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SUMMARY OF ENVIRONMENTALLY FRIENDLY TURBINE DESIGN CONCEPTS

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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.

1. 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.

2. 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 behaviour and damage to a specific injury mechanism.

3. A NEW TURBINE DESIGN CONCEPT

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 modelling 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.

4. 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.

5. 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; Cada 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.

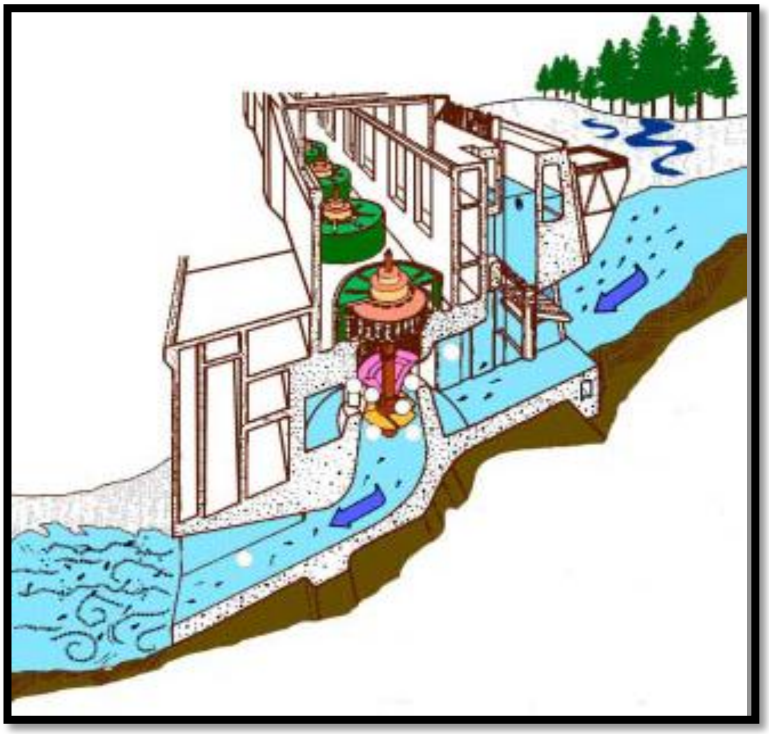


figure 1.schematic diagram showing locations within a turbine system

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 (Cada et al. 1997 and Cada 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 Cada 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 intake

6. 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 cavitations 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 enhance

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

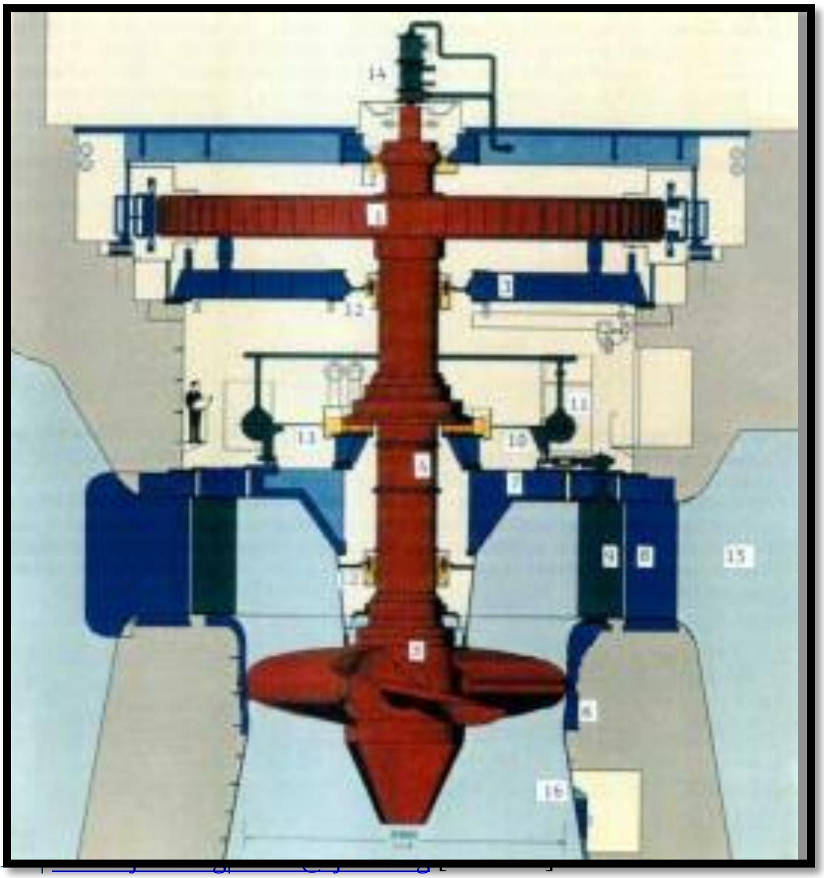


Fig. No.2- Kaplan Turbine

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, 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.

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,

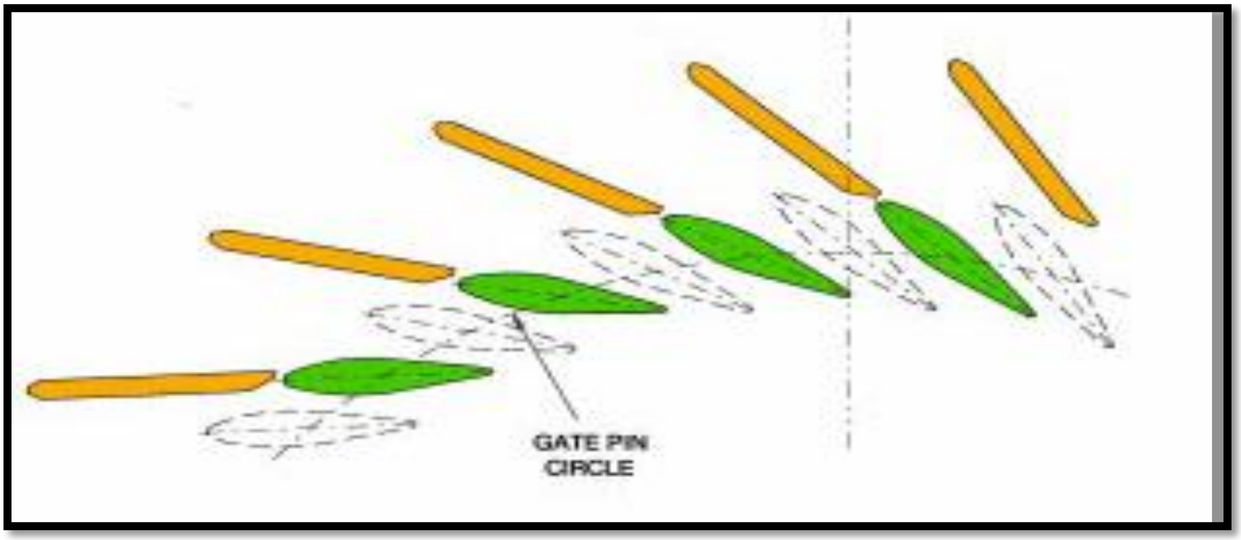


Fig. No 3. LOCATING WICKET GATES PROPERLY BEHIND STAY VANES MAXIMIZES

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.

7. FRANCIS TURBINE

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. to making a Francis turbine an environmentally and fish friendly.

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.
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. 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. Alignment of the wicket gates with the stay vanes at least at one gate opening, can be achieved in existing Francis turbines but will require changes to other components in the turbine
4. Use greaseless and self-lubricating wicket gate bushings, where the grease is an integral part of the bushing.

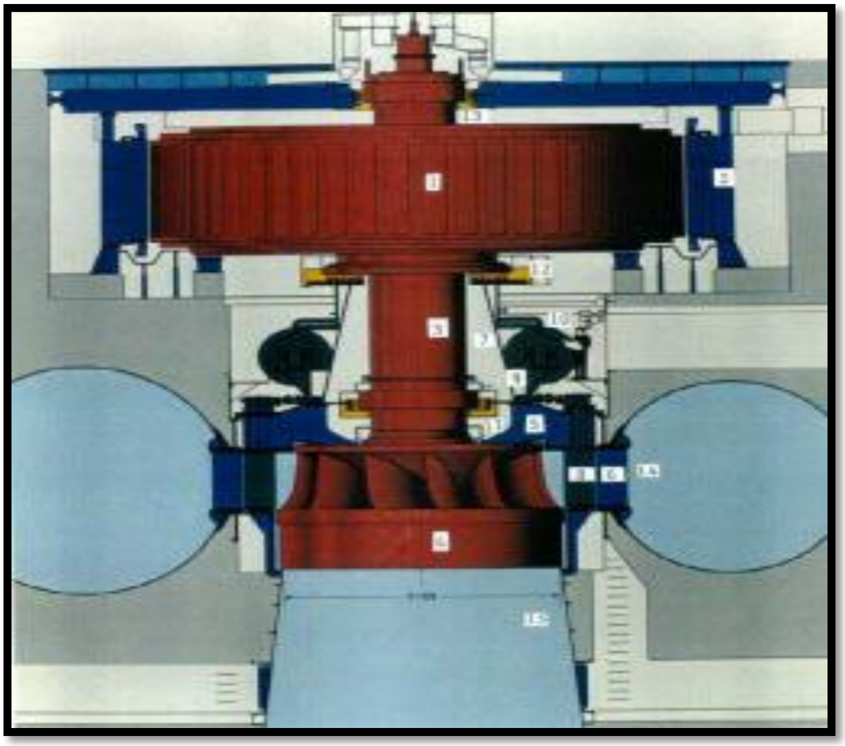


Fig. no. 4: Francis Turbine

5. Provide smooth surfaces on stay vanes, wicket gates and upper draft tube cone to reduce potential abrasion and descaling damage to fish.

6. Use of advance turbine control system, adjustable speed, variable speed generator clean trash racks.

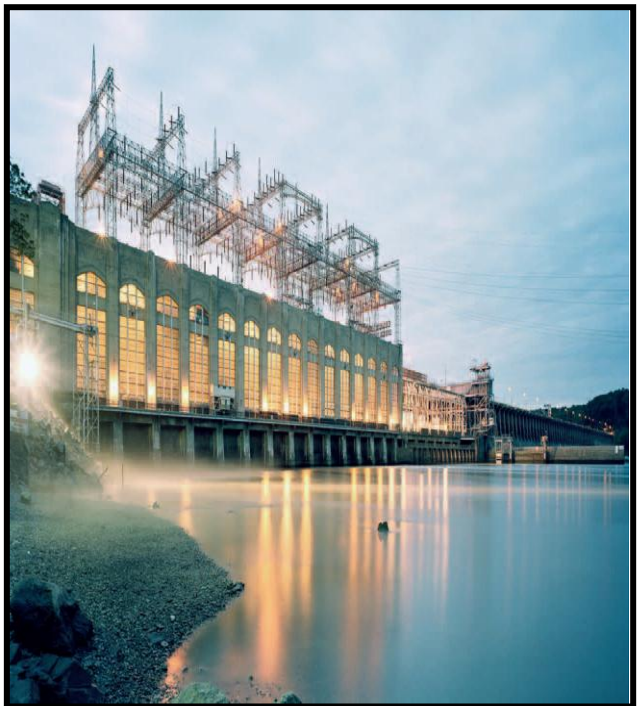
8. ENVIRONMENTAL ISSUES

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.

9. IMPROVING WATER QUALITY

Aerating Turbine Technology



Over the years, Vomit Hydro has become leader in providing aeration solutions that improve environmental compatibility through the increase of dissolved oxygen uptake downstream of hydro power facilities. These advancements address common issue faced by hydro power producers: the need to improve water quality, specifically dissolved oxygen content, as water is discharged from existing and new hydroelectric equipment. The water in the lower reaches of many reservoirs is oxygen deficient, and passing this low dissolved oxygen water through a hydro site can result in damage to downstream ecosystems. Often, low pressure regions below the runner can be utilized to draw atmospheric air into the turbine during operation. These machines are referred to as auto-venting turbines (AVT) and are particularly cost-effective for injecting large quantities of air into the discharge.

10. ADVANTAGES AND DISADVANTAGES

10.1. ADVANTAGES

1-It is a renewable source.
2-Fish ladders or coils can be built so fish are not harmed.
3-It is cheap way to get clean energy.
4-A turbine is a low velocity and high efficiency.

10.2. DISADVANTAGES

1-It is expensive to build a dam.
2-You need a good ,wide ,clean, fast flowing river ,which are sometime hard to find or not available.

11. 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.

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