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A Summary of Environmentally Friendly Turbine Design Concepts

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U.S. Department of Energy
Idaho Operations Office

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(Concepts Developed by Alden Research Laboratory, Inc.,
Voith Hydro, Inc. and their Teams)

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ABSTRACT

The Advanced Hydropower Turbine System Program (AHTS) was created in 1994 by the U.S. Department of Energy, Electric Power Research Institute, and the Hydropower Research Foundation. The Program's main goal is to develop "environmentally friendly" hydropower turbines. The Program's first accomplishment was the development of conceptual designs of new environmentally friendly turbines. In order to do so, two contractors were competitively selected. The ARL/NREC team of engineers and biologists provided a conceptual design for a new turbine runner*. The new runner has the potential to generate hydroelectricity at close to 90% efficiency. The Voith team produced new fish-friendly design criteria for Kaplan and Francis turbines that can be incorporated in units during rehabilitation projects or in new hydroelectric facilities**. These include the use of advanced plant operation, minimum gap runners, placement of wicket gates behind stay vanes, among others. The Voith team will also provide design criteria on aerating Francis turbines to increase dissolved oxygen content. Detailed reviews of the available literature on fish mortality studies, causation of injuries to fish, and available biological design criteria that would assist in the design of fish-friendly turbines were performed. This review identified a need for more biological studies in order to develop performance criteria to assist turbine manufacturers in designing a more fish-friendly turbine.

This paper is a summary of final reports submitted to the U.S. Department of Energy's Advanced Hydropower Turbine System Program by ARL/NREC and Voith teams:

* ARL/NREC team report: *"Development of a more fish tolerant turbine runner – Advanced hydropower turbine project"*, prepared by T.C. Cook, G.E. Hecker, H.B. Faulkner, and W. Jansen. DOE Contract No. DE-AC07-95ID13383. Hereafter referred to as Cook et al. (1997).

** Voith team report: *"Development of environmentally advanced hydropower turbine system concepts"*, prepared by G.F. Franke, D.R. Webb, R.K. Fisher, D.Mathur, P.N Hopping, P.A. March, M.R. Headrick, I.T. Laczo, Y. Ventikos, and F. Sotiropoulios. DOE Contract No. DE-AC07-96ID13382. Hereafter referred to as Franke et al. (1997).

ACKNOWLEDGEMENTS

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* ARL/NREC team: Alden Research Laboratory, Inc. and Northern Research and Engineering Corporation.

* Voith team: Voith Hydro, Inc., Normandeau Associates, Tennessee Valley Authority, Harza Engineering Company, and Georgia Institute of Technology.

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INTRODUCTION

The development of an environmentally friendly hydropower turbine stems from the need to continue using a reliable source of renewable energy along with maintaining a healthy environment and a sustainable ecosystem. The U.S. Department of Energy (DOE), Electric Power Research Institute (EPRI), and the Hydropower Research Foundation envisioned the Advanced Hydropower Turbine System Program (AHTS) in 1993. The program was created in 1994 with the objective of developing new hydropower turbine designs that would minimize fish injury and mortality, are environmentally friendly (i.e., maintain adequate water quality), and produce hydroelectricity efficiently. The Hydropower Research Foundation, a non-profit organization formed by the National Hydropower Association, provided matching funds from industry to DOE for the conceptual design phase.

DOE issued a Request for Proposals for environmentally friendly turbine design concepts in October 1994. Submitters were encouraged to be innovative and to start from ground zero. Responses were received in February 1995 from companies, universities, state agencies, research labs, and individuals. Proposals were reviewed and rated according to their suitability to the AHTS Program's objectives, engineering soundness, and environmental application.

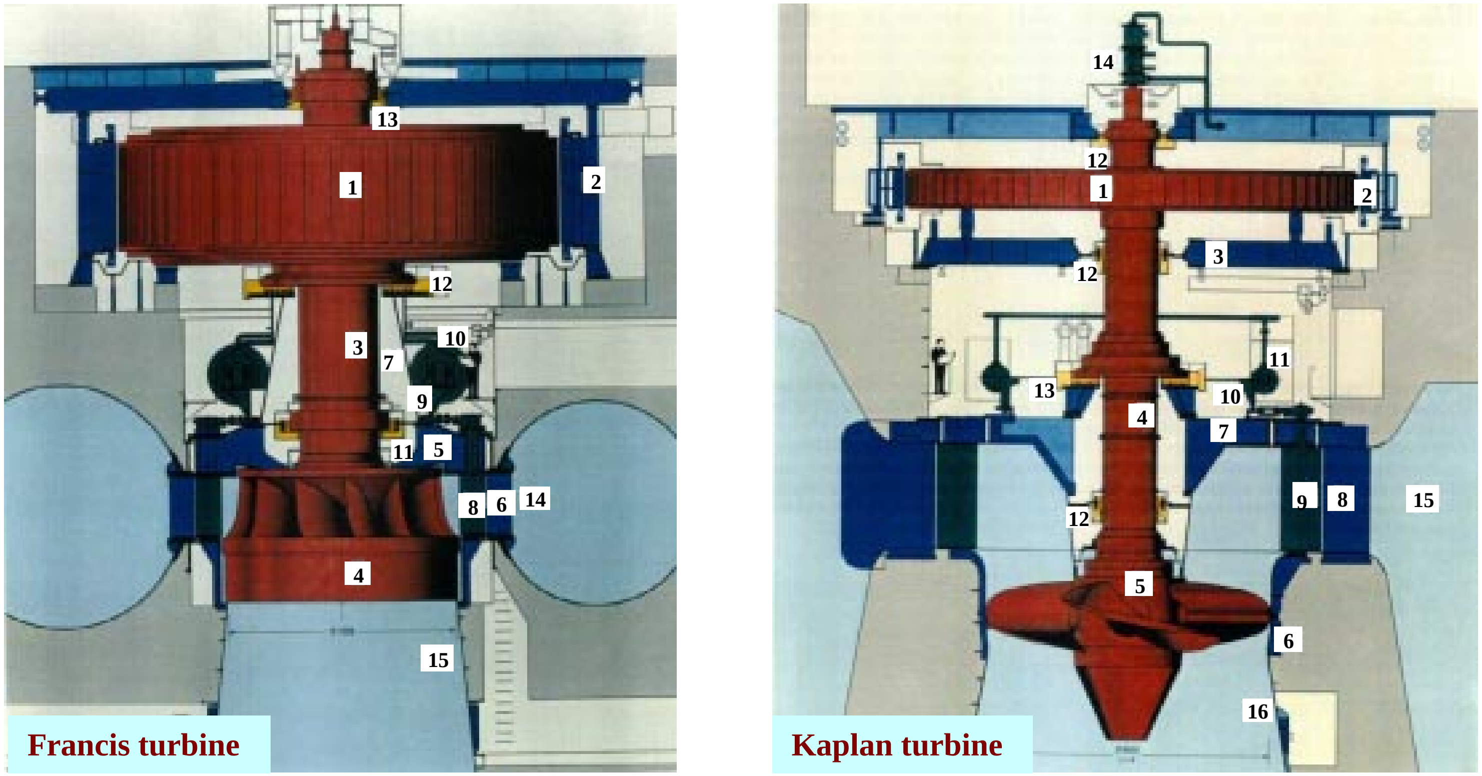
Two proposals were chosen for funding in October 1995. One came from a team of engineers and biologists at Alden Research Laboratory, Inc. and Northern Research and Engineering Corporation (ARL/NREC team, DOE contract No. DE-AC07-95ID13383). Another proposal came from a team led by Voith Hydro, Inc., and included Tennessee Valley Authority, Harza Engineering, Normandeau Associates, and Georgia Institute of Technology (Voith team, DOE contract No. DE-AC07-96ID13382). The two teams took two different approaches to achieving the AHTS Program objectives. ARL/NREC proposed to design a new turbine runner, whereas Voith chose to improve existing runner designs.

The proposal from ARL/NREC team outlined a method to design a totally new turbine runner. Their idea was to start with a single-bladed impeller that is a combined screw/centrifugal pump, which is widely used in the food processing industry to transport fish and vegetables with minimal damage. This impeller is also used to pump fish safely around diversion structures and bypass systems at some locations in the U.S. This innovative approach would later yield a multi bladed turbine runner design that may be used in new installations or to replace existing turbine runners, where feasible.

The Voith team submitted a detailed proposal aimed at reviewing existing engineering and biological design criteria and available turbine technology, and proposed to make design concepts that would lead to enhanced fish survivability. The unique capabilities of the Voith team enabled them to study important environmental issues related to hydropower turbines, evaluate mortality studies of turbine passed fish, and provide three new design concepts that can be used for rehabilitation of existing turbines and in new hydroelectric facilities. Environmentally friendly design concepts for Kaplan and Francis turbines were submitted to DOE by the Voith team. Schematic diagrams of Francis and Kaplan turbines are shown on Figure 1 to familiarize the reader with the various components of these two typical designs. A supplemental report on the third concept dealing with an environmentally friendly aerating Francis turbine will be submitted at a later date.

In order to formalize new concepts and improve on existing designs both ARL/NREC and Voith teams started their projects with a literature search to identify probable causes of fish injury and mortality, as well as other environmental issues impacted by turbines. Both teams reached the conclusion that the available literature lacks adequate biological information or design criteria on which to base new turbine concepts. These biological design criteria include quantitative values (or thresholds) for damage-causing mechanisms that a turbine designer would take into consideration to make their turbine fish-friendly. For example, the cavitation coefficient must meet a certain value, velocity shear stress in certain passage areas should be limited to defined numbers of force per unit area, etc. As a result, DOE recommended that an independent study of the biological design criteria needed for the design of advanced turbines be performed. Čada et al. (1997) provided a review of available literature, suggested provisional biological design criteria, and gave recommendations as to what biological design criteria relative to fish injury mechanisms need to be developed further. This can be accomplished by simulating turbine hydraulics in the laboratory coupled with using fish species of interest for testing.

Although gaps in biological information were presented, both teams identified biological and engineering performance goals, based on existing information, for their new concepts and proceeded with their assignment. Both teams made use of the Computational Fluid Dynamics (CFD) method of solution to refine their conceptual designs.



1. Generator Rotor
2. Generator Stator
3. Turbine Shaft
4. Runner
5. Turbine Head Cover
6. Stay Ring Discharge Ring
7. Supporting Cone
8. Guide Vane
9. Operating Ring
10. Guide Vane Servomotor
11. Lower Guide Bearing
12. Thrust Bearing
13. Upper Guide Bearing
14. Spiral Case
15. Draft Tube Cone

1. Generator Rotor
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7. Turbine Cover
8. Stay Ring
9. Guide Vane
10. Operating Ring
11. Guide Vane Servomotor
12. Guide Bearing
13. Thrust Bearing
14. Oil Supply Head
15. Concrete Semi-spiral Case
16. Draft Tube Cone

Figure 1. Schematic diagrams of Francis and Kaplan turbines. (Source: Franke et al. 1997)

BIOLOGICAL CONSIDERATIONS AND DESIGN CRITERIA

The issue of safe fish passage dominated the decision of whether a new turbine design concept was environmentally friendly. Fish passage is an important issue to many hydroelectric plants' operators. However, improving water quality of turbine discharge, such as increasing low dissolved oxygen content, and plant operating conditions were also considered priorities. Available information on fish injury and mortality was reviewed by both teams to assess the types and causes of injury and to develop the criteria to be used for evaluating new designs. Biological design criteria were needed to assist in establishing allowable limits of hydraulic parameters that may contribute to new design concepts, fish mortality, and plant operation.

Power plant owners, Department of Energy, Electric Power Research Institute (EPRI), Federal Energy Regulatory Commission, Fish and Wildlife Service, National Marine Fisheries Service, and others have conducted studies designed to identify the levels of fish injury and mortality, and precise causes of mortality as a result of passing through hydropower turbines. Although findings from these studies are useful in establishing qualitative guidelines, their use for predicting the performance of new designs is somewhat limited. This is due to the methods used and the different objectives the studies set out to accomplish. Both ARL/NREC and Voith teams reached this same conclusion regarding available information from past mortality studies.

Field studies have been used to identify injury of fish passing through turbines. However, these can be complex, costly, and may yield results that can be biased by the mark/recapture techniques used. Furthermore, the complex flow field inside the turbine system makes it nearly impossible, without as yet undeveloped instrumentation, to accurately attribute observed fish behavior and damage to a specific injury mechanism.

In 1987 EPRI conducted a review to identify turbine designs and their operating characteristics that may contribute to the mortality of turbine-passed fish (EPRI 1987, reported in Cook et al. 1997). The review indicated that, generally, rapid pressure drops (including cavitation), higher head differential across the turbine, and low turbine efficiency may increase fish mortality. However, the impracticality of locating damaging zones and observing injury mechanisms within a turbine made it difficult to explain exact causes of fish mortality (EPRI 1987).

The EPRI (1987) review indicated that in Francis turbines the runner entrance (where wicket gates, blades, and the runner's peripheral speed interact), higher peripheral runner speeds, and greater wicket gate openings were correlated to higher fish mortality. Fish mortality did not change with operating head in Francis turbines (similar mortality at 40 ft and 410 ft). In Kaplan turbines comparing the peripheral runner speed and plant operating head with fish mortality yielded little correlation (mortality at 20 ft and 110 ft was the same). This was in contrast with the general belief that hydraulic head is a major contributing factor to turbine mortality. However, the clearance between the blade tips and the discharge ring in a Kaplan turbine, where fish could be caught, was of concern (EPRI 1987).

Another recent review of fish entrainment and mortality studies by EPRI (EPRI 1992, reported in Cook et al. 1997 and Franke et al. 1997) included data from many projects with riverine as well as anadromous fish species throughout the U.S. The EPRI study findings showed that estimated mortality averaged 20% for Francis turbines, 12% for Kaplan turbines, and 9% for bulb turbines, and that a wide variety of species suffer similar mortality rates in a given turbine type. Several studies indicated lower rates of mortality for naturally entrained fish compared to fish that were artificially introduced into the turbine system (averaging 6% mortality for both Francis and Kaplan turbines). The EPRI review included studies of juvenile clupeid species (American shad and blueback herring) conducted after 1987, which confirmed the higher mortality rates in the case of Francis turbines compared with Kaplans (mortality was 16% for Francis turbines and about 4% for Kaplans). The difference in mortality percentages in the more recent studies was attributed to two factors (according to the authors of the EPRI 1992 review); artificially entrained fish (i.e., test fish) were larger in size than naturally entrained ones, and in later studies (beyond 1987) researchers had better handling and evaluation techniques.

The Voith team conducted their own review of available mortality studies in order to arrive at design criteria on which they would base their new design concepts for improvements to features of existing and new turbine designs (see Chapter 4, Franke et al. 1997 for details). The multidisciplinary team looked into fish-damage-causing mechanisms and evaluated existing injury and mortality data. That led to new understandings, the need for further testing of new perceptions, and some conclusions for the new design concepts. Following is a summary of some of the Voith team’s findings and opinions. Also, references are made to the Voith team’s review where appropriate throughout this report.

- Injury and mortality mechanisms are dependent on the zone which the fish takes to pass through the turbine system. At Wanapum Dam in Washington, fish that passed through a zone near the turbine hub experienced 5% higher mortality than fish that passed through the zone in the middle of the runner.
- Fish encountering the zone surrounding the blade sustain injury due to blade strike, blade end gaps, and local fluid flow effects. However, quantifying exact sources of

turbine passed fish injury and mortality is difficult due to the lack of controlled experiments. Also, observed injuries may be the result of multiple damage mechanisms. And, most studies to date used juvenile salmonids of limited size range and did not provide data regarding turbine operating conditions or the location of test fish injection zones. Planned injury and mortality tests should take into consideration the zone in which the test fish are to be released, turbine operating hydraulic conditions, and use various fish species.

- Injuries caused by pressure appear to be related to the difference between the acclimation pressure upstream of the turbine and the exit pressure within the draft tube zone.
- Turbines can be designed to operate cavitation free while increasing power production. Proper turbine operation at cavitation-free conditions will reduce maintenance costs and fish mortality that is believed to be related to cavitation.
- A threshold value of the shear stress indicator (the indicator here refers to the rate of deformation OR rate of strain of the fluid, dv/dy) was identified as 450 ft/s/ft (using Computational Fluid Dynamics and existing literature). Values above this rate are believed to cause mortality.
- Turbine operating point has significant effect on fish survival. Tests at Wanapum Dam showed that peak fish survival did not coincide with peak efficiency, but occurred at a discharge where the predicted blade strike probabilities were low and before cavitation became significant. Analyzed mortality data showed no conclusive evidence supporting the belief that maximum fish survival occurs at discharges within 1% of peak efficiency. Data did not preclude the possibility that maximum survival can occur at greater than peak efficiency discharge.
- Fish survivability in fish-friendly turbines ought to be evaluated at before and after conditions (benchmarked) using the same hydraulic and biological evaluation techniques.

Injury Mechanisms

The survival of a turbine-passed fish is highly dependent on the path that the fish takes through the turbine system (Franke et al. 1997; Čada et al. 1997). Once a fish departs the forebay and enters a turbine system it must contend with changes in physical geometry and flow characteristics that are very rapid and believed to be injurious in certain zones along the path. An illustration of the damaging zones within a turbine system is shown in Figure 2.

1 Increasing Pressure
2 Rapidly Decreasing Pressure
3 Cavitation
4 Strike
5 Grinding
6 Shear
7 Turbulence

Figure 2. Schematic diagram showing locations within a turbine system where fish injury mechanisms are believed to occur. (Modified from: Čada et al. 1997)

The U.S. Army Corps of Engineers organized a turbine passage survival workshop in 1995 to identify causes of stress and injury to fish when passing through a hydropower turbine system. Potential damage mechanisms were identified and loosely grouped into four categories; mechanical, pressure, shear, and cavitation (USACE 1995). Mechanical causes include strike, abrasion, and grinding. Pressure fluctuations, shear stress, turbulence, and cavitation are related to flow characteristics.

After identifying the damage mechanisms, the next logical step would be to determine biological design criteria that, when incorporated in new and rehabilitated turbines, would make them more fish friendly. That necessitated a comprehensive literature review to identify existing information that would lead to these criteria. Only laboratory experiments conducted to study individual damage mechanisms under controlled conditions were reviewed (Čada et al. 1997 and Čada 1998). The reviewers also briefly examined field techniques used to observe fish movements in and out of turbine systems and to examine the resulting overall injury and mortality. Among the most important findings of the review by Čada et al. (1997) are:

- The least damaging turbine system design is one that directs the majority of the migratory fish away from turbine intakes and towards their natural surface oriented migration route;
- Shear stress and related turbulence are among the least understood of damage mechanisms (see description below). Varying levels of shear stress and fish response to them need to be studied in a laboratory setting;
- Further quantitative evaluation of indirect mortality, such as predation and disease, of turbine passed fish is needed;
- Further understanding and data collection and analysis of fish trajectories inside turbines are needed. Computational Fluid Dynamics is a valuable tool to understand flow behavior inside turbines. CFD may be used to simulate fish as passive objects in the flow field, given that data on fish behavior from field studies are incorporated to calibrate the CFD model; and
- Further studies using hydroacoustic techniques and low-light underwater video are needed to understand fish behavior and distribution as they approach turbine intakes.

Following is a brief description of each of the damage mechanisms and some of the related information presently available.

Mechanical: Abrasion, Grinding, and Strike

The rubbing action of a fish against a turbine system component or objects in the flow field is referred to as abrasion, and can cause damage to the fish (USACE 1995). Abrasion damage is dependent on flow discharge and velocity, number of turbine blades and spacing between them, and the geometry of flow passages (USACE 1995). Data are not available to identify the amount of or to distinguish injury due to abrasion.

Grinding injury can occur when a fish is drawn into small clearances (gaps of sizes close to that of the fish) within the turbine system (USACE 1995). Gaps with high velocity zones that may cause grinding injury are present between the turbine blade leading edge and the hub, the blades and the throat ring, the wicket gates and stay vanes, and between the wicket gates and the distributor ring (USACE 1995). Grinding injury can be documented by examining the fish's body for localized bruises, deep cuts, and even decapitation. However, precise prediction of injury due to abrasion and grinding is not possible, and some of the fundamental symptoms of grinding may also be caused by other fish injury mechanisms (Čada et al. 1997).

A fish may be damaged when it collides with (strikes) a turbine system component. The probability of a fish striking parts of the turbine system depends on several factors which include the size of the fish, number of blades and their spacing, turbine speed, flow velocity and discharge, among others. Several equations have been developed to calculate the probability of strike in Francis and Kaplan type turbines (von Raben 1957 and Montén 1985, cited in Čada 1997; USACE 1991, cited in Cook et al. 1997). Also, a new equation, based on the von Raben's model, was derived by the Voith team (Franke et al. 1997). These probability equations make the assumption that a strike means serious injury or death, which may not always be true (Bell and Kidder 1991, cited in Čada et al. 1997). The probability of a fish dying from striking an object within the turbine system is variable (Bell and Kidder 1991). A blade and a fish striking each other (colliding) may cause scale and mucous loss, eye injury, and internal bleeding depending on the velocities involved and the shape of the blade's leading edge (Turnpenny et al. 1992). Direct visual observations are not available to correlate mortality to strike (USACE 1995) and to verify the strike probability models. Data on specific causes of mechanical injury to fish passing through turbines are very limited and when compared to the field results, probability models yield varying results.

Data relating fish mortality to entry into a water body showed that mortality varied between 0% at 65 ft/sec and 100% at 145 ft/sec. Also, upon impact onto solid objects fish mortality varied between 0% at 15 ft/sec and 100% at 95 ft/sec (USACE 1991, cited in Cook et al. 1997). Data from EPRI (1987) indicated that mortality increases with runner peripheral velocities; minimal mortality could be expected at runner peripheral velocities of 40 ft/sec or lower in Francis turbines. The data in EPRI (1987) also showed that more strikes would occur at higher tip speeds and that a peripheral runner velocity of 20 ft/sec or less may eliminate strike mortality.

Pressure

Fish are subjected to rapid pressure changes throughout the turbine system. Damage due to pressure is dependent on the amount and rate of change of pressure experienced by the fish as well as the type of the fish. Physostomous fish, such as salmon and trout, have a pneumatic duct that connects the swim bladder to the esophagus, which is used, along with the mouth, to rapidly take in or vent gas (Lagler et al. 1962, cited in Čada et al. 1997). Physoclistous fish, such as perch and bass, do not have a pneumatic duct and must adjust their body's gas content by diffusion into the blood. Because this diffusion process may take hours, these fish are more susceptible to damage due to rapid pressure decrease. Pressure changes felt by a fish are relative to its acclimation pressure prior to entering the turbine system. These typically range from 15 ft of water (21.2 psi or 146 kPa Absolute) at low-head plants to 170 ft of water (87.7 psi or 605 kPa Absolute) at high-head plants (USACE 1995).

It is believed that fish are more sensitive to pressure decreases than pressure increases, and that pressure-related mortality is due to injury to the swim bladder from decompression (Tsvetkov 1972, cited in Čada 1990 and in Čada et al. 1997). Swim bladders in 10-cm perch burst when pressure was reduced to 40% of acclimation values (Jones 1951, cited in Čada 1990). However, rainbow trout exposed to pressure increases of 35 to 185 psia (241 kPa to 1,275 kPa) in less than one minute followed by near instantaneous depressurization exhibited normal activity, and no mortality was attributed to the test conditions (Rowley 1955, cited in Čada 1990).

Gradual pressure increases, up to 2064 kPa (300 psia), did not seem to cause significant damage to sockeye salmon or six species of freshwater fishes (Harvey 1963 and Foye and Scott 1965, cited in Čada et al. 1997). However, in both studies the rate at which pressure increased was low (about 1 psi per second), which is unlike the rapid rate of pressure increase through a turbine system. Whitefish fry and common carp exposed to a rapid increase in pressure from atmospheric to 725 psia (4,997 kPa), followed by a 10-minute depressurization back to atmospheric pressure experienced no mortality (Lampert 1976, cited in Čada 1990). Alewives pressurized to 50.7 psia (350 kPa), held for about 15 minutes, and depressurized back to 14.7 psia over a 2 minute period had difficulty maintaining horizontal disposition due to swim bladder compression at first, but fully adjusted over the holding period (SWEC 1975). Overall, the test fish mortality did not differ from the control fish mortality.

Swim bladder rupture and embolism are caused by suddenly and severely lowering the pressure from the fish's acclimated pressure (USACE 1991). Theoretical information on mortality in salmonids, relative to pressure changes, indicated that when the minimum pressure is 30% of the acclimation pressure (i.e., Exposure Pressure/Acclimation Pressure ratio is 0.3), or higher, no mortality is expected (USACE 1991). This general rule was supported by plotting data from several fish mortality studies relating exposure of fish to minimum pressures below their initial acclimation pressure; Figure 3. The few data showing mortality to the right of the 0.3

pressure ratio were from tests using physoclistous fish, such as bass and crappie, which are non-anadromous.

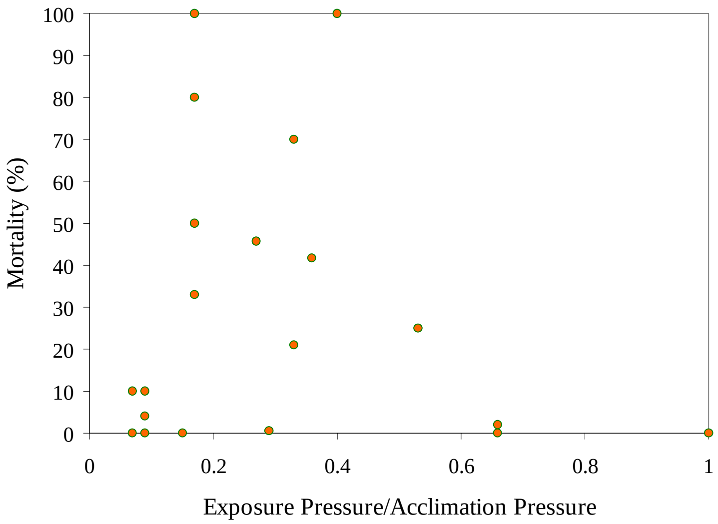


Figure 3. Percent of fish mortality as a result of exposure to rapid pressure reductions in laboratory tests. (Source: Čada et al. 1997)

In the 1995 Corps of Engineers Turbine Passage Survival Workshop, the following conclusions were reached regarding the rate of pressure change in turbines:

- High head turbines are typically smaller units and have a high rate of pressure change per unit time, and low head turbines are typically large units with a lower rate of pressure change per unit time.
- Fish experience depressurization from as high as 88 psia (607 kPa Absolute) on the upstream side of the runner to about 7 psia (48 kPa Absolute) on the discharge side of the runner.
- Differential pressure per square inch of blade surface (Energy density) affects the passage time through the runner, and the greatest rate of pressure change occurs in 0.1 to 0.2 seconds .
- In Kaplan turbines, generally the rate of pressure change across the blades is about 160 psi/sec, assuming a 75-ft head and a 0.2-second time period from high to low pressures.

Cavitation

The presence of voids in the liquid has a damaging effect on marine and hydraulic turbine propellers (Euler 1754, cited in Odeh 1988). Cavitation is the rapid vaporization and condensation process of liquid. It normally occurs when the local pressure in the liquid drops to or below vapor pressure, and with nuclei present in the liquid vapor cavities (bubbles) are formed. These bubbles grow within the vapor pressure region and then become unstable and collapse as they travel to areas with higher pressures. The collapse of bubbles can sometimes be violent and cause noise, vibrations, pressure fluctuations, erosion damage to solid surfaces, and loss of efficiency or flow capacity (Odeh 1988 and Tullis 1989). Cavitation damage can occur as a result of high-pressure shock waves (that can reach up to 10^6 psi) or high-velocity microjets shooting through the center of the bubble creating a local pit to the bubble's adjacent solid boundary (Tullis 1989).

Mortality in fingerling salmon was 50% when they were subjected to vapor pressure followed by instantaneous return up to atmospheric pressure; the damage was attributed to the high-pressure shock waves as vapor pockets in the test chamber collapsed (Muir 1959, cited in Čada 1990). Cavitation can also reduce turbine efficiency, which in some cases indicates an increase in fish mortality (USACE 1995). Turnpenny et al. (1992) devised a spark–gap apparatus to generate cavitation bubbles near the head and body of herring *Clupea harengus* and sole *Sloea solea*. The apparatus in Turnpenny et al. (1992) was believed to have not generated the high energy levels associated with cavitation bubble collapse that might be found in real turbines. The freshly killed fish in their study showed no injury as a result of exposure to the bubble collapse within their experimental apparatus.

A widely used non-dimensional cavitation parameter, σ, can be defined as the ratio of operating pressure conditions to the available gross hydraulic head, H, on the turbine runner. This is expressed as $\sigma = (H_{atm} - H_s - H_v) / H$, where H_{atm} the absolute atmospheric pressure (ft absolute), H_s the turbine runner setting relative to tailwater level (ft), and H_v is the vapor pressure (ft absolute). To avoid cavitation at a hydro plant, its operational σ must be higher than its critical value, σ_{cr}, where σ_{cr} is when cavitation starts to be damaging to the turbine. The highest fish survival at the Foster Project occurred when the turbine had an operational σ almost one-half to one-third the critical value (Bell 1981). Cavitation can also be minimized by properly designing the runner geometry to minimize parameters governing cavitation, which include high velocity/low pressure zones, surface irregularities, abrupt changes in flow direction, and location or submergence (Cook et al. 1997).

Tests at Lower Granite Dam indicated no significant differences in fish injury and mortality between the unit operating at best efficiency and under cavitation conditions (Normandeau Associates et al. 1995). However, since cavitation and best efficiency conditions occurred at the same flow, cavitation may have not been severe (Cook et al. 1997). Study results at Lower Granite Dam showed 2 - 6% mortality, where 19% of the observed injuries were attributed to pressure (Normandeau Associates et al. 1995).

Turbulent Shear Stress

Shear stresses in the flow field are a result of the change of velocity with respect to distance, or the rate of deformation of the fluid. Shear stress is expressed as the force acting on an area parallel to its direction (Gordon et al. 1992). The spatial change of velocity can be attributed to both viscous forces and fluid flow properties, or fluid-induced forces due to its acceleration and local turbulence (Franke et al. 1997). The highest values of shear stress are found close to the interface between the flow and solid objects it speeds by, such as the blade leading edges, vanes, and gates. The Voith team utilized CFD analysis to confirm the presence of high shear stresses at these locations (Franke et al. 1997). Fish are believed to sustain injuries, sometimes lethal, when they encounter zones of ‘damaging’ shear stress within the turbine system; injuries are dependent on fish species, size, and the manner they enter the shear zone (USACE 1995). Various researchers attempted to verify the limits of shear stress at which a fish of certain size and species sustains injury using laboratory experiments; detailed reporting on these can be found in Čada et al. (1997). Some researchers introduced fish to a submerged water jet at varying velocities, up to 120 ft/sec (Groves 1972; SWEC 1975; Turnpenny et al. 1992), and others sent fish through a 14-inch pipe with varying size nozzles at the end of it, 4 and 6 inches in two different tests (Johnson 1970a; 1970b; and 1972). Results from these experiments varied according to the test fish size, species, and method of exposure. Tests with salmonids indicated no mortality at submerged water jet velocities of 30 ft/sec (Groves 1972) or through the 14-inch pipe at nozzle velocities of 67 ft/sec and less (Johnson 1970b). Tests with alewives and smelt showed no signs of injury at jet velocities of 30 and 40 ft/sec (SWEC 1975).

Typical velocity changes across shear zones are on the order of 30 ft/sec, which is higher than velocity gradients inside Kaplan turbines (USACE 1995). Shear stress zones are also associated with vortices within the flow field. Most Kaplan turbines have gaps near wicket gates and runner blades, and leakage from these and non-optimal turbine operation produce flow separation which creates vortices with high shear stress zones (USACE 1995). Quantifying these high shear stress zones can assist in designing and operating a turbine so that shear stress zones are minimized and fish survivability is enhanced. For example, maximizing the blade tilt and matching its leading edge angle to the incoming velocity vector minimizes vortices in a Kaplan turbine, which reduces shear stress zones (USACE 1995). Vortices in the draft tube swirl also have associated shear stresses and may be a primary source of shear stress damage to fish in Francis turbines (USACE 1995).

A NEW TURBINE DESIGN CONCEPT

(Developed by ARL/NREC team)

A new "fish-friendly" turbine runner must have characteristics that are superior to existing turbine designs that are known to adversely affect fish mortality. In order to achieve that Alden Research Laboratory, Inc. and Northern Research and Engineering Corporation (ARL/NREC team) re-evaluated existing fish mortality studies and gathered information on the causes of injury to turbine passed fish; see the previous section "Biological Considerations and Design Criteria". Their evaluation of available information was used to identify criteria for designing and evaluating the new runner and its potential to pass fish without injury.

The ARL/NREC team based their concept for the new turbine runner on a commercially available pump that is used to pump fish and vegetables with minimum damage. The team used a one-dimensional computer model for evaluating the power performance and a two-dimensional computer model to develop the new runner geometry. Finally they performed three-dimensional Computational Fluid Dynamics (CFD) analyses, a mathematical modeling technique, for three design iterations of the new runner. The basic design assumptions were evaluated and operating conditions were predicted for the new turbine. The detailed calculated flow conditions were compared with the fish survival design criteria and geometric changes were made until the criteria were satisfied.

Design and Evaluation Criteria

Available information on fish injury and mortality provides an aggregate view of what happens to turbine-passed fish. Historically, mortality studies were conducted for reasons other than the establishment of quantitative design criteria to be used for fish-friendly turbines. However, several design criteria based on currently available biological information were chosen by the team to provide guidance to design, improve, and evaluate their new runner. A list of the criteria that were considered by the ARL/NREC team for design and evaluation are shown in Table 1 below.

Table 1. Criteria for design and evaluation of the new ARL/NREC fish-friendly turbine runner.

Criteria Description	Value Chosen	Reasoning
Fish-friendly turbine runner	A new runner design	Project's objective
Hydraulic design parameters	Flow ≡ 1,000 ft^3/sec (28.3 m^3/sec) Head ≡ 75 ft to 100 ft (23 – 30 m)	Representative of most hydroelectric turbines installed in the U.S., including Kaplan and Francis Tube turbines.
Turbine operating efficiency	85% minimum (3-D calculations included scroll case and draft tube)	Efficiency for most turbines peaks at 90% to 93%. 85% was chosen so the new runner can be competitive with existing designs.
Peripheral runner speed	Less than 40 ft/sec (preferably 20 ft/sec)	Reduces strike injury and minimizes shear stresses and vortices between moving and stationary parts
Minimum pressure	10 psia (68.8 kPa)	Downstream migrating fish are typically found within the top 34 ft, i.e., at 30 psia (206 kPa), and mortality occurs when pressure drop is more than 30% of acclimation pressure.
Rate of change of pressure	Less than 80 psi/sec (550.3 kPa/sec)	Assuming fish injury occurs at a pressure rate of 160 psia/sec in Kaplan turbines.
Shear stress indicator (Rate of Strain, du/dy)	Less than 15 ft/sec/in (180 ft/sec/ft OR 180 m/sec/m)	Tests of alewives, a fragile fish, at ARL with 15 ft/sec/in did not cause injury.
Number and total length of leading blade edges	Minimize	Fewer blades and shorter leading edges reduce probability of strike
Clearance between runner and fixed turbine housing components	2 mm or less	Small clearances reduce possibility of mechanical injury. 2 mm is less than the 3 mm gap chosen by the USACE for testing in a Kaplan turbine.
Flow passage Sizes	Maximize	Large amounts of water between blades should reduce abrasion injury by keeping fish away from the blades
Flow control and plant configuration (Not tested for during this phase of the AHTS project)	Maximize distance between runner and wicket gates and minimize travel time from intake to runner	Kaplan turbines are more fish-friendly than Francis turbines. A small distance between wicket gates and the runner in Francis turbines may increase the chance for abrasion and grinding injury.

Development of a New Turbine Runner

A commercially available screw/centrifugal pump impeller was selected for initial evaluation; the selected impeller was based on performance comparison of six different pump models. The chosen single-bladed impeller had a long leading edge, a large flow passage, and hardly any gaps, and has been proven safe for the transport of fish and vegetables with minimum damage (Johnson et al. 1993; EPRI 1994, and other ARL studies cited in Cook et al. 1997). The impeller is clog-free, gentle, and fairly electrically efficient (80% when used for solids handling and 75% when used for fish). Also, the combined screw/centrifugal pump is currently used in some fish diversion and bypass systems, such as the U. S. Bureau of Reclamation's Red Bluff Diversion Dam on the Sacramento River (Johnson et al. 1993 and Liston et al. 1997). Biological data from this and other studies conducted at Alden Research Laboratory, Inc. showed this pump to be effective and safe to transport live fish. An impeller model with the highest operating efficiency was chosen for the initial evaluation; an important parameter in selecting the initial geometry is for the new runner to be competitive with efficiencies of existing turbines.

The design process, using NREC's computer design software, included three stages: (1) a one-dimensional power performance model was used to obtain overall dimensions of the runner; (2) geometric design, quasi-three-dimensional flow model was used to arrive at an optimal runner shape; and (3) three-dimensional CFD analysis was used to provide an accurate assessment of flow characteristics inside the turbine and finalize the runner design.

Preliminary Design

During the preliminary design stage, the pump impeller performance in the turbine mode was analyzed. Peak electrical efficiency reached 79% at 1000 cfs, 96 ft of head, and the rotor diameter was about 22.2 ft. A new design was needed because this efficiency was well below the desired value of 85%, and the efficiency was reduced drastically when the unusually large rotor diameter was made smaller. This meant a new runner design had to be developed, and two- and three-bladed runners were compared with the large pump impeller operated as a turbine, see Table 2. Here, although Case 3 was chosen for further analysis because of the lower number of blades, Case 2 may be used if a smaller diameter runner is desired.

Table 2. Preliminary design of the new ARL/NREC runner. (Source: Cook et al. 1997)

Case	Design Description	Number of Blades	Runner Diameter (ft)	Runner Length (ft)	Rotational Speed (rpm)	Head[b] (ft)	Overall Efficiency (%)
1	Scaled up Impeller as a Turbine	1	22.2	10.8	61.2	96	79
2	New Turbine Design	3	16.2	12.3	73	84	90
3	New Turbine Design	2	17.5	13.3	68	85	89[d]

[a] Runner diameter at best efficiency.

[b] Head between scroll case inlet and tailwater.

[c] Efficiency includes estimates for draft tube and scroll case losses

[d] For Case 3, the overall efficiency would be reduced by about 1% with a 30% reduction in runner diameter (12.3 ft diameter and 9.4 ft length).

Geometric Design

Using quasi-three-dimensional flow modeling, a detailed geometric design analysis was conducted to predict the velocity and pressure distributions along the blade, hub, and shroud surfaces of a new runner. This assisted in avoiding designs that produce turbulent flows with vortices (which cause high head losses) and low pressure zones (where cavitation damage may occur). The final runner design for this conceptual phase is shown in Figure 4. Flow analyses were performed for various iterations of this design; each had two blades and a shroud attached to the blade edges. Geometric refinements were made until the overall design criteria (Table 1) were satisfactorily met by the final design. The final geometric design refinements were made with the assistance of the CFD modeling of the fluid flow inside the turbine.

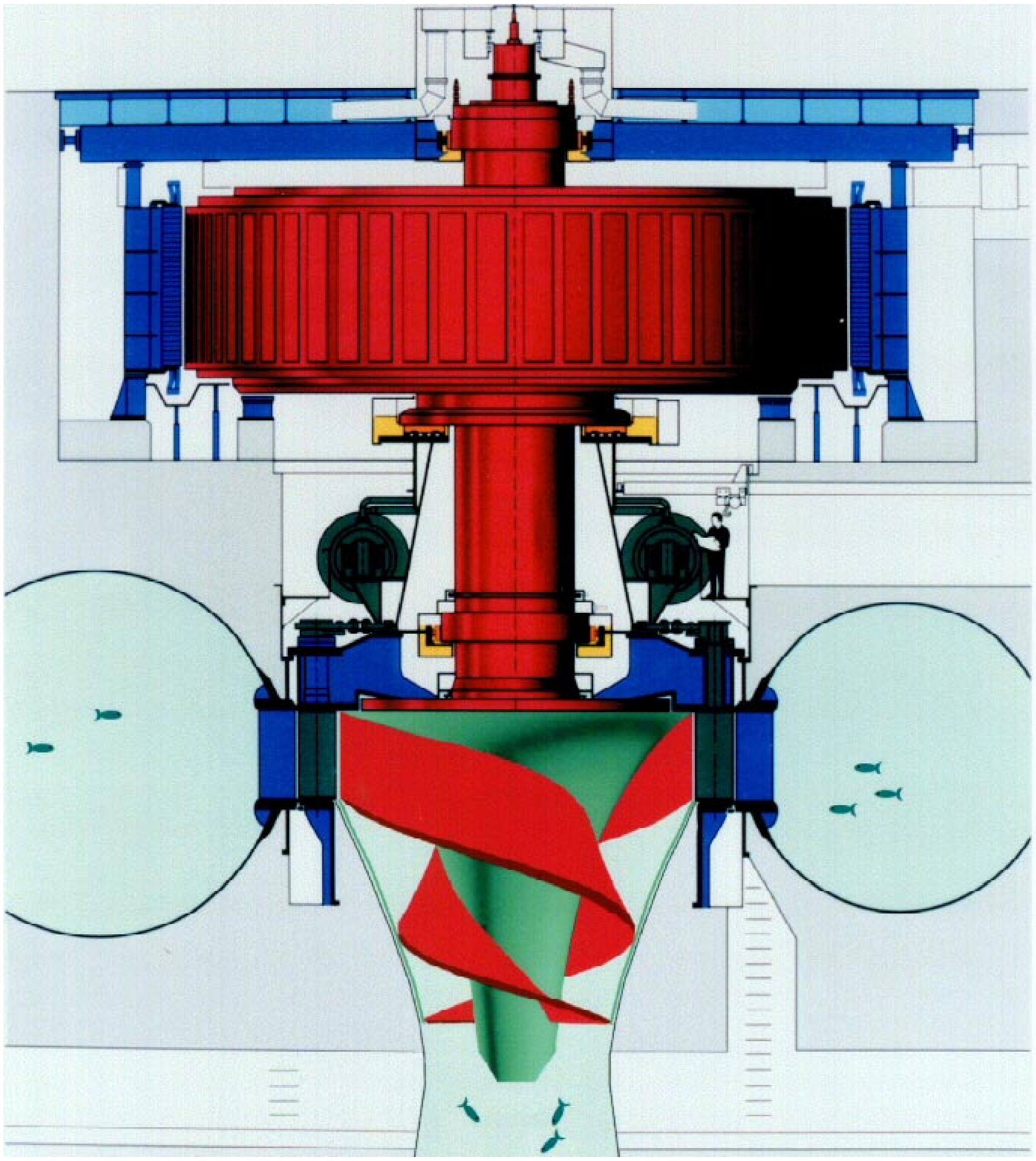


Figure 4. Schematic of the new ARL/NREC fish-friendly turbine. (Courtesy Alden Research Laboratory, Inc.)

Flow Assessment Using CFD

Once the overall dimensions were established and local refinements in the runner geometry were made to avoid severe turbulence and head loss-producing flow characteristics, VISIUN^{TM} (a 3-D CFD program developed by NREC) was used to analyze the new runner, Case 3 design in Table 2 above. CFD programs solve the complicated Navier-Stokes equations governing fluids in motion by numerically integrating flow properties, such as velocity and pressure, over very small areas within a grid system throughout the flow field. Using an iterative procedure and starting with known hydraulic boundary conditions (e.g., head, velocity, and pressure at inlet and exit), the CFD program solves the equations over the entire grid system using an iterative procedure. Finally, the results are displayed to allow evaluation and to make alterations to enhance the design.

In their flow analyses, the ARL/NREC team optimized the runner design by continuously making judgements regarding the turbine operating efficiency and fish survivability. To simultaneously satisfy both criteria sometimes created a conflict, and a "balanced design" was sought rather than favoring one aspect over the other. Design criteria outlined in Table 1 were used as guidelines to make judgements and alterations to the design. Among the chief contributing factors to optimizing the design were: (a) avoiding flow separation to minimize losses and turbulence; (b) keeping pressures above the set minimum and the rate of change of pressure was to be kept below the set value to prevent fish injury due to decompression; (c) balancing factors that may affect the peripheral speed, such as head, blade shape, runner diameter, and number and length of blades to minimize potential fish injury; and (d) minimizing high shear stress zones. Because large flow passages means lower number of blades, this led to having longer blades to extract the available energy from the flow. Also, to avoid excess loading and rate of change of velocity and pressure on the blades, they were wrapped around the hub.

Improvements were made and a final design was obtained. Results of the analyses of three different runner designs indicated that a two-bladed, 17.5 ft diameter and 13.3 ft long runner will be 90% efficient (at 84 ft head and 70.1 rpm rotational speed) and is expected to provide safe fish passage.

Satisfying the Design Criteria

The new runner had to meet the engineering and biological design criteria in order to be considered a viable new concept for further development as a fish-friendly hydropower turbine. Preliminary two-dimensional and advanced three-dimensional CFD analyses were performed to determine overall performance and flow characteristics, respectively. Important findings that resulted from this conceptual design phase of the new runner included:

- The final design was a vertical shaft runner with two blades, 17.5 ft diameter, and 13.3 ft long runner. The runner blades will be 4 inches thick with the trailing edge rounded. (The one-bladed pump impeller became unusually large and inefficient when evaluated as a turbine.)

- The turbine will have a mixed flow inlet with the inlet blade tip angle set tangent to the relative flow, and the exit blade angle set differently at the hub surface compared to at the shroud surface.

- Predicted performance efficiency was 90% at 84 ft head and 1000 cfs, exceeding the set criterion of 85%. This means this runner should be competitive with traditional turbines' operational efficiencies.
- Peripheral runner speed was 64 ft/sec. This was higher than the maximum design criterion set at 40 ft/sec. Peripheral speed is fixed by the head and runner diameter.

- The minimum flow passage was 36 in. (i.e., a sphere of 36-in. diameter can pass through the smallest zone within the runner). Because of the large amounts of water in a flow passage of this size, fish will be kept away from the blades and their injury reduced.

- A shroud was fixed to the blades' edges to rotate along with them, eliminating clearances between the runner and fixed surfaces. This eliminates the possibility of fish being caught in gaps that may cause grinding injury.

- The rate of change of velocity with respect to distance (shear indicator, *du/dy*) away from a solid boundary remained below 2 ft/sec/in., well below the maximum of 15 ft/sec/in. allowed. This was throughout the flow field outside a boundary layer, 2–3 inches thick, at the blade surfaces. Inside this layer the shear stress is not believed to increase damage to fish beyond any mechanical type injury resulting from contact with the blades.

A close look at the velocity distribution near the blade shows the flow is proceeding in the downstream direction and does not separate from the blade between the hub and the shroud, Figure 5. Further geometry refinements can still be made to reduce velocity decrements at the hub and shroud, that cause flow separation, which cause higher velocity gradients (i.e., higher strain rate and as a result higher shear stresses).

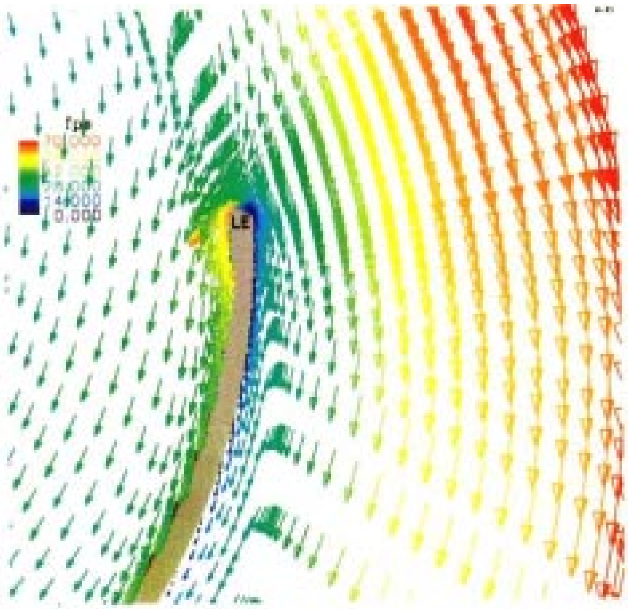


Figure 5. New ARL/NREC runner leading edge velocity distribution, shown here at mid-span between the shroud and hub. 3-D CFD results. (Source: Cook et al. 1997)

- Pressure distribution and change rate throughout the runner are important factors in assessing the turbine for engineering and biological performance. Local pressure at or below vapor pressure causes cavitation, which is undesirable in turbo-machinery and is believed to cause damage to fish. Rapid pressure changes are also believed to cause injury to fish. Pressure distribution and its decrease from runner inlet to exit were found to be reasonably uniform, Figure 6. The minimum absolute pressure, 8.6 psia, was found to be at the trailing edges of the blades. Although less than the 10 psia design criterion the 8.6 psia minimum value found was associated with only 0.0001% of the total volume of the water passing through the runner and cavitation is not expected anywhere in the runner.

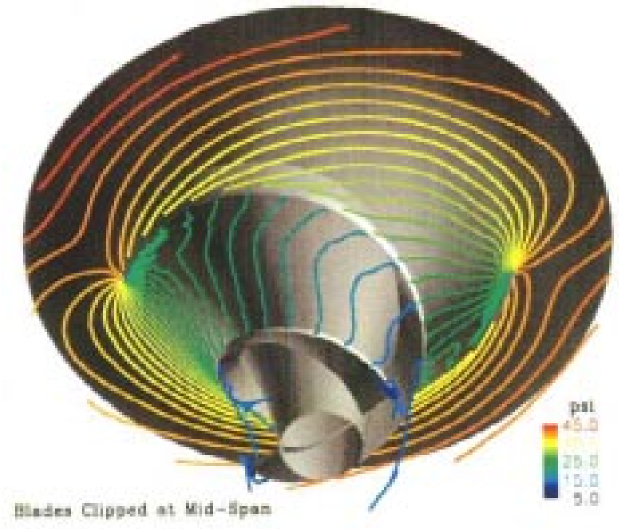


Figure 6. New ARL/NREC runner pressure contours, shown here at mid-span between the shroud and hub. 3-D CFD results. (Source: Cook et al. 1997).

About 1% of the total volume of the runner flow passages was found to experience pressure change rates greater than the maximum design criterion of 80 psi/sec. The pressure change rate remained below the limit throughout the runner except in small areas on the suction side of the leading edge of the blade, Figure 7.

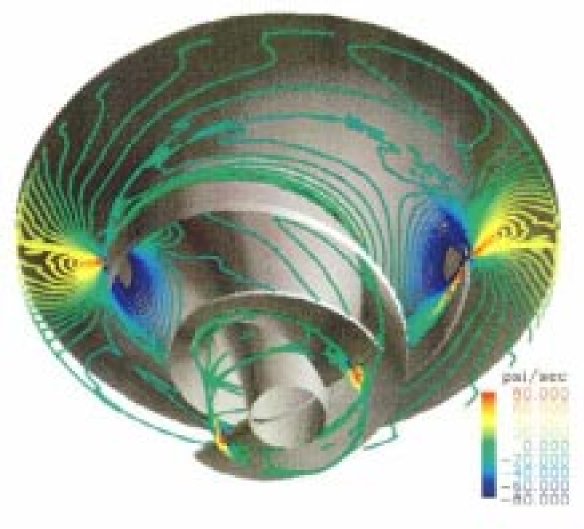


Figure 7. New ARL/NREC runner pressure change rate contours, shown here at mid-span between the shroud and hub. 3-D CFD results. (Source: Cook et al. 1997)

CFD analysis of the new runner design concept showed that it would perform well and is not likely to injure fish passing through it. It can be used to replace existing turbine runners where fish injury is of primary concern. However, a reduced power output may be the result because the new runner may not have the same flow capacity or efficiency as the outgoing one. An ideal situation for existing application is one where the plant had an open turbine bay that was designed for the purpose of plant expansion. This new runner can be used in new applications, or situations where minimum discharge requirements must be achieved by the power plant operator. It can also be used downstream of return pipes of diversion systems (e.g., flow from bypass fish screens).

There were no wicket gates or scroll case included in the analysis of the new runner. This will be accomplished in the next step of the turbine design process. It is expected that this new turbine design will have a draft tube expansion similar to that which was used during the new runner development study.

Next, to be certain of this new runner's abilities to generate power efficiently and pass fish with minimum injury, a pilot test is planned. The ARL/NREC team will be designing a 42-inch-diameter runner and test stand to be located at the Alden Research Laboratory, Inc. facilities in Holden, Massachusetts. The planned pilot test of the new runner is a cost-shared project between the ARL/NREC team and DOE's AHTS Program.

NEW DESIGN CONCEPTS FOR EXISTING AND NEW TURBINES

(Developed by Voith Hydro, Inc. and their team)

The Voith team took a different approach to accomplishing their assignment. Their objectives were broader and dealt with several environmental issues, including fish passage and water quality (i.e., dissolved oxygen). They accomplished this by assembling a multidisciplinary team to analyze existing data to guide them towards new design concepts.

Environmental Issues

The team studied various environmental issues associated with hydropower turbine applications throughout the United States. These included fish passage, dissolved gasses in turbine discharge, and minimum flows downstream of power plants. The team compiled a database on 2,555 hydroelectric dams and examined another with over 6,000 turbine manufacturers' entries. Following is a brief summary of their findings (Franke et al. 1997).

- A large share of the hydroelectric power in the U.S. is generated by low and medium head Francis turbines (about 23% of the total design discharge), mostly found in the eastern and central states. Most of the flow passes through low head axial turbines, such as Kaplan turbines, which are typical of installations throughout the Western states (31% of total power and 57% of total discharge on the West coast). In the southeast, 48% of the design discharge passes through low head axial turbines and 22% in low head Francis turbines.

- Turbine sizes were found to be evenly distributed through the U.S. (about 27-29% in each size category of 2, 2-4, and larger than 6 meter diameter). More of the smaller turbines are found in the Upper Midwest.

- Upstream and downstream passage of salmon species is a concern at hydropower sites on both the East and West coasts, anadromous American shad are important to the East coast, and passage of freshwater fish is of significance to the Upper Midwest and inland states.

- Dissolved oxygen is an important issue to the Southeast and Ohio valley states, and is considered significant for the Great Plains and Northeast.

- Dissolved oxygen and minimum flow problems were found to occur at sites with low plant factor, below 0.35. Francis turbines were found at projects with low plant factor (about 80% of the capacity and 67% of the design flow). Plant factor is defined as the yearly power produced (kWh) divided by the product of the plant capacity multiplied by the operating hours in a year.

As a result of their investigation and after consultation with the AHTS Program, the Voith team identified three specific objectives to be achieved. These consisted of providing new design improvements that can be applied to a specific turbine site to make it more environmentally friendly. The three were:

1. Provide new Kaplan turbine design features to increase fish survivability.
2. Provide new Francis turbine design features to increase fish survivability.
3. Provide new Francis turbine design features to increase dissolved oxygen in the turbine water discharge. The Voith team will submit a supplemental report on this third objective at a later date.

Design Concepts

Faced with the same dilemma of lacking biological design criteria as others (e.g., ARL/NREC team), the Voith team made use of the available fish mortality studies to aid them in providing new design concepts. The Voith team also made extensive use of CFD analyses of all aspects and components of Kaplan and Francis turbines. The team used their experience and CFD tools to further their studies and to develop an understanding of turbine flow velocity and pressure distributions and how these may lead to fish injury. Independent investigations of basic turbine flow physics and issues dealing with low dissolved oxygen and ways to mitigate it were also conducted.

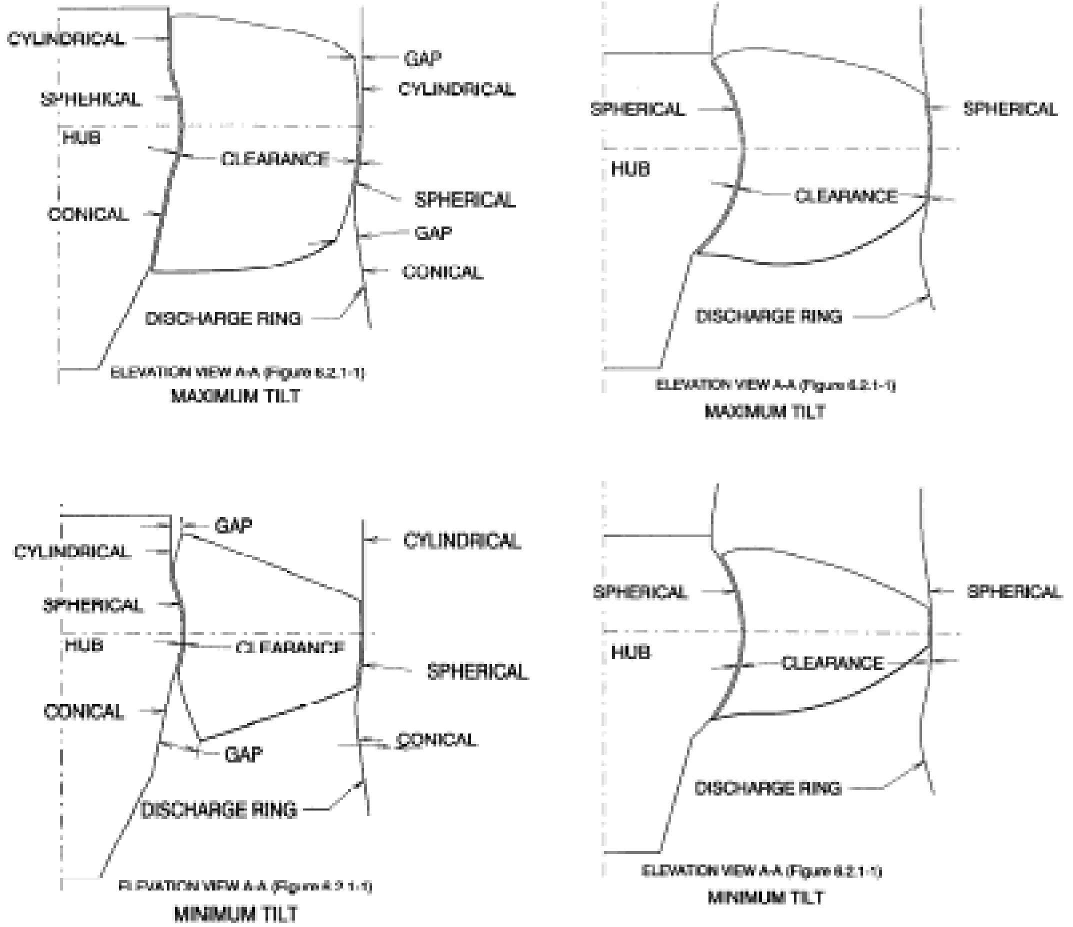
The design concepts provided here can be used for both rehabilitating existing turbines as well as new turbines in order to improve their compliance with the new age of environmental awareness and safe fish passage. These new concepts would also benefit the hydropower plant in more ways. The Voith team believes that incorporating the suggested design modifications would result in a more efficient operation; more generated power, and reduced operation and maintenance costs.

Kaplan Turbines

An environmentally friendly Kaplan turbine is one that generates power efficiently, passes fish safely, and costs less to operate and maintain. Following is a list of design concepts that was suggested by the Voith team in order to make existing and new turbine designs more fish and environmentally friendly.

1. A turbine should be operated at high efficiency with no cavitation and reduced back-roll; reducing the probability for fish injury and decreasing runner replacement costs,

2. Removing the gaps within a turbine system eliminates the added probability of fish injury and enhances the turbine efficiency. Eliminating gaps at the wicket gates or between the blades and the hub and discharge ring is believed to minimize fish injury due to grinding. Side by side comparison of a typical Kaplan runner and a fish-friendly Kaplan runner are shown on Figure 8. The gaps were removed by changing the shape of the hub and discharge ring from the cylindrical-spherical-conical shape to one that is all spherical, and recessing the blades into the discharge ring.



(a) **(b)**

Figure 8. Schematic diagrams of a typical Kaplan turbine runner. (a) runner with gaps and (b) gapless runner (fish-friendly). (Source: Franke et al. 1997)

3. Eliminate wicket gate overhang. Eliminating the overhang of wicket gates by changing the shape of the discharge ring from cylindrical to spherical results in eliminating the gaps between the wicket gates and the discharge ring. Leakage through gaps causes strong vortices with high shear stress that can potentially injure fish. Reducing the wicket gate overhang will also increase the efficiency of the power plant by reducing losses caused by the leakage at the wicket gate/discharge ring gap, see Figure 9.

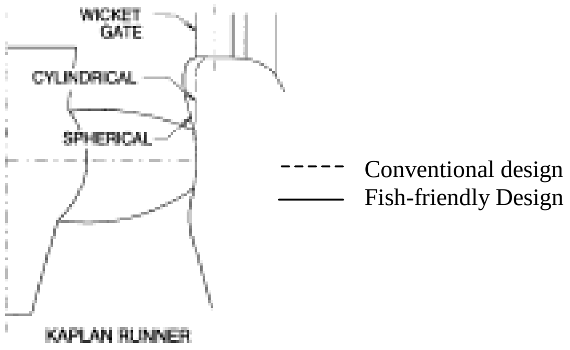


Figure 9. Elimination of wicket gate overhang in Kaplan Turbines. (Source: Franke et al. 1997)

4. Properly place wicket gates and stay vanes to minimize the potential for fish injury due to strike and flow behavior induced stresses. Use a hydraulically smooth stay vane and place it relative to the gates in such a way as to provide efficient operation of the turbine and decrease fish injury. Flow visualization tools such as CFD can help optimize the placement of these two important components of the turbine system to minimize fluid disturbances and the potential mechanical strike for different gate openings, Figure 10.

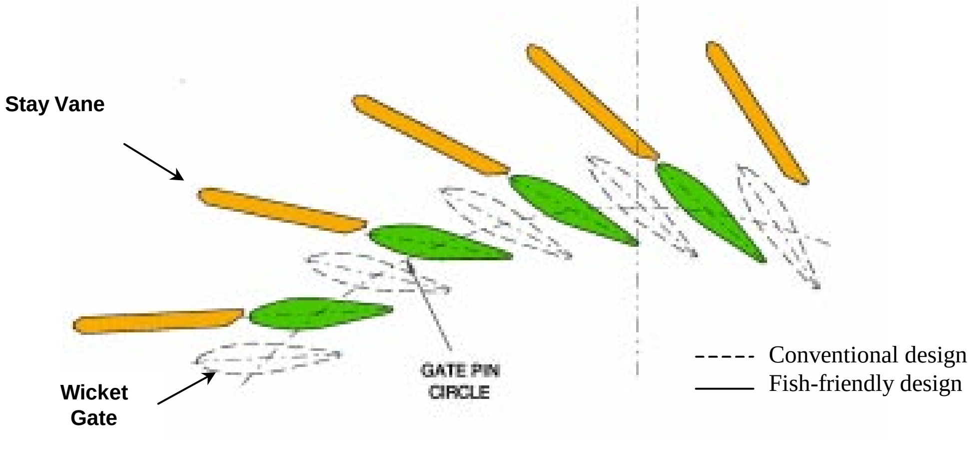


Figure 10. Locating wicket gates properly behind stay vanes maximizes efficiency and minimizes probability of strike. (modified from: Franke et al. 1997)

5. Use environmentally friendly lubricating fluids and greases. Use a biodegradable fluid in the hub and greaseless wicket gates bushings. This prevents pollutants from being discharged into the water, enhancing water quality for the aquatic habitat downstream of the power plant.

6. Polish the surfaces. Keep surfaces smooth on the turbine's stay vanes, wicket gates and draft tube cone. Welds on the various parts of a turbine system can be made smoother to reduce abrasion injury to fish, Figure 11. In certain areas where the velocity is low smoothing the surfaces and weld may not be a necessity and could be costly.

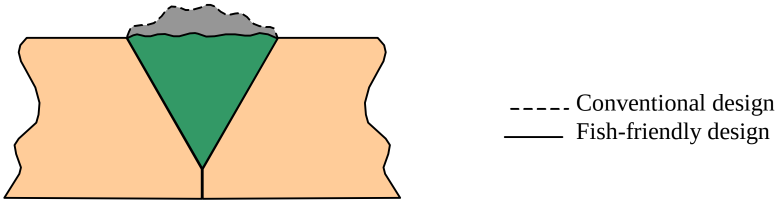
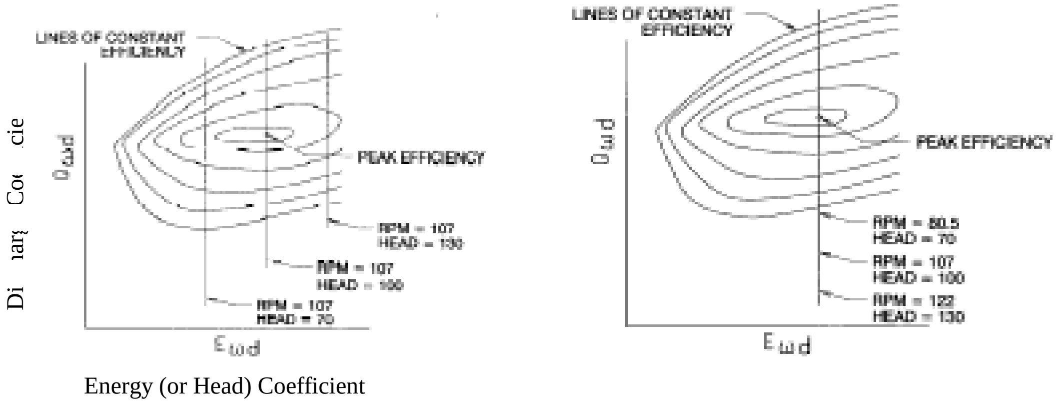


Figure 11. Schematic of a rough weld joint smoothed over for fish safety (modified from: Franke et al. 1997).

7. Use an advanced control system to operate the hydropower plant electrical components efficiently, which is also believed to be more fish friendly.

   - Runner rotational speed and generator speed can be adjusted to maintain turbine operation at the "fish friendly" point at any required discharge. Electrical conversion equipment is available to make it permissible for the turbine to operate with adjustable speeds yet maintain its peak hydraulic efficiency, Figure 12. It is recommended that the addition of this type of equipment be accompanied with a new runner upgrade at the same time.



(a) **(b)**

Figure 12. Turbine efficiency when operated with: (a) constant runner rotational speed, and (b) adjustable runner rotational speed. (Source: Franke et al. 1997)

- Ensure cam optimization to provide maximum efficiency operation and minimize flow stresses by maintaining turbine blade and wicket gates positions for maximum efficiency, and perhaps minimal fish injury.
- Install sounding devices to give warning when the trash racks need cleaning. Clean trash racks minimize flow disturbance and allow surface oriented fish to enter the intake from its upper portion, therefore minimizing blade tip strike that may occur when fish are forced to enter at the bottom of the intake.

8. Draft tube piers. Total removal of draft tube piers may not be a possibility due to structural reasons. However, design the draft tube piers to be hydraulically smooth (round nose) to reduce flow separation and possibility of strike.

Francis Turbines

An environmentally friendly Francis turbine is one that also operates at optimized hydraulic conditions. It would have a low number of blades, high efficiency with no cavitation, reduced back-roll, and would have well designed wicket gates' interaction with the discharge ring and stay vanes. These conditions are believed to reduce the probability of fish injury. Following are the primary issues to making a Francis turbine an environmentally and fish friendly one.

1. Low number of blades. This reduces the probability of strike and maximizes the size of flow passages, which also minimizes the probability of abrasion damage to fish. A lower number of blades results in having longer blades to maintain the same capacity, power production, and minimize cavitation, see Figure 13.

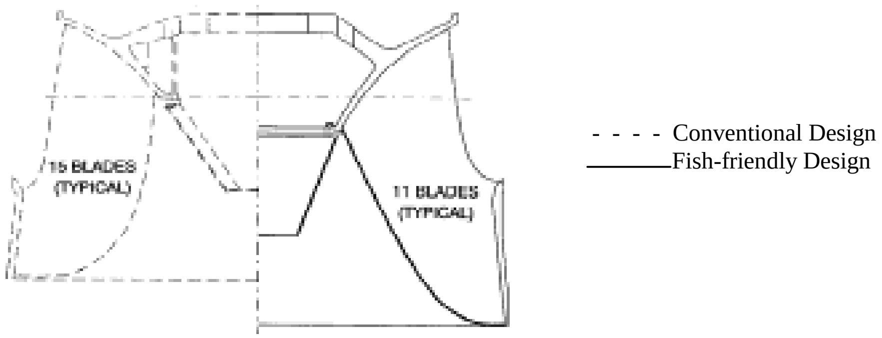


Figure 13. Resulting shape of reduced number of Francis turbine runner blades. (Source: Franke et al. 1997)

2. Use a thicker blade edge. Using a thicker blade entrance edge would produce a runner with fairly flat efficiency performance characteristics related to the head. This means entrance edge will not cavitate at high heads and flow separation may not occur. As a result injury due to flow stresses is minimized. Also, a thicker edge may

enhance the chance that fish will be carried around the edge rather than collide against it, lowering the probability of strike.

3. Reduce wicket gate overhang, increase wicket gate to runner distance, and align wicket gates with stay vanes. Eliminating the wicket gate overhang will increase the turbine efficiency and reduce gaps that cause vortices created by leakage. Eliminating the gaps is also expected to prevent fish injury due to grinding. See Figure 14. Increasing the distance between the edge of the wicket gate and the runner can be achieved by enlarging the pin circle diameter. This would also reduce the probability of the fish grinding between the trailing edge of the wicket gate and the runner, see Figure 15. Alignment of the wicket gates with the stay vanes (Figure 10), at least at one gate opening, can be achieved in existing Francis turbines but will require changes to other components in the turbine system.

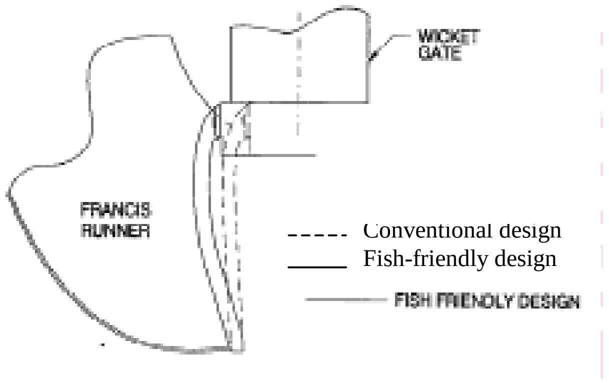


Figure 14. Elimination of wicket gate overhang by using spherical discharge ring. (Source: Franke et al. 1997)

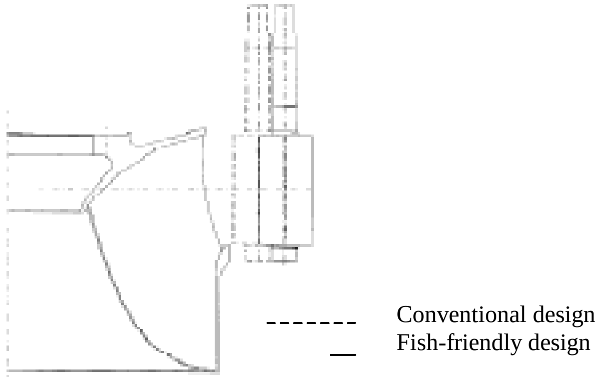


Figure 15. Increasing the distance between wicket gates and the runner. (Source: Franke et al. 1997)

4. Use greaseless and self-lubricating wicket gate bushings, where the grease is an integral part of the bushing.

5. Provide smooth surfaces on stay vanes, wicket gates and upper draft tube cone to reduce potential abrasion and descaling damage to fish. Examples include restoring damaged surfaces, use of special coatings, and reduced weld roughnesses, see Figure 11.

6. Operate the turbine with adjustable speeds. As in the case of Kaplan turbines, operating a Francis turbine with adjustable rotational runner speeds may result in reducing the probability of strike, shear stress zones, cavitation, and pressure fluctuations. Figure 12 above shows how the combination of adjustable speeds along with adjustable gates enables the turbine to operate at its optimum point at various hydraulic conditions.

7. Use an advanced turbine control system. Adjustable speeds, variable speed generator, clean trash racks, and optimized multiunit operation are important conditions to making a turbine unit more environmentally and fish friendly.

8. Minimize pressure changes experienced by turbine-passed fish. For new power plant designs it is recommended to provide fish with a passage route that minimizes sudden changes in pressures. Figure 16 shows the difference between a conventional plant design (Figure 16a) and one that is more fish friendly (Figure 16b). In Figure 16a fish would be acclimated at high pressures prior to entering the penstock and are exposed to much lower pressures on the downstream end of the turbine in a very short period of time. However, in Figure 16b a safer route would be provided; fish would travel from a zone of low acclimation pressure, through higher pressures for a short time, and back to a low pressure region within the tailrace. Figure 17 also shows another pressure related fish-friendly design. Here (Figure 17a), the fish are in the pipe for a long period of time and would acclimate to the high pressure inside the pipe, only to experience sudden reduction in pressure after passing through the turbine. This may cause injury due to sudden decompression. In the fish-friendly design shown in Figure 17b, the fish remain at low pressure in the pipe, travel through high pressure regions for a short time, and go back to the low pressure in the tailrace.

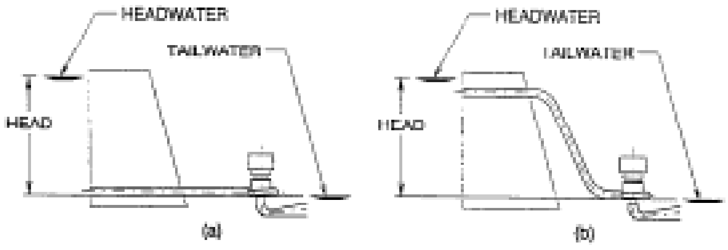


Figure 16. Providing mild pressure changes in short penstocks. (Source: Franke et al. 1997)

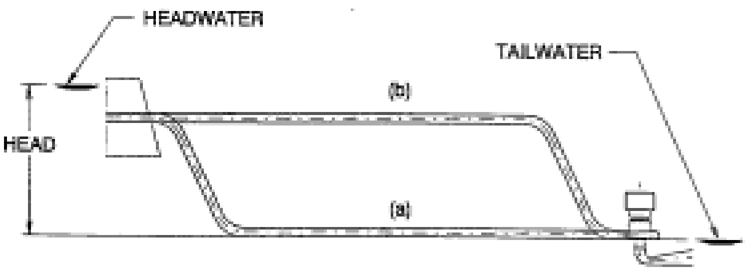


Figure 17. Providing mild pressure changes in long penstocks. (Source: Franke et al. 1997)

Francis Turbine with Increased Dissolved Oxygen

A supplemental report will be submitted at a later date by Voith Hydro, Inc. The report will include design concepts relating to aerating Francis turbines to increase dissolved oxygen in the turbine discharge. Voith will also include a discussion on using advanced CFD modeling of test conditions at Wanapum Dam.

CONCLUSIONS

DOE's Advanced Hydropower Turbine System Program achieved its initial objective. Two contractors provided new turbine system design concepts that can be utilized in the development of new hydropower turbines as well as rehabilitating existing facilities. The ARL/NREC new runner design concept predicts efficient power generation and fish friendliness. If successful, Voith's new concepts would also make it feasible to obtain power efficiently while making new and existing traditional turbines more environmentally and fish friendly.

The next step is moving forward with prototype testing of the new design concepts to demonstrate their effectiveness. DOE and the ARL/NREC team have initiated steps to design and test a prototype turbine similar to the one described in this report. The new ARL/NEC turbine will be hydraulically and biologically evaluated at the Alden Research laboratory, Inc. facilities in Holden, Massachusetts. Voith Hydro, Inc. is in the process of testing some of their new design concepts already implemented at power plants in the Pacific Northwest, such as at the Wanapum Dam on the Columbia River, in Washington.

Once a proof of concept test has been conducted and results are favorable, DOE hopes to issue a Request for Proposals for final engineering design and full-scale prototype testing at an existing hydropower facility. If funding is available, this activity is planned to start during the fiscal year 2000.

GLOSSARY OF TERMS

** (Modified from Cook et al. 1997 and Franke et al. 1997) **

Abrasion damage - Damage to fish resulting from rubbing contact with moving or stationary objects in a turbine flow passage (USACE 1995).

Absolute pressure - Atmospheric pressure plus gauge pressure.

Anadromous fish - Fish that ascend rivers from the sea to breed.

Atmospheric pressure - The force per unit area of air; varies with elevation; at sea level atmospheric pressure (1 atmosphere) equals 14.7 psia (101.3 kPa).

Best efficiency point - The operating point at which a turbine produces the highest ratio of power output relative to the flow through the unit and the net head across the unit.

Bulb turbine - Axial flow turbine that has the generator, enclosed in a bulb-shaped housing, within the water passage to the runner (USACE 1991).

Cavitation - Formation and implosion of water vapor bubbles that occur in water. The formation occurs when local pressure is reduced to vapor pressure.

Cavitation Coefficient - The ratio of operating pressure conditions to the available gross hydraulic head, H, on the turbine runner; $\sigma = (H_{atm} - H_s - H_v) / H$, where H_{atm} the absolute atmospheric pressure (ft absolute), H_s the turbine runner setting relative to tailwater level (ft), and H_v is the vapor pressure (ft absolute).

Clupeid species - Family of fish that includes several anadromous species such as alewife, blueback herring, and American shad.

Critical sigma - The runner sigma at which cavitation is initiated; the value of critical sigma is lower than the value of plant sigma, with the difference representing the margin of safety against cavitation.

Decompression - Lowering of pressure from the value at which fish are acclimated.

Discharge coefficient - $Q_{\omega d}$ is dependent on the turbine discharge, Q, the rotational speed, ω, and the turbine diameter, D. Where: $Q_{\omega d} = \frac{Q}{\omega D^3}$.

Discharge ring - The stationary cylinder surrounding the blades.

Francis turbine - A reaction turbine, named for the inventor, in which water passes through the runner first in a radial and then axial direction.

Grinding damage - Damage to fish drawn into narrow gaps between turbine components. "Gap damage" to fish is considered to be the same as grinding damage.

Head coefficient - OR Energy Coefficient, $E_{\omega d}$, is dependent on the net head, H, the acceleration of gravity, g, the rotational speed, ω, and the turbine diameter, D.
Where: $E_{\omega d} = \frac{gH}{(\omega D)^2}$.

Kaplan turbine - A propeller turbine, named for the inventor, with runner blades which are adjustable in angle when the unit is in operation (adapted from USACE 1991). Flow downstream of the wicket gates is turned in an axial direction prior to reaching the runner.

Leading edge - The edge of the runner blade on the upstream side of the runner.

Leakage - Flow through gaps between rotating and stationary turbine components.

Mechanical injury - Damage to fish resulting from abrasion, grinding, and/or strike (as defined elsewhere) on turbine rotating or stationary components.

Naturally-entrained - Fish that were present in a water body and have passed through a hydraulic turbine on their own volition.

Navier-Stokes equations - The set of partial differential equations that govern the unsteady, incompressible, viscous flow of fluids.

Peripheral runner speed - The speed at which the outside edge(s)of the runner travels (tip speed).

Plant sigma - The value of sigma for the site conditions and turbine setting.

Pressure damage - Damage to fish resulting from increases or decreases in the pressure from values to which the fish have acclimated.

Pressure Surface - The side of the runner blades with higher pressure than the other side.

Rotational Speed – Turbine runner rotational speed, ω. Where: $\omega = RPM \cdot \frac{2\pi}{60}$.

Runner sigma - The value of sigma at referenced to a particular place elevation of the runner; usually calculated at the centerline or bottom of the runner in a vertical axis turbine, or at the highest point of the runner in a horizontal axis turbine.

Shear damage - Damage to fish resulting from their passing through regions of rapid velocity changes (shear zones).

Shear zone - Adjacent flow regions in a turbine having different velocities.

Shroud - Surface of revolution associated with the tips of the turbine blade.

Sigma - A non-dimensional parameter (σ) representing pressure conditions at a turbine runner; the ratio of the pressure above vapor pressure on the underside of the runner and the total pressure across the runner.

Strike damage - Damage to fish resulting from their direct collision with rotating or stationary turbine components.

Suction surface - The side of the runner blade with lower pressure than the other side.

Turbine efficiency - Percent of useful shaft power developed relative to hydraulic input power.

Turbine (runner) setting - The runner elevation relative to the tailwater level.

Vapor pressure - Pressure at which water vaporizes (boils); varies with water temperature.

Velocity Shear Stress - Stresses in the flow field resulting from the change of velocity with respect to distance, or the rate of deformation of the fluid. Shear stress is expressed as the force acting on an area parallel to its direction.

Vortex - Water flowing in a well defined circular motion with a lower pressure in the center; vortices may be caused by flow disturbances at the runner's leading edge and by leakage through gaps (USACE 1995); vortices in the turbine draft tube are caused by residual swirl leaving the runner (USACE 1995).

Wicket gate - One of a series of gates in the flow passage leading to the runner which regulates quantity and direction of water; the series of movable, flow-regulating gates impart rotation to the flow (adapted from USACE 1991).

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