

CHAPTER 25

FISH-FRIENDLY TURBINE DEVELOPMENT

Fish-Friendly Advanced Turbine Technologies

In recent years, considerable advancements have been made in the development and application of fish-friendly turbines. These advancements have included new and unique runner designs, as well as modifications to conventional turbines. Most of the advancements in fish-friendliness have been based on biocriteria developed from lab and field studies that have investigated the various mechanisms believed to injure fish during turbine passage (e.g., blade strike, grinding in gaps between moving parts, shear and turbulence, and pressure changes). Much of the research and development for fish-friendly turbines was conducted under the U.S. Department of Energy's original Advanced Hydro Turbine Systems (AHTS) Program, which supported biocriteria research and the development of two turbine designs from 1994 to 2006. The DOE initiated a new program for research and development of water power technologies in 2008, which will include studies and projects associated with conventional hydro turbines and wave power and hydrokinetic technologies.

U.S. Department of Energy Hydropower Program

The DOE's hydro program was involved in hydro power research and development activities for nearly 30 years before it was ended in 2006. The program's primary focus during the last 12 years of operation was associated with the development of advanced turbine designs that had improved environmental performance and greater generating efficiency (i.e., AHTS Program). The primary environmental issues that were addressed by the AHTS Program included turbine passage survival and dissolved oxygen. Conceptual designs for two fish-friendly turbines were developed as part of this program: (1) the minimum gap runner (MGR), which is a modified Kaplan turbine designed by a team lead by Voith Hydro (now Voith-Siemens Hydropower Generation); and (2) the Alden/Concepts NREC turbine (ACT), which was a completely new runner concept based on the design of centrifugal pumps used for safely transferring fish between and from hatchery ponds. The Voith-Siemens MGR turbine has been installed and field tested for biological performance at two hydropower projects on the Columbia River (Bonneville and Wanapum dams). Biological and preliminary engineering performance of the ACT was evaluated during pilot-scale laboratory tests conducted at Alden. These field and lab studies were also sponsored primarily or in part by the DOE. In addition to the fish-friendly turbines, a retrofit aeration system (RAS) for hydro turbines was developed by American Hydro Corporation and was field tested at the Osage Hydroelectric Project on the Osage River in Missouri as part the AHTS program (Ware et al. 2004).

In parallel with the development of advanced turbine technologies designed for improved environmental performance and greater generating efficiency, the AHTS Program supported

several research efforts to better understand the mechanisms that injure fish during turbine passage. These have included studies examining the effects of pressure changes on fish (Abernethy et al. 2001, 2002, 2003; Becker et al. 2003), injuries caused by shear (Guensch et al 2002; Neitzel et al. 2000, 2003; Cada et al. 2006a), sub-lethal stress effects (Ryon et al. 2004; Cada et al. 2003, 2006b), and physical forces experienced by an artificial “sensor” fish passing through turbines (Carlson and Duncan 2003; Weiland et al. 2003). Other studies have used laboratory techniques and physical and theoretical models to explore fish injury mechanisms (Deng et al. 2004), fish trajectories through turbines (Weiland et al. 2005), and to compare empirical data with predictive methods (Ploskey and Carlson 2004; Deng et al. 2005). These studies have considerably increased our understanding and knowledge of how fish are injured and/or killed when passing through turbines and have contributed to improvements in turbine design and operation that are expected to result in lower mortality rates.

Although the new DOE Water Power Program will focus primarily on waver energy and hydrokinetic technologies, funding is being provided for a two-year program to prepare the ACT for commercialization. This effort is being led by EPRI and will include preliminary design and model testing by Voith-Siemens. At the completion of this program, Voith-Siemens is expected to design and fabricate an ACT for installation at Brookfield Power’s School Street Hydroelectric Project on the Mohawk River, near Albany, NY, where it will be field tested to determine turbine passage survival rates for several species and size groups of fish.

Minimum-Gap Runner (MGR) Turbines

The MGR Kaplan turbine was first developed through DOE’s AHTS Program by a team of companies led by Voith-Siemens Hydro (Franke et al. 1997). Since the initial MGR design was completed and field tested, other turbine manufacturers have developed MGR turbines. However, with the exception of the Voith-Siemens turbine, prototypes of alternative MGR designs have not been installed and field tested at any projects. The premise for the MGR design is that the elimination of gaps within a turbine system will reduce fish injury and improve turbine efficiency (Franke et al. 1997; Odeh 1999). In particular, grinding of fish can be prevented if gaps at the wicket gates and between blades and the hub and discharge ring are eliminated (Figures 25-1). The Voith-Siemens team also addressed issues with stay vanes, wicket gates, and other turbine components that could be modified to reduce fish injury and improve turbine efficiency.

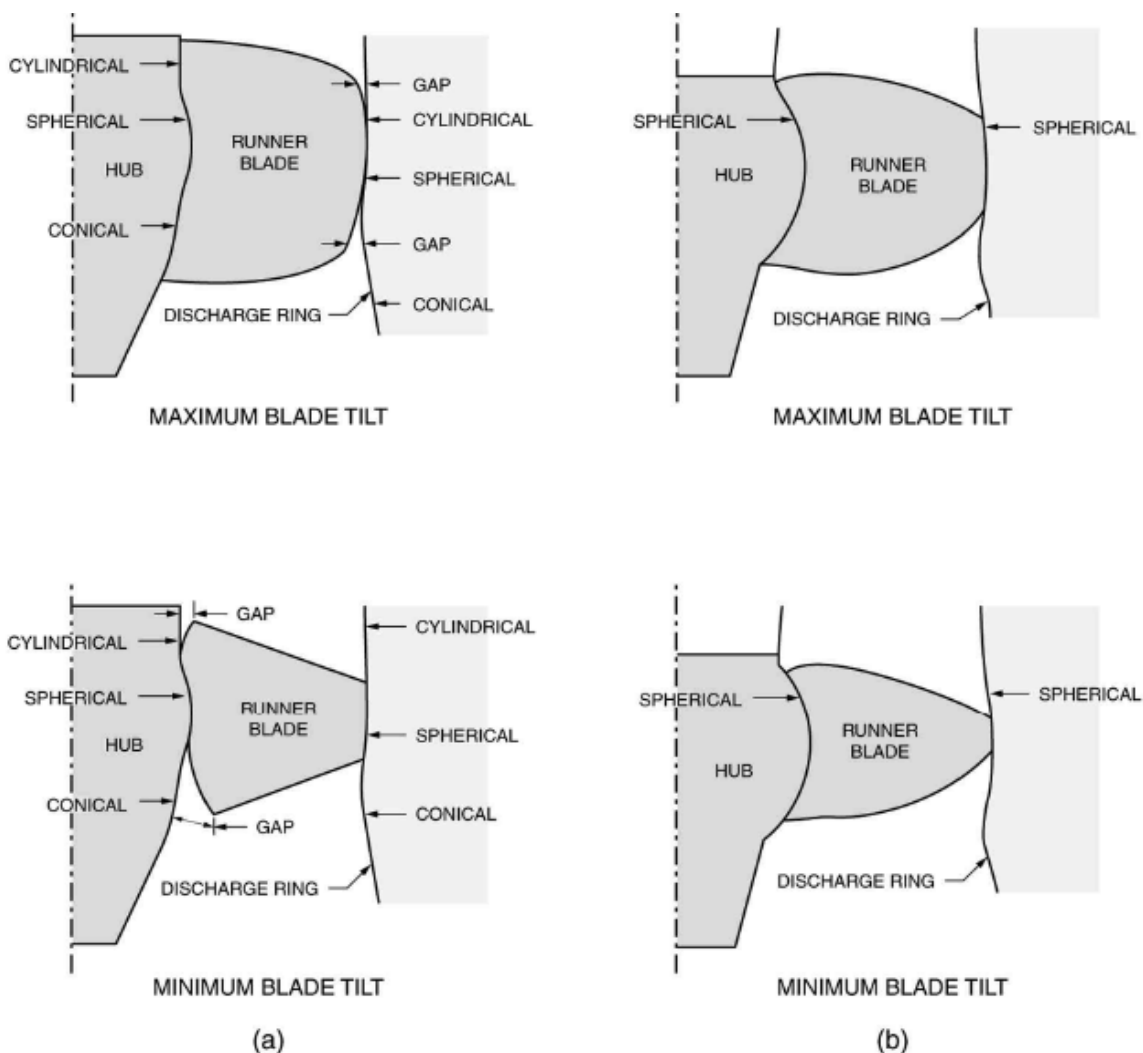


Figure 25-1
Comparison of a Conventional Kaplan Runner (a) and a Minimum Gap Runner (MGR) (b)
(as Presented in Franke et al. 1997, Odeh 1999, and Cada 2001)

The Voith-Siemens MGR Kaplan turbine has been installed and tested for biological performance at two hydro projects on the Columbia River. The first installation was at the Bonneville Dam and the second at Wanapum Dam. The results of field tests conducted at Bonneville demonstrated that fish survival for the MGR unit was equal to or greater than for an adjacent conventional Kaplan turbine (Normandeau et al. 2000; Cada et al. 2001). Field tests at Wanapum indicated that overall turbine passage survival was high (about 97%) and approximately the same for the MGR and an existing conventional Kaplan (GCPUD 2005). However, there were some differences in fish survival between the two runner designs related to release depth (i.e., passage near the hub or discharge ring) and turbine discharge. Although the MGR did not result in an increase in overall turbine survival at Wanapum compared to the

existing conventional units, it was more efficient and provided for increased power production. Consequently, all of the original turbines at Wanapum will be replaced with MGR units.

Alstom Power has also developed a fish-friendly Kaplan turbine design based on the MGR concept (Figure 25-2) (Vinh et al. 2002; Ahmann et al. 2005; Loiseau et al. 2006). Although the Alstom MGR turbine has been modeled and tested for potential injury to fish based on the trajectory of neutrally-buoyant beads through the model (Ahmann et al. 2005; Loiseau et al. 2006), it has not been installed at any projects. Alstom, has also examined modifications to stay vanes and wicket gates to reduce the potential for shear and strike-related injuries (Loiseau et al. 2006). In addition to the MGR turbine, Alstom has developed a design for a vortex turbine (Figure 25-2) that could be used at lower head projects and is expected to have low fish mortality rates due to the elimination of stay vanes and wicket gates and the reduction of swirl and turbulence downstream of the runner through the use of a straight draft tube.

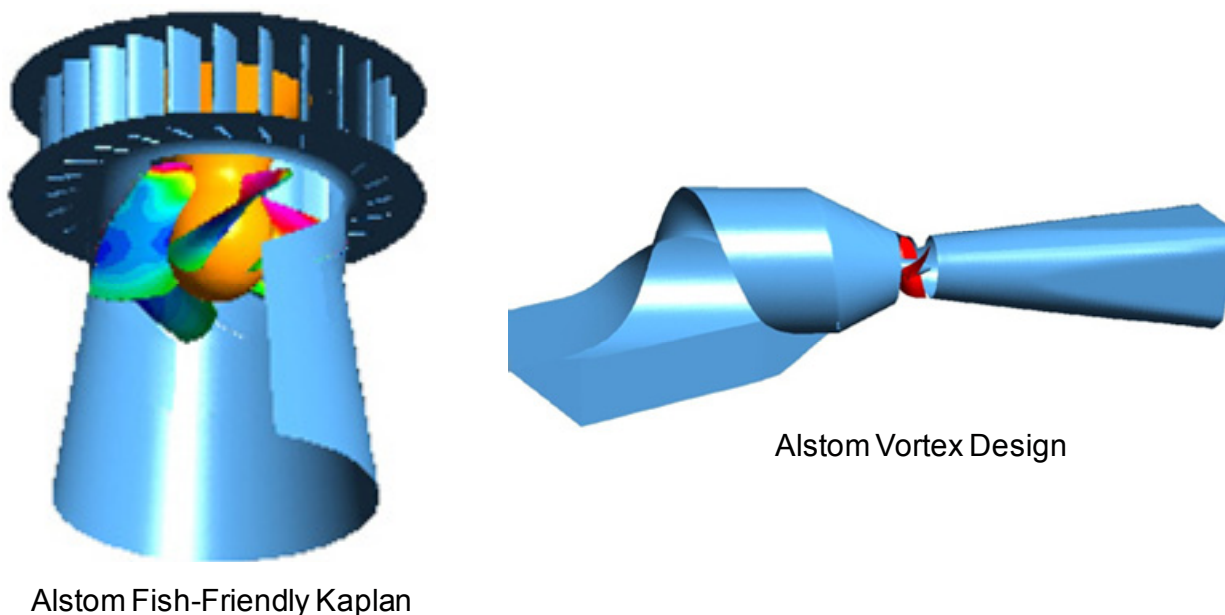


Figure 25-2
Alstom Fish-Friendly Turbine Designs: MGR Kaplan Runner and a Vortex Turbine (No Stay Vanes or Wicket Gates) (Ahmann et al. 2005; <http://www.hydro.power.alstom.com>)

Andritz VA Tech Hydro has been contracted by the Pend Oreille PUD to provide four fish-friendly turbines for the Box Canyon Hydroelectric project on the Pend Oreille River in Washington State. Few details are currently available on this turbine upgrade project, but the new units are expected to improve turbine passage survival and reduce total dissolved gases while increasing power production. GE Hydro has also been working on the design of a fish-friendly turbine using criteria that minimizes the number of blades, eliminates gaps, and reduces pressure and velocity gradients. The GE Hydro design appears to be very similar to the ACT runner (i.e., three long blades wrapping around a conical hub), but is an axial-flow turbine, not radial.

Alden/Concepts NREC Turbine (ACT)

The ACT is a completely new hydro turbine design developed and pilot-scale tested through the former DOE AHTS Program (Figure 25-3). The ACT runner shape is based on the impeller design of fish-friendly centrifugal pumps and minimizes the number of blades and clearances between the runner and runner housing (Figure 25-4) (Cook et al. 1997). Pressure versus time and velocity versus distance gradients are also reduced within the runner. Two and three-dimensional CFD models were used to develop the runner design and to evaluate hydraulic performance (Cook et al. 1997, 2003; Lin et al. 2004; Hecker and Cook 2005).

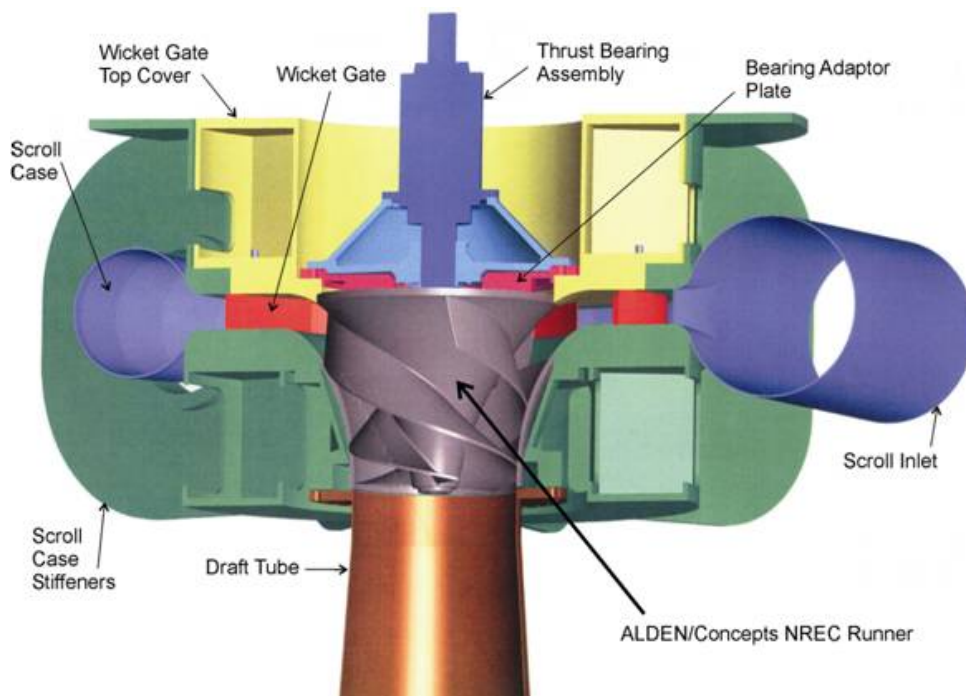


Figure 25-3
Schematic of ACT as Designed for Pilot-Scale Laboratory Evaluation

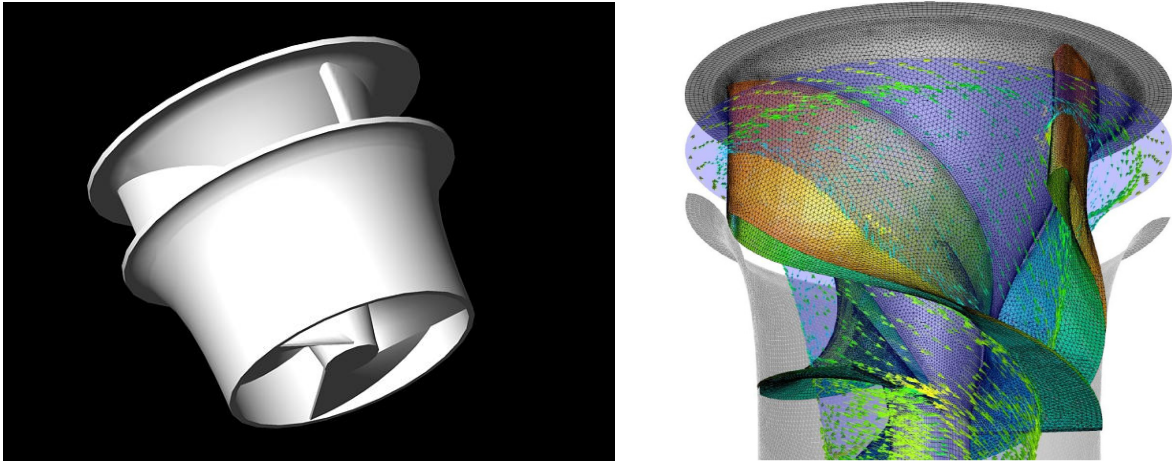


Figure 25-4
ACT Runner with Shroud Attached (Left) and Image from Numerical Model of the Runner Redesigned for Improved Generating Performance (Right)

The pilot-scale biological evaluation of the ACT was conducted at Alden using a closed-loop system driven by a 2,000 hp pump and with the turbine speed controlled by a dynamometer (Cook et al. 2003; Hecker et al. 2002). Preliminary engineering data were also collected on the operation of the turbine during this study. Biological test parameters included the following:

- Six species (mean lengths in parentheses): rainbow trout (38, 90, and 175 mm), coho salmon (102 mm), smallmouth bass (70 and 155 mm), alewife (75 mm), white sturgeon (103), and American eel (250 and 430 mm)
- Two operational heads: 40 and 80 ft
- With and without wicket gates
- Best efficiency point (BEP) and five off-BEP gate settings

Rainbow trout were tested with all of the test conditions, whereas the other species were evaluated at a head of 40 ft, with the wicket gates installed, and at the BEP gate setting.

The results of the pilot-scale evaluation demonstrated that turbine passage survival was primarily dependent on fish length and operational head (Figure 25-5) (Cook et al. 2003; Amaral et al. 2003). There was no apparent differences in survival rates among typical teleost species (trout, salmon, bass, alewife). However, white sturgeon (cartilaginous skeleton and no true scales) and American eel (long, flexible, and sinuous, and lacking scales) had significantly greater survival rates than the other species (97% immediate survival for sturgeon and 100% for eels). Although approach velocities and blade speed of the pilot-scale runner were similar to a prototype ACT

design, the rotational speeds (rpm) were much higher and the blade spacings considerably narrower, resulting in greater mortality than would be expected with a full-scale unit. Therefore, the lab data were used to develop a predictive model (i.e., blade strike probability and probability of mortality from strike) for estimating turbine passage survival for a full-scale ACT at the two heads that were tested (40 and 80 ft). Predicted survival rates for the prototype ACT indicated that most fish less than 200 mm in length, which comprise more than 90% of fish entrained at hydro projects (Winchell et al. 2000), would have survival rates greater than about 95% for heads of 40 and 80 ft (Figure 25-6). Further analysis using blade strike probability models has shown that fish mortality rates for an ACT would be 1/5 of those predicted for an MGR unit designed for the same site (i.e., head and flow; Figure 25-7) (Hecker and Allen 2005). Recent and ongoing efforts to modify the ACT runner design have been sponsored by EPRI and are expected to improve operational performance and turbine passage survival rates for all species and size classes (EPRI 2007, 2009).

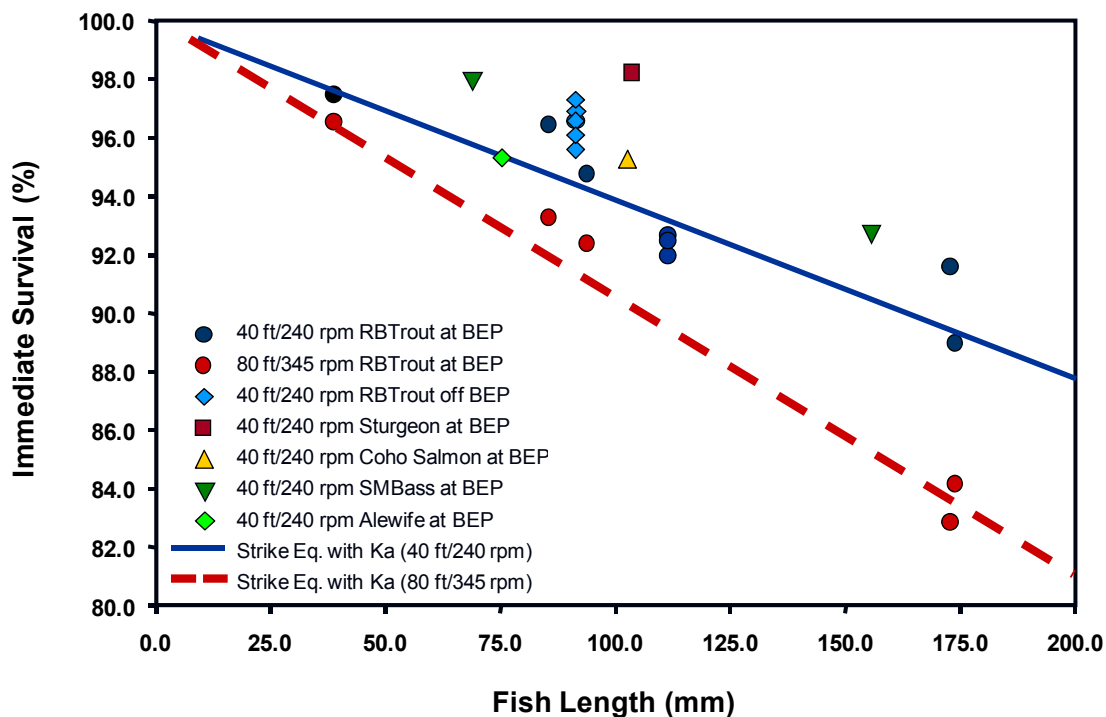


Figure 25-5
Relationship Between Fish Length and Immediate Survival for Five Fish Species Tested with the Pilot-Scale ACT (Tests with Rainbow Trout Included Two Heads and Off-BEP Operation; All other Species Were Evaluated at a Head of 40 ft and at The BEP)

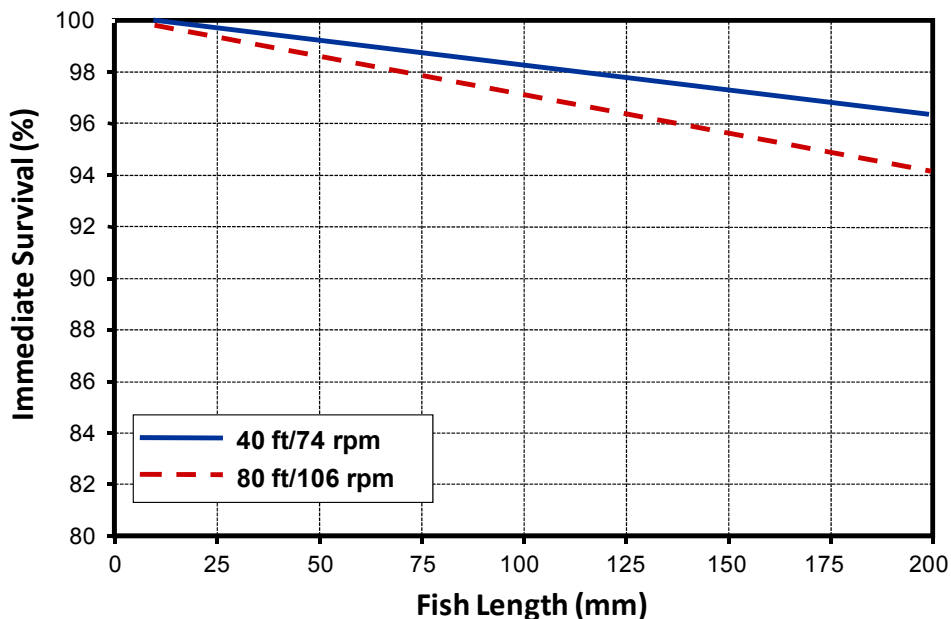


Figure 25-6
Immediate Survival Versus Fish Length Predicted for a Full-Scale Prototype ACT Operated at Two Heads

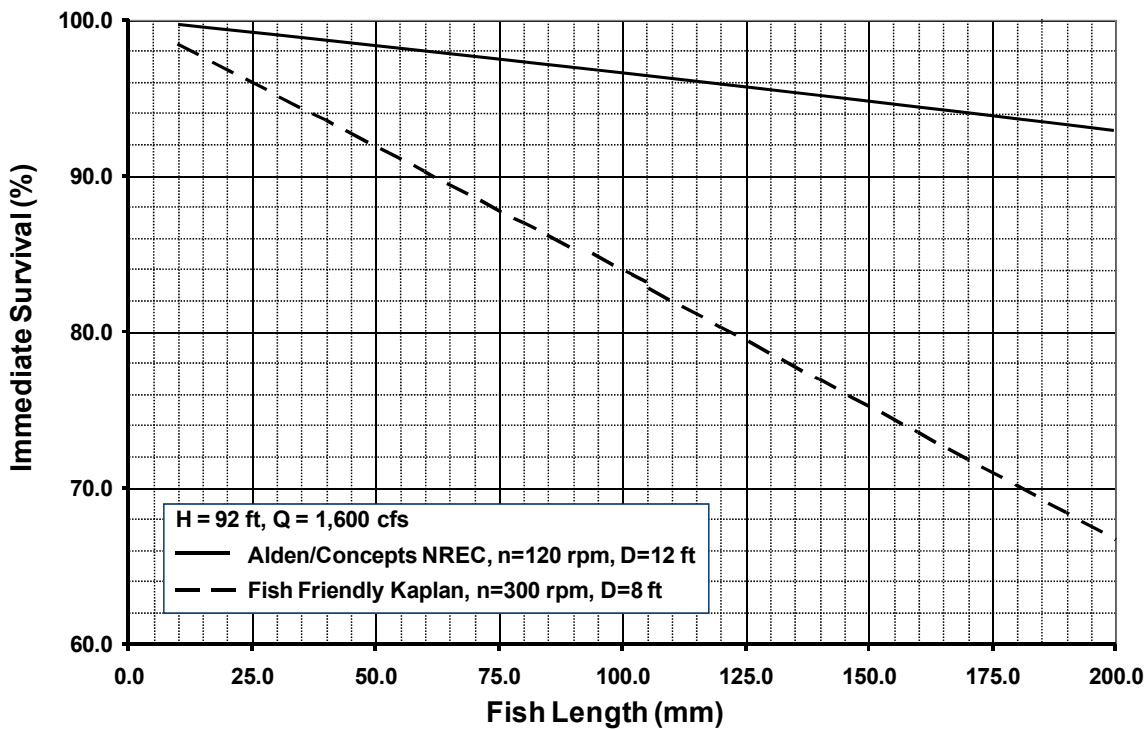


Figure 25-7
Immediate Survival Versus Fish Length Predicted for an ACT and a MGR Turbine Designed for the Same Site (i.e., head and flow)

In 2008, EPRI was awarded a two-year grant from the DOE to complete the preliminary engineering design and model testing of the ACT in preparation for commercialization. This work will be conducted by Voith-Siemens Hydro with support from Alden. Following completion of these efforts, an ACT is expected to be developed for installation at Brookfield Power's School Street Hydroelectric Project on the Mohawk River in New York. After the ACT is installed, a field study will be conducted to determine if turbine passage survival of juvenile blueback herring, one or more riverine species, and silver American eels will be equivalent to or greater than a conventional fish diversion system (i.e., angled bar rack and surface bypass).

Alternative Fish-Friendly and Low Head Turbine Designs

With increased interest in the development of renewable power resources, several very low-head turbine designs have been developed in the past 10 years for use at non-power dams or small dams with decommissioned or abandoned power facilities. Some of these designs have also been described as being fish-friendly turbines, where others have provided information or data indicating that turbine survival rates will be high due to design and operational parameters that will result in low injury rates.

Alstom Vortex Turbine

Alstom's Vortex Turbine (see Figure 25-5) is an axial flow, fish-friendly design which eliminates sources of fish injury and mortality in the inlet and draft tube flow passages. There are no stay vanes or wicket gates and a straight draft tube reduces hydraulic conditions which can injure or disorient fish (e.g., swirl and turbulence). Alstom's MGR runner design can be used with the Vortex Turbine to further improve fish survival by eliminating gaps between the runner blades and the hub and outer ring.

Vaneless Axial Flow Turbine

Natural Resources Canada and Rapid-Eau Technologies Inc. have been working on the development of a "vaneless" turbine that has features designed to minimize injury to fish (de Montmorency et al. 2006; de Montmorency 2008). Water enters a rectangular opening and passes down through an inlet tube with a section of flaring that leads to the runner (Figure 25-8). Because there are no stay vanes or wicket gates, the inlet tube is referred to as a vaneless casing. Computer modeling was performed to optimize energy efficiency and fish-friendliness (i.e., reduction in shear levels, pressure rate changes, and the potential for blade strike) (de Montmorency et al. 2006). The resulting design for the runner includes three blades spiraling around the hub (Figure 25-9) and shrouded with a runner skirt. This is very similar to the ACT runner, but with axial flow, not radial. Physical modeling was conducted with a scaled unit and indicated that efficiency was less than predicted by the computer modeling (de Montmorency 2008). Subsequent testing with an improved mechanical system resulted in an overall efficiency that was slightly less than the predicted 88%. Field tests still need to be conducted on this turbine design to determine operational and biological performance of a full-scale prototype.

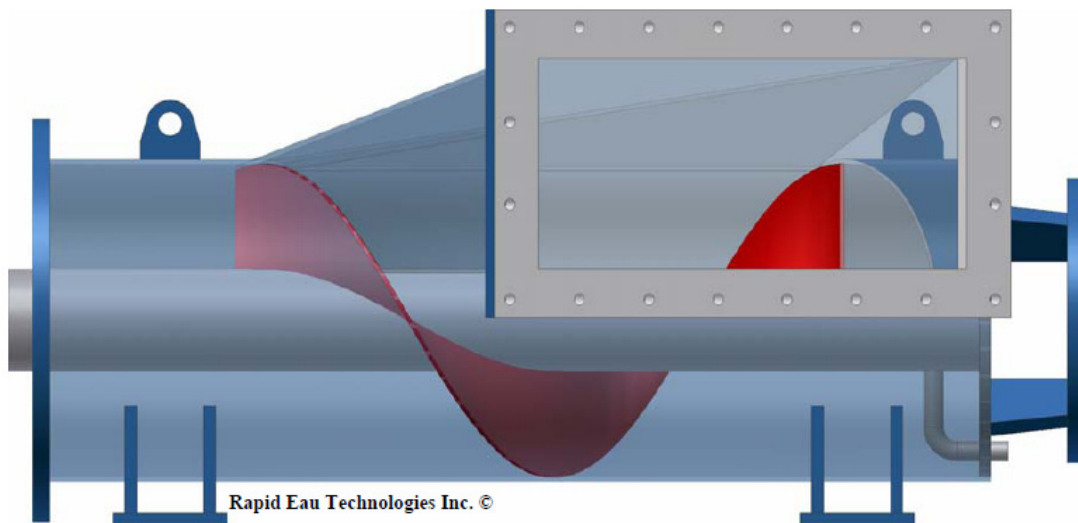


Figure 25-8
Vaneless Inlet Casing of Fish-Friendly Turbine Developed by Rapid-Eau, Inc. (de Montmorency Et Al. 2006)



Figure 25-9
Fish-Friendly Turbine Runner Developed by Rapid-Eau, Inc. (de Montmorency 2008)

Very Low Head Turbine (VLH)

A very low head turbine design (VLH) that incorporates a Kaplan runner with eight blades has been developed by MJ2 Technologies (Leclerc 2008) (Figure 25-10) and has been promoted as a fish-friendly technology. The VLH design is described as having an integrated generating set (IGS) that includes the runner, a fixed distributor with 18 wicket gates, flat bars that serve as trash racks, a permanent magnetic generator, and an automated trash rack cleaner. These design features prevent the need for sophisticated inlet and outlet civil structures, allowing it to be installed in sluiceway-type passages from which it can be easily removed with a crane (Leclerc 2008). The VLH has been designed for heads ranging from 1.4 to 3.2 m and flows of 10 to 30 m³/s with power output between 100 and 500 kW.

A prototype VLH turbine was installed in a 6 m wide intake channel at site in Millau, France. Generating performance of the prototype was consistent with the results of model tests conducted at Laval University in Canada. The prototype runner had a diameter of 4.5 m and full load output of 438 kW at a head of 2.5 m and flow of 22.5 m³/s. With the exception of 4.5 mm gaps between the blades and discharge ring, the VLH design is considered fish-friendly by the developer based on established criteria for minimum and maximum pressures and flow speed variations (i.e., shear). The peripheral runner speed (4.5 to 8.0 m/s) was also concluded by the developer to be within acceptable standards for minimizing fish injury.



Figure 25-10
Very Low Head (VLH) Turbine Runner (Left Photo) and Full Unit Installed at a
Demonstration Site in Millau, France (Right Photo) (Leclerc 2008)

Turbine passage mortality tests were conducted with the prototype VLH using European eels (700 to 1200 mm in length) and Atlantic salmon smolts (Leclerc 2007, 2008). Survival rates were 100%, 97%, and 84% for eels released directly into the turbine near the hub, at mid-blade, and near the blade tips, respectively. When the data are averaged, the overall survival rate for passage of eels through the VLH is 95%. Although this survival rates is considerably higher than has been estimated for adult eels passing through conventional turbines (e.g., Kaplan and Francis) in Europe and North America (EPRI 2002), the VLH turbine is a unique design that would not be considered at many sites where conventional turbines have been or would be installed due to head and flow constraints. Data from tests with salmon smolts are currently unavailable.

Archimedes Screw Turbine

Archimedes screw turbines (Figure 25-11) are considered to be fish-friendly because they have very low rotational and tip speeds (about 30 rpm and 3.8 m/s, respectively), no significant pressure changes or damaging shear forces, and no more than three runner blades (i.e., leading edges that can strike fish). Archimedes screw turbines typically have diameters between 1.5 and 3.5 m and are appropriate for sites with a head of 8 m or less. Biological evaluations of injury and mortality of fish passed through Archimedes screw turbines has been conducted with a variety of species and size classes (Spah 2001; Merkx and Vriese 2007; Fishtek Consulting 2007, 2008). All of the biological studies have demonstrated that fish passing through screw turbines experience minimal or no injury and no mortality, including adult European eels and sea-run brown trout and Atlantic salmon kelts (i.e., post-spawned adults).

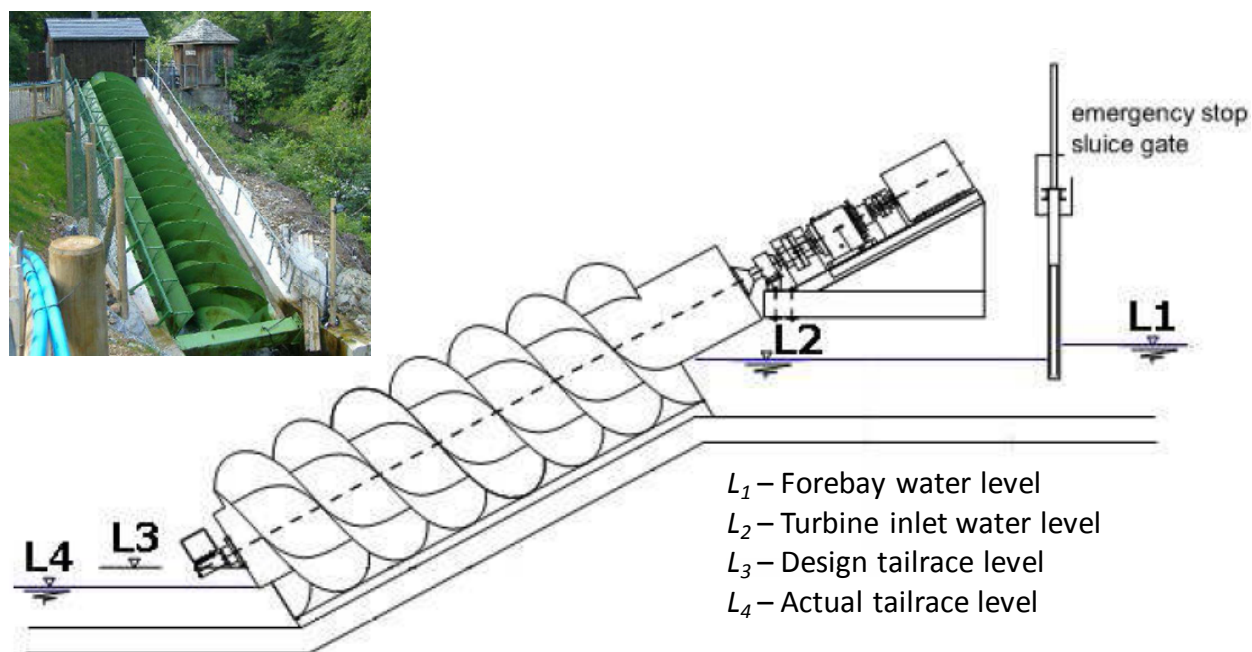


Figure 25-11
Archimedes Screw Turbine Design Installed at a Site on the River Dart in England
 (Modified From NBHS 2006)

Effects of Turbine Blade Leading Edge Design and Speed on Fish Injury and Survival

EPRI's efforts to support the development of fish-friendly turbines has included computer modeling and biological evaluations of the effects of leading edge blade shape, thickness, and speed on blade strike survival (Hecker et al. 2007; Amaral et al. 2008; EPRI 2008). These studies have significantly expanded the existing information and data on extent of injury and mortality when fish are struck by turbine blades. The results of blade strike tests are applicable to most turbine designs and can be considered as means to improve turbine passage survival when replacing or rehabilitating existing units.

The computer modeling of elliptical and semi-circular leading edge blade shapes demonstrated that the differential forces and moments on a simulated rigid fish just before impact on the leading edge were greater for the semi-circular shape compared to a 4:1 ellipse. These forces were concluded to be due to the flow conditions near the leading edge and not due to the fish being caught on the blade. Consequently, for comparable conditions of flow and fish approach to the blade, the semi-circular shape would cause greater deflection of the fish around the blade. Therefore, the computer simulations imply that the half-round leading edge shape may produce less fish injury than the “sharper” 4:1 ellipse. A semi-circular leading edge shape may be applied to any type of hydro turbine, with the leading edge thickness defining the radius at the leading edge and thus its “sharpness.”

The biological evaluation of blade strike was conducted in a linear flume (3 by 3 by 25 ft; Figure 25-12) using a motor/clutch/brake drive mechanism to accelerate blades of varying thicknesses at speeds up to about 12 m/s. Rainbow trout, white sturgeon, and American eel were tested with blade thicknesses 9.5, 25.0, 50, 100, and 150 mm (Figure 25-13). The data were non-dimensionalized by a ratio of fish length (L) to blade thickness (t). Test fish were anesthetized and suspended vertically in the path of the simulated turbine blades (Figure 25-14). Most fish were struck in the mid-body region, but some were struck in the head and caudal region to assess the effects of strike location on injury and mortality.

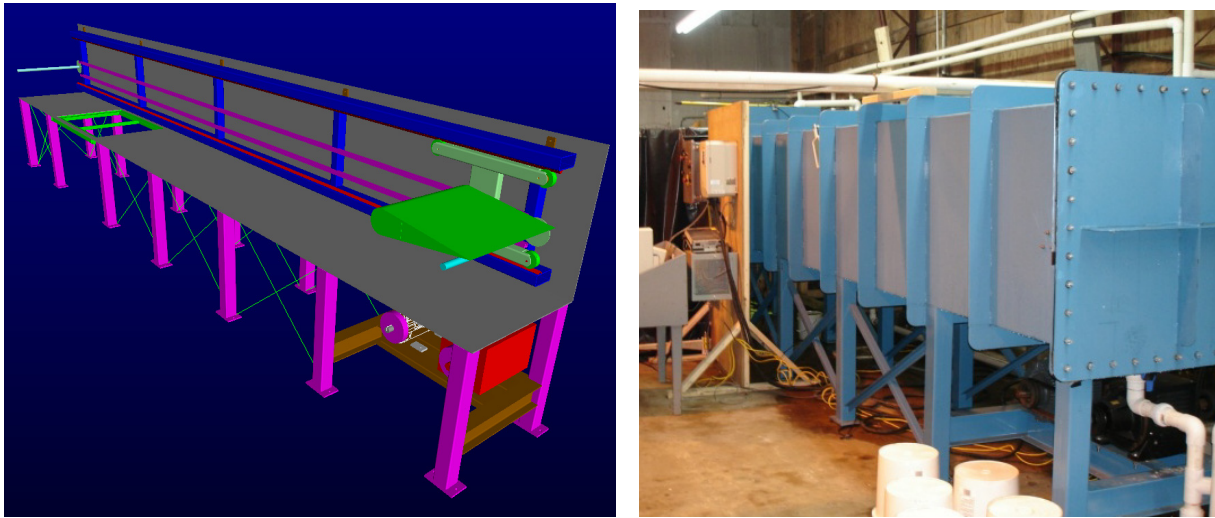


Figure 25-12
Schematic of Blade Strike Test Flume (Left) without Side Wall and Top and Actual Flume (Right)

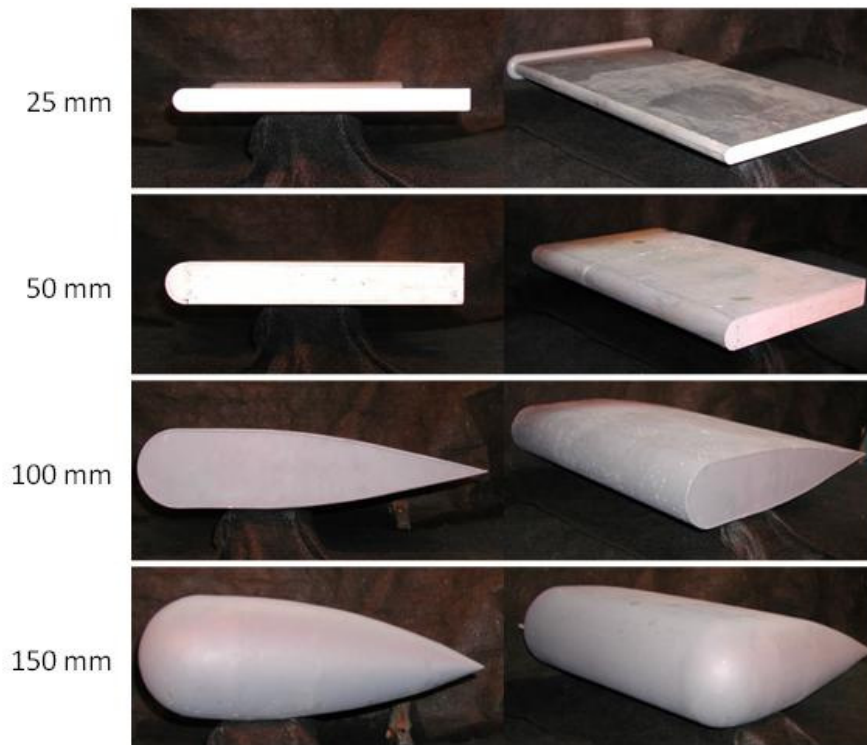


Figure 25-13
Simulated Turbine Blade Leading Edges Used During EPRI Blade Strike Study

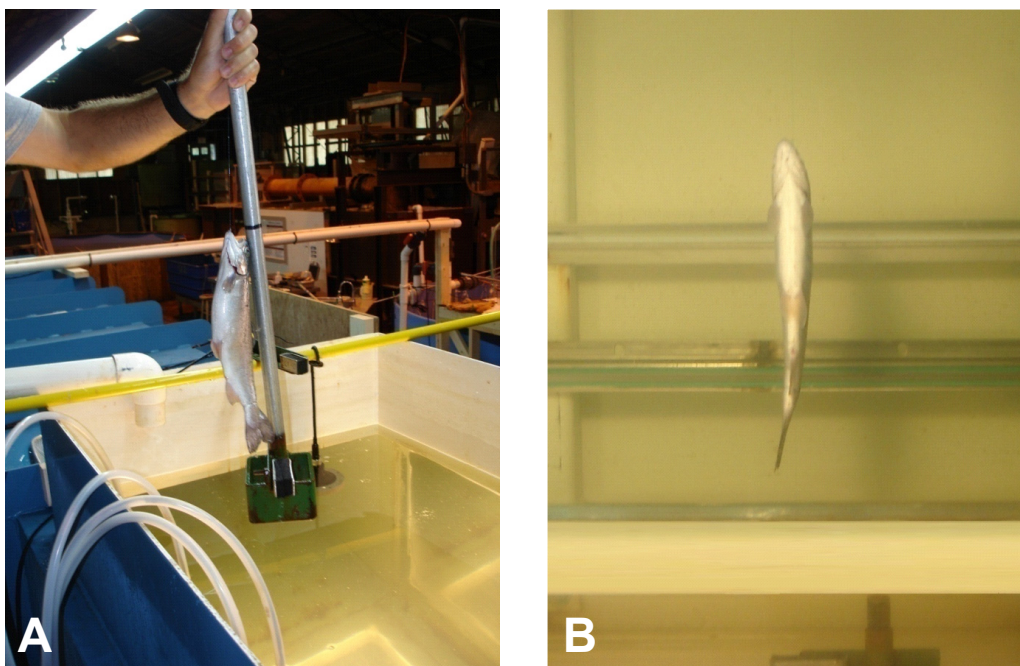


Figure 25-14
Rainbow Trout Being Placed in Test Tank (A) and Positioned Immediately Prior to Blade Strike

Test results of immediate (1 hr) and total (immediate and 96-hr combined) fish survival demonstrated a very consistent trend. Immediate and total survival of rainbow trout were greater than 90% for all L/t ratios at strike speeds up to about 5 m/s. At greater strike speeds, strike survival decreased with increasing L/t ratios (i.e. for thinner blades and larger fish) (Figure 25-15). High speed video indicated this was due in part to the leading edge pressure wave deflecting the fish away from the blade (Figure 25-16). The results from rainbow trout tests suggest that when fish length is about the same or less as the leading edge blade thickness, strike survival will be high (90% or greater) for turbines with relative blade velocities up to about 12 m/s (likely higher for L/t ratios less than 1).

White sturgeon suffered less mortality than rainbow trout at equivalent and larger L/t ratios and strike speeds (greater than 97% strike survival for an L/t ratio of 3.4 and blade speed of about 11 m/s), indicating they have physical features (e.g., cartilaginous skeleton, no scales) that make them less susceptible to blade strike injury compared to typical bony fishes. These results support observations from the biological evaluation of the ACT for which white sturgeon total survival (97%) was significantly greater than it was for alewife and coho salmon of similar size (about 93.5%) (Amaral et al. 2003; Cook et al. 2003). The L/t ratio for white sturgeon passing through the ACT was about 11 (100-mm fish, 9.5-mm leading blade edges with a near semi-circular geometry) and the relative blade velocity was about 8.2 m/s.

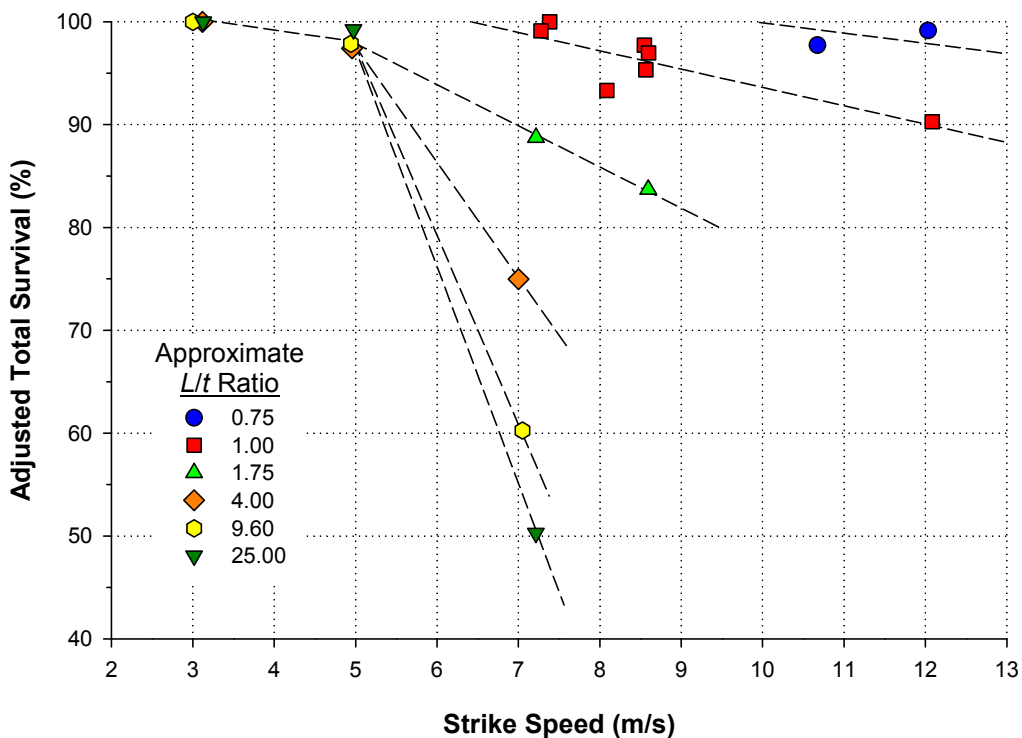
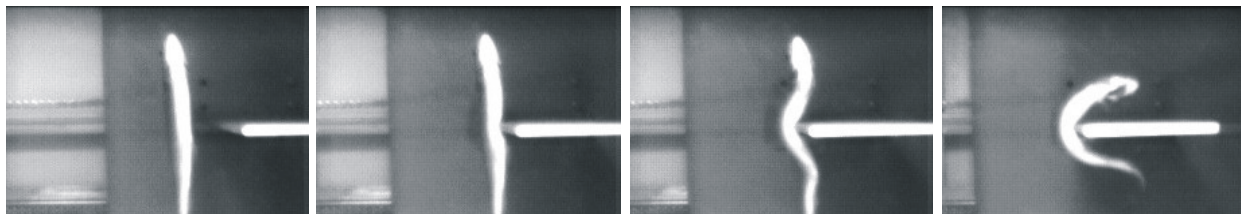


Figure 25-15
Total Blade Strike Survival Rates by Strike Speed and L/T Ratio for Tests Conducted with Rainbow Trout

L/t ratio = 25 (250 mm fish; 9.5 mm leading edge thickness)



L/t ratio = 1 (150 mm fish; 150 mm leading edge thickness)

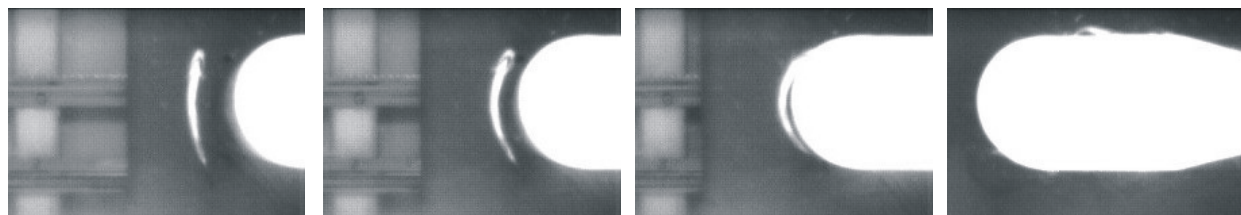


Figure 25-16
Images from High-Speed Video of Rainbow Trout Blade Strikes for L/T Ratios of 25 (Top Photos) and 1 (Bottom Photos)

Juvenile American eels also had higher blade strike survival rates (100% for an L/t ratio of about 2 and a blade speed of about 10 m/s) than rainbow trout tested at equivalent or smaller L/t ratios. Although eels have true bones, they appear to be more flexible than trout, which may make them less susceptible to strike-related injury. Also, their thinner and more elongate shape may improve displacement and sliding away from a leading edge, which results from the pressure wave preceding an approaching blade. Similar to white sturgeon, juvenile American eels also had significantly higher survival rates than other species evaluated during the biological evaluation of the ACT, including 100% immediate survival and greater than 98% total survival for both size groups of eels that were tested (mean lengths of 250 and 430 mm). The L/t ratios for the two size groups of eels tested with the pilot-scale ACT (9.5-mm leading blade edges with near semi-circular geometry) were about 26 and 45 and the relative blade velocity was about 8.2 m/s. This suggests that either few eels were struck during turbine passage and/or blade strike survival was very high, even with these large L/t ratios.

The high speed video was effective for estimating the strike region and orientation of fish relative to the approaching blade. Test videos also demonstrated differences in fish movement prior to a fish being struck by either a narrow (9.5 to 50 mm) or thick blade (100 and 150 mm) (Figure 25-16). Pre-strike movement included fish moving away from the blade, bending to the curvature of the leading edge shape, and sliding up or down as the blade approached and struck a fish. These fish movements likely were the result of pressure waves, which were much more evident with the thicker blades (i.e., 100 and 150-mm blades). At the larger L/t ratios (4 and greater) when blade thickness was 50 mm or less, movement of fish prior to blade strike was minimal. The ability of fish to bend to the curvature of a blade's leading edge and to slide up or down just prior to and during a strike likely reduced the potential for injury with the thicker blades (i.e., smaller L/t ratios).

The results of the CFD and biological evaluation of blade strike have produced valuable information and data that can be used by project owners and turbine manufacturers to develop more fish-friendly turbines by improving the leading edge blade geometry and identifying a leading edge thickness that will minimize injury and mortality of target species. This information is being used in the design of the ACT (Figure 25-17), which is planned to be installed at Brookfield Power's School Street Project on the Mohawk River in New York. At this site, the new turbine is intended to be a safe downstream passage route for juvenile blueback herring, which are about 75 to 100 mm in length. Consequently, blade thicknesses of 100 and 150 mm are being considered for the School Street application. These thicknesses should benefit other species as well, particularly since most fish entrained at hydro projects are less than 200 mm in length.

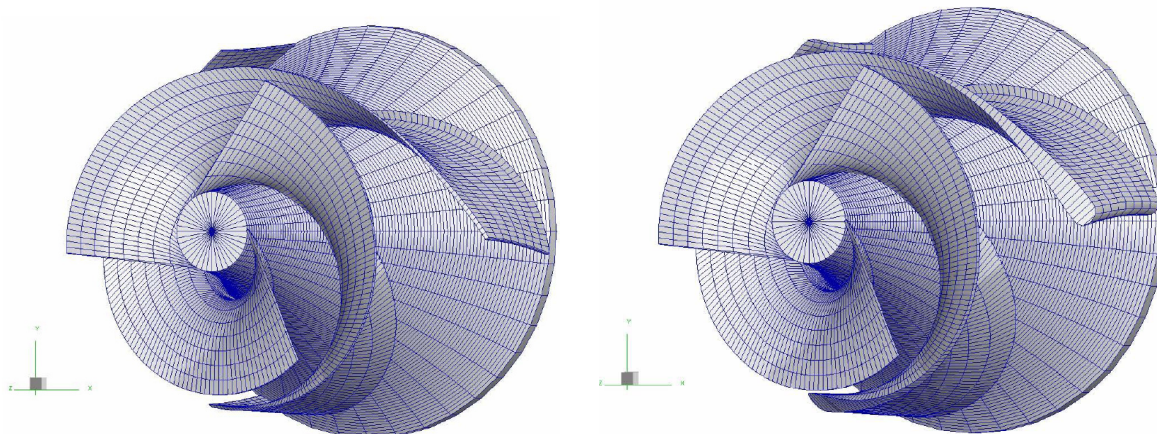


Figure 25-17
Original ACT Runner Design (Left) and Modified Design Incorporating Thicker Leading Edges for Increased Fish Survival (Right)

Literature Cited

Abernethy, C. S., B. G. Amidan, G. F. Cada. 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. Cada. 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. Cada. 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.

Ahmann, M., R. Davidson, F. Loiseau, J Purvis, and J. Kirejczyk. 2005. Modeling the Fish Passage Environment for a Comparison of a Minimum Gap Kaplan and a Classical Kaplan Runner. Proceedings of Waterpower XIV, HCI Publications, Inc., St. Louis, Missouri.

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.

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.

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

Cada, G. F., M. G. Ryon, D. A. Wolf, and B. T. Smith. 2003. Development of a New Technique to Assess Susceptibility to Predation Resulting from Sublethal Stresses (Indirect Mortality). U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies, ORNL/TM-2003/195.

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

Cada, G. F., M. G. Ryon, J. G. Smith, and C. A. Lockett. 2006b. The Effects of Turbine Passage on C-Start Behavior of Salmon at the Wanapum Dam, Washington. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies, ORNL/TM-2006/88.

Carlson, T. J., and J. D. Duncan. 2003. Evolution of the Sensor Fish Device for Measuring Fish Passage Conditions in Severe Hydraulic Environments. U.S. Department of Energy, DOE/ID-11079.

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.

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.

de Montmorency, D., J. Swiderski, and J. Juang. 2006. Application of Fish Friendly Criteria in the Design of a “Vaneless” Turbine. Proceedings of HydroVision 2006. HCI Publications, St. Louis, Missouri.

de Montmorency, D. 2008. The Design and Testing of a “Fish-Friendly” Axial Flow Runner in a “Vaneless” Turbine. Unpublished manuscript.

Deng, Z., M. C. Richmond, G. R. Guensch, and R. P. Mueller. 2004. Study of Fish Response Using Particle Image Velocimetry and High-Speed, High-Resolution Imaging. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies, PNNL-14819.

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.

EPRI. 2009. Redesign of the Alden/Concepts NREC Helical Turbine for Increased Power Density and Fish Survival: Evaluation of Conceptual Prototype Turbine. Prepared by Alden Research Laboratory, Inc. EPRI Report No. 1015600.

EPRI. 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. 2007. Program on Technology Innovation: Redesign of the Alden/Concepts NREC Helical turbine for Increased Power Density and Fish Survival: Scroll Case Redesign. Prepared by Alden Research Laboratory, Inc., EPRI Report No. 1014810.

EPRI. 2002. Review and Documentation of Research and Technologies on Passage and Protection of Downstream Migrating Catadromous Eels at Hydroelectric Facilities. Prepared by Versar, Inc., EPRI Report No. 1000730.

Fishtek Consulting. 2007. Fish Monitoring and Live Fish Trials. Archimedes Screw Turbine, River Dart. Phase 1 Report: Live Fish Trials, Smolts, Leading Edge Assessment, Disorientation Study, Outflow Monitoring. Prepared for Mann Power Consulting Ltd.

Franke, G. F., D. R. Webb, R. K. Fisher, D. Mathur, P. N. Hopping, P. A. March, M. R. Headrick, I. T. Laczko, 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.

Fraser, R., C. Deschenes, C. O'Neil, and M. Leclerc. 2007. VLH: Development of a New Turbine for Very Low Head Sites. Proceedings of Waterpower XV. HCI Publications, St. Louis, Missouri.

Fishtek Consulting. 2008. Archimedes Screw Turbine Fisheries Assessment. Phase II: Eels and Kelts. Prepared for Mann Power Consulting Ltd.

GCPUD (Grant County Public Utility District). 2005. P-2114 Advanced Turbine Unit No. 8 Status Update on Biological Testing July 23, 2004 FERC Interim Order Authorizing Installation of Advanced Turbine and December 16, 2004 FERC Order Amending License. FERC File No. 20050819-0053 for Docket No. P-2114.

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.

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 T. C. Cook. 2005. Development and Evaluation of a New Helical Fish Friendly Hydro-Turbine. *Journal of Hydraulic Engineering* 131(10): 835-844.

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.

Leclerc, M. 2007. Turbine de Tres Basses Chutes, Very Low Head Turbine: Newsletter No. 6. MJ2 Technologies SARL.

Leclerc, M. 2008. Turbine de Tres Basses Chutes, Very Low Head Turbine: Newsletter No. 7. MJ2 Technologies SARL.

Leclerc, M. 2008. Getting Down with VLH Turbine R&D. *International Water Power and Dam Construction*, May 2008.

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.

Loiseau, F., R. A. Davidson, M. Couston, M. Sabourin. 2006. Fish Environment and New Turbine Designs. Proceedings of the 23rd IAHR Symposium.

NBHS (Nick Bard Hydro Services). 2007. River Dart Hydro Performance Assessment. Prepared for Mannpower Consulting Ltd.

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.

Odeh, M. 1999. A Summary of Environmentally Friendly Turbine Design Concepts. Prepared for the U.S. Department of Energy, Idaho Operations Office, DOE/ID/13741.

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.

Ryon, M. G., G. F. Cada, J. G. Smith. 2004. Further Tests of Changes in Fish Escape Behavior Resulting from Sublethal Stresses Associated with Hydroelectric Turbine Passage. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies, ORNL/TM-2003/288.

Ware, A. D., W. Colwill, and A. Sullivan. 2004. The Retrofit Aeration System – A Comprehensive Design Approach to Enhance Dissolved Oxygen Uptake in Existing Hydroturbines. Proceedings of HydroVision 2004. HCI Publications, St. Louis, Missouri.

Weiland, M. A., R. P. Mueller, T. J. Carlson, S. D. Deng, and C. A. McKinstry. 2005. Characterization of Bead Trajectories through the Draft Tube of a Turbine Physical Model. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies, PNNL-14879.

Vinh, P., P. Mora, L. Tomas, and J. Kirejczyk. 2002. Model Results on a New Fish Friendly Kaplan Turbine. Proceedings of HydroVision 2002, HCI Publications, Inc., St. Louis, Missouri.

Winchell, F., S. Amaral, and D. Dixon. 2000. Hydroelectric Turbine Entrainment and Survival Database: An Alternative to Field Studies. Proceedings of HydroVision 2000. HCI Publications, Inc., St. Louis, Missouri.