pressure changes, cavitation, shear strain rates, and strike probability and mortality rates can be developed and compared to existing bio-criteria in order to determine fish-friendliness and ways that turbine design and operation can be modified, if needed, to reduce the potential for injury to entrained fish. For some applications and technologies, it may be important to support these conclusions using CFD modeling to identify areas where bio-criteria for acceptable pressure conditions (including the absence of cavitation) and shear levels may be exceeded, and by conducting flume and/or field studies to validate strike probability and mortality predictions. A summary of recommended bio-criteria for that should be met for safe fish passage through hydrokinetic turbines is provided in Table 3-2.

Table 3-2
Recommended bio-criteria for hydrokinetic turbines

Injury Mechanism	Suggested criteria
Pressure	Minimum: 50 kPa (7.4 psia)
Shear (stain rate)	Maximum 500/sec
Mechanical	Minimize gaps between turbine components
Blade strike	Minimize number of blades Design for strike velocities of less than 4.8 m/s Design blades with blunt leading edges if strike velocities exceed 4.8 m/s

Another factor that will influence potential effects of hydrokinetic turbines on fish that has not been adequately addressed is the proportion of fish that move downstream past turbines installed in riverine or tidal locations that actually encounter a turbine and are entrained through the blade sweep. Evidence from studies conducted at the RITE project on the East River in New York indicate that fish may avoid turbine impact zones (i.e., abundance was greater in non-impact zones; Verdant Power 2010). The most simplistic approach to addressing this issue would be to assume fish are uniformly distributed across a river or tidal reach and, therefore, the number (or percent) of fish exposed to a turbine is proportional to the cross sectional area of a turbine versus the entire cross section of the channel. For example, if the blade sweep of one or more turbines covers 25% of the cross sectional area of channel then it would be assumed that 25% of fish moving downstream would approach and potentially pass through the blade sweep. However, fish distributions will vary with species and life stages, with some being concentrated along shorelines and others preferring mid-channel habitats. Depth preferences (i.e., benthic or pelagic) will also affect fish distributions vertically within a channel. Consequently, some species and life stages may never encounter hydrokinetic turbines depending on their habitat preferences and where turbines are located (Cada and Bevelhimer 2011, Schweizer et al. 2011). A similar approach would be to assume that the number (or percent) of fish entrained is proportional to the volume of water passing through a turbine's blade sweep compared to the total channel discharge (i.e., if 25% of the channel discharge is passing through a turbine's blades, then 25% of fish also encounter the blade sweep). The flow volume method has often been used to provide gross estimates of fish entrainment at water intakes (including at hydroelectric projects). Alternatively, encounter rates could be higher than might be implied by the fractional cross section or flow intercepted by the turbines if fish distribution were biased toward these areas.

Even if fish encounter a hydrokinetic turbine, entrainment through the blade sweep may not occur if fish exhibit avoidance behavior and swim away from and around a turbine (EPRI 2011). Fish that are entrained may also be capable of avoiding blade strike by taking evasive actions as a blade approaches. The burst swimming capabilities of many species and life stages could easily allow fish to avoid being struck by an oncoming blade. The ability of fish to detect hydrokinetic turbines and react quickly enough to avoid entrainment or blade strike will depend on many factors, including, but not limited to, turbine noise (both acoustic and hydrodynamic), ambient light conditions, turbidity, physiological state/health of the fish, and species-specific sensory perception capabilities. Also, the probability of entrainment and blade strike may be affected by schooling behavior because lead fish will typically influence the path of a school and reactions to hydraulic disturbances, underwater structures and objects, and the presence of predators or prey. Depending on how lead fish react to hydrokinetic turbines, schooling may result in either higher or lower rates of entrainment and blade strike.

Similar to conventional turbines, the probability of strike for fish passing through hydrokinetic turbines is primarily dependent on approach velocity, rotational speed, and fish length. For fish that are struck, the probability of mortality is dependent on blade and flow velocities (and the consequent relative velocity of fish to blade), leading edge blade thickness, orientation of fish (i.e., angle to blade), sensitivity of the fish to strike forces, and fish length. Combining strike probability with strike mortality provides a measure of turbine passage survival, assuming no mortality occurs due to damaging pressure or shear conditions. The estimation of strike probability and mortality does not account for fish that actively avoid passage through an operating turbine or that evade an oncoming blade. Also, unlike for conventional hydro turbines where inflow velocities are high (greater than 15 ft/s) and it can be reasonably assumed fish are traveling at the speed of the water, assumptions for estimating strike probability must be made regarding the speed of fish approaching hydrokinetic turbines that may not be reliable because approach velocities are much lower (less than 10 ft/s). At the range of velocities over which many hydrokinetic turbines operate, most fish will have the ability to move through the blade sweep slower or faster than the approaching flow. If fish pass through a turbine's blade sweep slower than the approach velocity, strike probabilities will be higher than if they were moving at the speed of the ambient current; for fish moving faster than the flow, strike probabilities will be lower.

Our review of the literature on fish passage through conventional hydro turbines and its relevance to hydrokinetic turbines focused primarily on the effects of fish passing through a single turbine and does not fully address effects of hydrokinetic installations with multiple turbines. The number of fish exposed to turbine passage and the overall turbine passage mortality rates for an array of hydrokinetic turbines likely will be higher for multiple units compared to the operation of a single unit, but it is not yet known whether these increases would be proportional to the number of turbines. Future analyses will need to be conducted, perhaps on a site-specific basis, to account for the effects of multiple turbines and to consider hydraulic, environmental, and biological factors that will influence the potential for adverse effects on fish and to confirm the findings of this study. A detailed assessment of potential impacts will also need to determine the proportion of fish that will encounter a turbine or an array of turbines and, of those that do, what is the probability of avoidance. When encounter and avoidance probability rates are combined with expected survival rates for passage through the blade sweep of one or more turbines, an overall survival rate can be developed for fish populations in the vicinity of a hydrokinetic project. Finally, our review and assessment of conventional hydro data pertains to direct mortality from injury mechanisms associated with turbine passage. Indirect mortality (e.g., predation, disease) may result from sub-lethal injuries, increased stress, reduced fitness, and/or disorientation. Similar to direct mortality, the occurrence of injuries and physiological conditions that may lead to indirect mortality should be less than is experienced by fish passing through the harsher environment of conventional turbines. A review of indirect mortality studies conducted for conventional hydro projects may also be warranted to address this issue at hydrokinetic installations.

Turbine passage survival rates for conventional hydropower projects have generally been shown to range from about 70 to 97% (Franke et al. 1997; EPRI 1997), with the lower survival rates being representative of larger fish and/or Francis turbines (i.e., large number of blades and high rotational speeds) and the higher survival rates being representative of smaller fish and/or Kaplan turbines (fewer blades and lower rotational speeds). Based on the assessment of injury mechanisms provided in this report and their relevance and applicability to hydrokinetic turbines, survival of fish passing through hydrokinetic turbines will be greater than has been reported for conventional hydro. In addition, recent lab and field studies of fish passage through hydrokinetic turbines have reported direct survival rates of adult fish greater than 98% for three hydrokinetic turbine designs (one cross-flow and two horizontal-axis ducted turbines) (NAI 2009; EPRI 2011). These lab and field data and the review of conventional hydro data indicate hydrokinetic turbines are likely to achieve turbine passage survival rates exceeding 98% for a wide range of species and life stages. When combined with encounter and avoidance probabilities, as discussed previously, overall passage survival for fish moving past a hydrokinetic turbine may exceed 99% for many designs. Field monitoring studies focused on fish behavior and survival at selected projects will be needed to verify the information presented in this report and to expand the existing dataset developed from previous lab and field studies.

Section 4: Literature Cited

Abernethy, C. S., B. G. Amidan, G. F. Čada. 2001. Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish. U.S. Department of Energy, PNNL-13470.

Abernethy, C. S., B. G. Amidan, G. F. Čada. 2002. Fish Passage Through a Simulated Modified Kaplan Turbine Pressure Regime: A Supplement to "Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish." U.S. Department of Energy, PNNL-13470-A.

Abernethy, C. S., B. G. Amidan, G. F. Čada. 2003. Fish Passage Through a Simulated Horizontal Bulb Turbine Pressure Regime: A Supplement to "Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish." U.S. Department of Energy, PNNL-13470-B.

Amaral, S. G. Hecker, M. Metzger, and T. Cook. 2003. 2002 Biological Evaluation of the Alden/Concepts NREC Turbine. Proceedings of Waterpower XIII, HCI Publications, Inc., St. Louis, Missouri.

Amaral, S. V., G. E. Hecker, P. Stacy, and D. A. Dixon. 2008. Effects of leading edge turbine blade thickness on fish strike survival and injury. Proceedings of Hydrovision 2008. HCI Publications, St. Louis, Missouri.

ARL (Alden Research Laboratory, Inc.). 1996. Development of a More Fish Tolerant Turbine Runner. Technical Memorandum #2: Development of Biological Design Criteria.

Becker, J. M., C. S. Abernethy, and D. D. Dauble. 2003. Identifying the Effects on Fish of Changes in Water Pressure During Turbine Passage. Hydro Review, September 2003, HCI Publications, Inc., St. Louis, Missouri.

Brown, R.S., T.J. Carlson, A.E. Welch, J.R. Stephenson, C.S. Abernethy, C.A. McKinstry, and M.H. Theriault. 2007. Assessment of Barotrauma Resulting from Rapid Decompression of Depth-Acclimated Juvenile Chinook Salmon Bearing Radio Telemetry Transmitters. Prepared for the U.S. Army Corps of Engineers by Battelle – Pacific Northwest Division, Richland, Washington. PNNL-16790. September 2007.

Čada, G. F. 1990. A Review of Studies Relating to the Effects of Propeller-Type Turbine Passage on Fish Early Life Stages. North American Journal of Fisheries Management 10:418-426.

Čada, G. F., C. C. Coutant, and R. R. Whitney. 1997. Development of Biological Criteria for the Design of Advanced Hydropower Turbines. DOE/ID-10578, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Čada, G. F. 2001. The Development of Advanced Hydroelectric Turbines to Improve Fish Passage Survival. Fisheries 26:14-23.

Čada, G., J. Loar, L. Garrison, R. Fisher, D. Neitzel. 2006. Efforts to Reduce Mortality to Hydroelectric Turbine-Passed Fish: Locating and Quantifying Damaging Shear Stresses. Environmental Management 37(6):898-906.

Čada, G., J. Ahlgrimm, M. Bahleda, T. Bigford, S. Stavrakas, D. Hall, R. Moursund, and M. Sale. 2007. Potential impacts of hydrokinetic and wave energy conversion technologies on aquatic environments. Fisheries 32(4): 174-181.

Cada, G. F. and M. S. Bevelhimer. 2011. *Attraction to and Avoidance of Instream Hydrokinetic Turbines by Freshwater Aquatic Organisms*. Oak Ridge National Laboratory. ORNL/TM-2011/131. May 2011.

Carlson, T. J. and C. S. Abernethy. 2005. Pilot Study of the Effects of Simulated Turbine Passage Pressure on Juvenile Chinook Salmon Acclimated with Access to Air at Absolute Pressures Greater than Atmospheric. Prepared for the U.S. Army Corps of Engineers, Portland District by Battelle – Pacific Northwest Division, Portland, Oregon. PNNL-15011. May 2005.

Cook, T. C., G. E. Hecker, H. B. Faulkner, and W. Jansen. 1997. Development of a More Fish Tolerant Turbine Runner, Advanced Hydropower Turbine System. Prepared for the U.S. Department of Energy. Prepared for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon. Pacific Northwest National Laboratory Report No. PNNL-15011

Cook, T. C., G. E. Hecker, S. V. Amaral, P. S. Stacy, F. Lin, and E. P. Taft. 2003. Final Report – Pilot-Scale Tests Alden/Concepts NREC Turbine. Prepared for U.S. Department of Energy, Advanced Hydropower Turbine Systems Program.

Coutant, C.C., and G.F. Čada. 2005. What's the Future of Instream Hydro? Hydro Review 24(6): 42-49. HCI Publications, St. Louis, Missouri.

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 11:26-35.

Dauble, D. D., Z. D. Deng, M. C. Richmond, R. A. Moursund, T. J. Carlson, C. L. Rakowski, and J. P. Duncan. 2007. Biological Assessment of the Advanced

Turbine Design at Wanapum Dam, 2005. Prepared for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies. Pacific Northwest National Laboratory Report No. PNNL-16682.

Deng, Z., T. J. Carlson, G. R. Ploskey, and M. C. Richmond. 2005. Evaluation of Blade-Strike Models for Estimating the Biological Performance of Large Kaplan Hydro Turbines. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies, PNNL-15370.

DOE (U.S. Department of Energy). 2009. Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Wind and Hydropower Technologies Program, DOE/GO-102009-2955.

EPRI (Electric Power Research Institute). 2006. Instream Tidal Power in North America, Environmental and Permitting Issues. EPRI-TP-007-NA. Prepared by Devine Tarbell & Associates, Inc., Portland, Maine, for Electric Power Research Institute, Palo Alto, California.

EPRI (Electric Power Research Institute). 2008. Evaluation of the effects of turbine blade leading edge design on fish survival. Prepared by Alden Research Laboratory, Inc., EPRI Report No. 1014937.

EPRI (Electric Power Research Institute). 2011. Evaluation of Fish Injury and Mortality Associated with Hydrokinetic Turbines. Prepared by Alden Research Laboratory, Inc. EPRI Report No. TR-1024569.

EPRI (Electric Power Research Institute). In press. Additional Tests Examining Survival of Fish Struck by Turbine Blades. Prepared by Alden Research Laboratory, Inc.

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

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.

Franke, G. F., D. R. Webb, R. K. Fisher, D. Mathur, P. N. Hopping, P. A. March, M. R. Headrick, I. T. Laczo, Y. Ventikos, and F. Sotiropoulis. 1997. Development of Environmentally Advanced Hydropower Turbine System Concepts. Prepared for the U.S. Department of Energy, Voith Hydro, Inc. Report No. 2677-0141.

Guensch, G. R., R. P. Mueller, C. A. McKinstry, D. D. Dauble. 2002. Evaluation of Fish-Injury Mechanisms During Exposure to a High-Velocity Jet. U.S. Department of Energy, DOE/ID-11072, PNNL-14173.

Harvey, H. H. 1963. Pressure in the early life history of sockeye salmon. Doctoral dissertation, University of British Columbia, Vancouver.

Hecker, G., S. Amaral, P. Stacy, T. Cook, M. Metzger, and B. McMahon. 2002. Engineering and Biological Evaluation of the Alden/Concepts NREC Turbine. Proceedings of Hydrovision 2002, HCI Publications, Inc., St. Louis, Missouri.

Hecker, G. E., and G. S. Allen. 2005. An Approach to Predicting Fish Survival for Advanced Technology Turbines. Hydro Review, November 2005, HCI Publications, Inc., St. Louis, Missouri.

Hecker, G. E., S. V. Amaral, P. Stacy, and D. A. Dixon. 2007. Developing turbine blades to minimize fish mortality. Proceedings of Waterpower XV. HCI Publications, St. Louis, Missouri.

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.

Killgore, K. J., S. T. Maynord, M. D. Chan, and R. P. Morgan. 2001. Evaluation of Propeller-Induced Mortality on Early Life Stages of Selected Fish Species. North American Journal of Fisheries Sciences 21:947-955.

Lin, F., G. E. Hecker, and T. C. Cook. 2004. Understanding Turbine Passage Survival Using CFD. Proceedings of Hydrovision 2004, HCI Publications, Inc., St. Louis, Missouri.

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. *In*: Proceedings of the Symposium on Cavitation and Hydraulic Machinery, Sendai, Japan.

McEwen, D., and G. Scobie. 1992. Estimation of the Hydraulic Conditions Relating to Fish Passage through Turbines. NPC001. National Engineering Laboratory, East Kilbride, Glasgow, Scotland.

Monten, E. 1985. Fish and Turbines: Fish Injuries during Passage through Power Station Turbines. Vattenfall, Stockholm, Sweden.

Montgomery Watson. 1995. Allowable Gas Supersaturation for Fish Passing Hydroelectric Dams. Project No. 93-8. Final report prepared for Bonneville Power Administration, U.S. Department of Energy, Portland, Oregon.

Morgan, R.P., 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.

Neitzel, D.A., M.C. Richmond, D.D. Dauble, R.P. Mueller, R.A. Moursund, C.S. Abernethy, G.R. Guensch, and G.F. Čada. 2000. Laboratory Studies on the Effects of Shear on Fish: Final Report. U.S. Department of Energy, Idaho Operations Office, DOE/ID-10822, Idaho Falls, Idaho.

Neitzel, D. A., D. D. Dauble, G. F. Čada, M. C. Richmond, G. R. Guensch, R. P. Mueller, C. S. Abernethy, and B. Amidan. 2004. Survival Estimates for Juvenile Fish Subjected to a Laboratory-generated Shear Environment. Transactions of the American Fisheries Society 133:447-454.

NAI et al. (Normandeau Associates, Inc., J. R. Skalski, and Mid Columbia Consulting, Inc.) 2000. Direct Survival and Condition of Juvenile Chinook Salmon Passed Through an Existing and New Minimum Gap Runner Turbines at Bonneville Powerhouse, Columbia River. Prepared for Portland District, U.S. Army corps of Engineers, Portland, Oregon.

NAI (Normandeau Associates, Inc.), J. R. Skalski, and Mid Columbia Consulting, Inc. 2006. Fish Survival Investigation Relative to Turbine Rehabilitation at Wanapum Dam, Columbia River, Washington. Prepared for Public Utility District No. 2 of Grant County, Ephrata, WA.

NAI (Normandeau Associates, Inc.). 2009. An Estimation of Survival and Injury of Fish Passed through the Hydro Green Energy Hydrokinetic System, and a Characterization of Fish Entrainment Potential at the Mississippi Lock and Dam No. 2 Hydroelectric Project (P-4306), Hastings, Minnesota. Prepared for Hydro Green Energy LLC, Houston, Texas.

Odeh, M, J. F. Noreika, A. Haro, A. Maynard, T. Castro-Santos, and G. F. Čada. 2002. Evaluation of the Effects of Turbulence on the Behavior of Migratory Fish. Prepared for the Bonneville Power Administration, Report No. DOE/BP-00000022-1.

Ploskey, G. R., and T. J. Carlson. 2004. Comparison of Blade-Strike Modeling Results with Empirical Data. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies, PNNL-14603.

Rowley, W. E. 1955. Hydrostatic Pressure Tests on Rainbow Trout. California Fish and Game 41:243-284.

Schweizer, P. E., G. F. Cada and M. S. Bevelhimer. 2011. *Estimation of the Risks of Collision or Strike to Freshwater Aquatic Organisms Resulting from Operation of Instream Hydrokinetic Turbines*. Oak Ridge National Laboratory. ORNL/TM-2011/133.

Solomon, D. I. 1988. Fish Passage through Tidal Energy Barrages. Energy Technical Support Unit, Harwell, England, Contractors Report number ETSU Till 4056.

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.

Tullis, J. P. 1989. Hydraulics of Pipelines; Pumps, Valves, Cavitation, and Transients. John Wiley & Sons, Inc., Hoboken, New Jersey.

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, Southampton, England.

Turnpenny, A. W. H., G. Struthers, and P. Hanson. 2000. A UK Guide to Intake Fish-Screening Regulations, Policy and Best Practice with Particular Reference to Hydroelectric Power Schemes. Energy Technology Support Unit, Department of Trade and Industry, Report No. ETSU H/O6/00052/REP.

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 of the Turbine Fish Passage Survival Workshop. U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Verdant Power, LLC. 2010. Roosevelt Island Tidal Energy Project, FERC No. P-12611, Final Kinetic Hydropower Pilot License Application. Submitted by Verdant Power, LLC to the Federal Energy Regulatory Commission.

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

Von Raben, K. 1957. Regarding the problem of mutilations of fishes by hydraulic turbines. Originally published in Die Wasserwirtschaft (100):4:97. Fisheries Research Board of Canada Translation Series No. 448 (1964).

The Electric Power Research Institute Inc., (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent more than 90 percent of the electricity generated and delivered in the United States, and international participation extends to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

Program:

Waterpower

© 2011 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

1024638

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com