STATUS OF THE U.S. DEPARTMENT OF ENERGY'S ADVANCED HYDROPOWER TURBINE SYSTEMS PROGRAM

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ABSTRACT

Hydropower-related research and development within the U.S. Department of Energy (DOE) is focused on enhancing the environmental performance of hydroelectric generating systems. DOE's Advanced Hydropower Turbine Systems Program was started in 1994 as a partnership with the hydropower industry, represented by the National Hydropower Association, individual utilities, and EPRI. Targeted improvements in environmental performance include greater survival of fish passing through turbines, higher dissolved oxygen levels in tailwaters, and more beneficial flow regimes downstream of powerhouses. Current activities involve laboratory, field and computational studies in a coordinated effort to improve fish survival in turbines. Accomplishments to date include new conceptual designs for turbines, better understanding of biological criteria for design, and improved sensor technology for measuring the physical conditions inside working turbines.

INTRODUCTION

Hydropower poses a unique challenge in energy development, because it combines great benefits with some difficult environmental challenges. Techniques for producing hydro electricity from falling water have existed for more than a century. Hydroelectricity has tremendous advantages over other energy sources: it is a reliable, domestic, renewable resource with large undeveloped potential, and it emits essentially none of the atmospheric emissions that are of growing concern, such as greenhouse gases. Hydropower projects can provide substantial nonpower benefits as well, including water supply, flood control, and recreation. Unfortunately, the benefits of hydropower are often offset by adverse environmental impacts (e.g., Mattice, 1991).

One of the strategic missions of the U.S. Department of Energy (DOE) is to ensure that the nation has a clean and reliable energy supply, adequate to meet its current and future needs. Hydropower will have a role in that future, if its environmental problems can be overcome. Consistent with the Comprehensive National Energy Strategy of 1998, DOE is striving to maintain the viability of existing

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hydropower sources by working with industry to develop hydropower technology with improved environmental performance. In recent years, the major component of DOE's hydropower research and development (R&D) has been its Advanced Hydropower Turbine Systems (AHTS) Program, that was created with the objective of developing new, environmentally compatible hydropower turbine systems (Brookshier et al. 1995). This paper describes the background, current organization and activities, and planned future directions of the AHTS program.

BACKGROUND

The original concept for an advanced hydropower turbine arose from a meeting of DOE, EPRI, and the Research and Development Committee of the National Hydropower Association (NHA) in Denver in February 1993. Shortly thereafter, NHA formed a non-profit organization called the Hydropower Research Foundation, Inc. (HRF) to support this kind of research. Later in 1993, NHA and HRF assembled financial contributions from nine utility members and from EPRI into $500,000 to support joint research on advanced turbines. DOE agreed to match these industry contributions, producing a $1 million fund to support the first phase of advanced turbine development.

The current AHTS program is managed by DOE, through its Idaho Operations Office, in consultation with HRF. A unique aspect of the program is the collaborative management structure that has been set up and the interactions between engineering and environmental aspects of hydropower design. All program activities are overseen by an interagency Technical Committee comprised of engineers and environmental scientists representing a wide range of interests. The Committee currently includes ten hydropower industry representatives and personnel from the U.S. Army Corps of Engineers, the Bureau of Reclamation, the U.S. Geological Survey, Bonneville Power Administration, the National Marine Fisheries Service, and the Nez Perce Indian Tribe. Staff from Idaho National Engineering and Environmental Laboratory (INEEL) and Oak Ridge National Laboratory (ORNL) serve as *ex officio* members of the Committee and provide other technical support to DOE in managing the program. The Technical Committee provides several important functions, including program guidance, technical review of ongoing activities, coordination of related industry activities, and the development and evaluation of Requests for Proposal. The Committee structure reflects DOE's commitment to independent peer review and interagency cooperation in all of its research and development activities.

PROGRAM GOALS

The overall goal of the DOE AHTS program is to improve the overall performance and acceptability of hydropower projects by developing and demonstrating advanced technology that reduces or eliminates adverse environmental effects. The highest priority environmental problems are: 1) injury and mortality to fish as they pass through turbines, 2) low dissolved oxygen downstream of the dams, and 3) altered stream flows and associated habitat for aquatic organisms. The hydropower "system" that the current DOE program is concentrating on is defined by that area between the forebay of turbine inflows and the exit of the turbine's draft tube. We plan to expand these system boundaries in the future, as Congressional direction and funding allows.

RECENT ACCOMPLISHMENTS

The AHTS program's accomplishments to date include evaluations of current mitigation practices, literature reviews, and the development of conceptual turbine designs. The precursor to DOE's advanced turbine research was a series of Environmental Mitigation Studies (EMS) that were conducted to identify the most important R&D areas related to the hydropower industry. The first EMS report (Sale et al. 1991) was based on a detailed survey of environmental issues confronted by hydropower projects licensed in the 1980s. This identified instream flow requirements, fish passage requirements, and the need for dissolved oxygen enhancement as the most frequent practices. Another issue that was identified was the serious lack of information needed to quantify the performance and effectiveness of all types of mitigation at hydropower projects. The second EMS report concentrated on fish passage technologies (Frankfort et al. 1994), describing the available technologies, resources and economic requirements and other ramifications of mitigation choices. Subsequent reports in the EMS series were deferred due to lack of funding.

Literature reviews were conducted on fish passage issues to begin filling the information gaps. „ada et al. (1997) reviewed the science related to turbine-passage injury mechanisms and proposed biological criteria that could be used in design of new turbines. The primary injury mechanisms are pressure, cavitation, shear/turbulence, and mechanical injury. More recently, Coutant and Whitney (2000) have updated this review with specific attention to fish behavior and how it should be represented in the modeling of turbine systems. These studies provide an important basis for subsequent parts of the DOE program.

The first direct products from the AHTS program were conceptual designs for advanced turbines that were completed in 1997 (two contract reports by Cook et al. 1997 and Franke et al. 1997; summarized in Odeh 1999). Competitive awards were made in October 1995 to two research groups: 1) a team of Alden Research Laboratory and Northern Research and Engineering Corporation, and 2) a team lead by Voith Hydro Inc., including Harza, the Tennessee Valley Authority, RMC Environmental Services, and Georgia Institute of Technology (Georgia Tech). These winning proposals took two very different approaches to the AHTS goals. The Alden proposal planned to develop a completely new turbine design, beginning with a commercially available Hidrostal pump impeller. The Voith proposal took as its starting point existing technology and planned to make incremental improvements on three different designs.

The Alden team's research approach (Cook et al. 1997) is an excellent example of the spirit of AHTS program and its intended research process: i.e., first identification of biological design criteria, then design hydroelectric generating equipment aimed at operating within those constraints. Alden's first step was to identify biological performance goals that would avoid adverse effects to fish (Figure 1). Using these design criteria and the general Hidrostal impeller shape, Alden then applied a series of computational fluid dynamic (CFD) models to evaluate changes in runner geometry. The end result is a 2-bladed runner design that promises to produce hydroelectricity at a competitive efficiency (~90%) and minimize the stresses to fish that pass through the turbine.

Preliminary Design Criteria

- runner tip velocity < 40 ft/sec
- minimum pressure < 10 psia
- pressure gradient < 80 psi/sec
- velocity gradient < 15 ft/sec/inch
- clearance in flow passage < 2 mm
- maximize flow passage width
- minimize number/length of blades

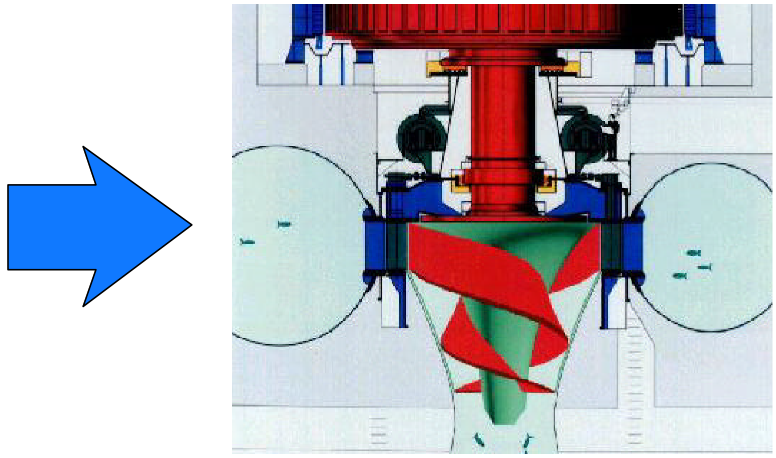


Figure 1: Alden's design process, starting with biological design criteria and ending with a new hydropower turbine concept.

The Voith team's approach was more broad than Alden's. It was organized around four tasks: 1) a study of environmental issues and turbine applications across the U.S. to identify three specific areas of turbine design for further study; 2) an examination of the most current information on fish response to turbine passage to see where performance can be improved; 3) application of CFD modeling to explore turbine modifications that can be made; and 4) specification of three new design concepts for advanced turbines.

The products of the Voith team (Franke et al. 1997) are in three areas: 1) improvements to Kaplan turbines for improved fish survivability, 2) improvements to Francis turbines for improved fish survivability, and 3) augmentation of dissolved oxygen in Francis turbines. The Voith results are targeted at rehabilitation of existing turbines with heads of 10 to 50 feet. The Voith efforts also examined how advanced instrumentation and control systems can be used to improve operation for both hydraulic and environmental performance. Some of the DOE-funded research results are reflected in Voith's latest designs for the Minimum Gap Runner (MGR) (Fisher et al. 2000).

To assist interagency cooperation and coordination, „ada and Rinehart (2000) have recently described the ongoing and planned R&D activities across the U.S. related to survival of fish entrained in hydroelectric turbines. This report identifies studies that are intended to develop new information that can be used to mitigate turbine-passage mortality. The review focused on the effects on fish of physical or operational modifications to turbines, comparisons to survival in other downstream passage routes (e.g, bypass systems and spillways), and applications of new modeling, experimental, and technological approaches to develop a greater understanding of the stresses experienced by fish during passage through turbines.

CURRENT ACTIVITIES

The current activities in the AHTS program have multiple components:1) laboratory studies, 2) field studies, and 3) computational studies. These three research directions complement each other and provide insights that would not be possible with a more unilateral approach. For example, our computer modeling is leading to a better understanding of the trajectories of fish inside turbines, an important factor influencing survival rates which cannot be measured directly. Similarly, the laboratory experiments are providing biological responses under controlled situations which cannot be directly measured in the field or modeled with existing information.

Laboratory Studies

In the laboratory arena, there are two main activities underway: 1) further design and pilot-scale testing of the Alden fish-friendly turbine concept, and 2) biological studies of how fish respond to various levels of shear and pressure inside turbines. The work on a prototype of the Alden turbine is a continuation of the first AHTS competition. In the first half of 2000, full engineering designs were completed for a test facility and construction of a scaled-down version of a new turbine following Alden's conceptual design. These designs are necessary to construct the project for the proof-of-concept test phase. The Alden prototype will be large enough to run live fish through it to evaluate its ability to pass downstream migrants successfully. In the second half of 2000, construction of the test facilities and building of the pilot-scale runner (about 1/3 scale) will be initiated. Construction and testing of the Alden prototype will continue into 2001 and beyond.

A better understanding of the physical conditions that injure fish is needed to provide the information or specifications that engineers should consider in the design of a turbine system. The second major set of laboratory studies being supported by the program is examining the biological effects of shear, turbulence, pressure, and gas supersaturation levels found inside hydropower turbines. These studies are being conducted at DOE's Pacific Northwest National Laboratory (PNNL) to further define the design criteria for new turbine technology (Neitzel et al. 2000). To study how fish respond to shear and turbulence inside turbines, a test flume was built in which fish could be exposed to a water jet, simulating the turbine environment (Figure 2). These laboratory studies are

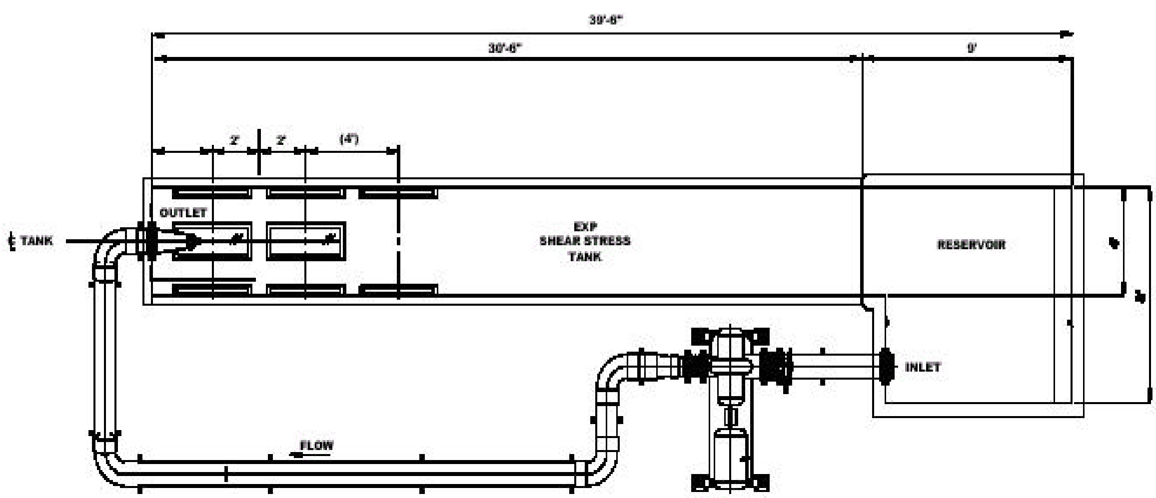


Figure 2: Plan view of the DOE shear test flume operating at PNNL.

demonstrating that specific biological responses are related to specific shear stresses (expressed as a strain rate) and that a “no effect” level can be estimated that is species-specific (i.e., results differ between salmonids and American shad).

Field Studies

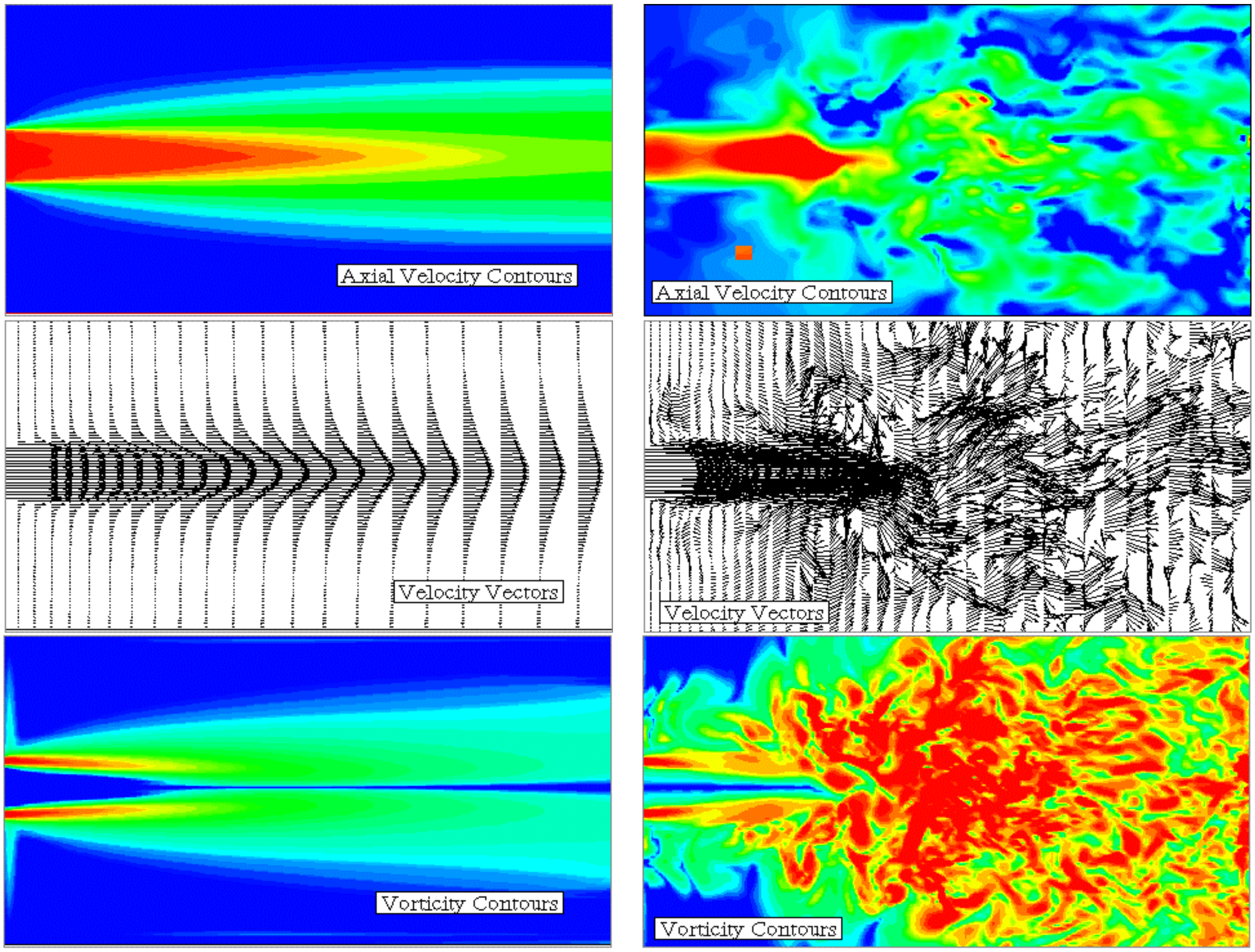
The field studies that are supported by the AHTS program involve measuring the success of new turbine installations to pass fish without excess mortality and developing new technology to measure the physical stresses inside real turbines. The DOE program is providing co-funding to the U.S. Army Corps of Engineers (Corps) fish passage tests at the Bonneville Dam on the Columbia River. These tests are evaluating Voith's MGR design, parts of which were developed in the earlier stages of the AHTS program.

In other field studies, a micro-sensor-equipped surrogate fish (sensor fish) is being developed as an alternative to testing live fish in the turbines. The smolt-sized artificial fish was developed by PNNL to better understand, in physical terms, the passage conditions that occur within a turbine. The sensor fish is instrumented to measure and record pressures, strain, temperature, bending moments, acceleration and other hydraulic parameters experienced during passage. Like real fish, it was attached to a balloon tag, introduced into the turbine flow at Bonneville Dam, and recovered downstream. An upgraded version of the sensor fish will be developed from the information obtained from these initial tests, from test data from real fish, and through the addition of emerging sensor technology.

Computational Studies

The DOE AHTS program is supporting two computational studies to help translate results from the testing in the PNNL test flume into the real world. Georgia Tech and Voith Hydro are conducting new computational fluid dynamics (CFD) simulations of experimental tests in turbulent jet flows. This research is designed to better understand the physical stresses that fish experience as they pass through hydroelectric turbines, to refine the previous CFD analyses of existing turbines, and to derive new design guidance for advanced turbines. These CFD studies complement the other lab and field studies and vise-versa.

The work at Georgia Tech uses two CFD modeling approaches: (1) steady 3-D Reynolds-Averaged Navier-Stokes (RANS) equations coupled with advanced, non-isotropic turbulence models and (2) unsteady simulations using the Very Large Eddy Simulation (VLES) approach, which solves non-linear, two-equation RANS equations of turbulent flow. Figure 3 illustrates the differences between steady and unsteady hydraulic conditions in the test flume that the Georgia Tech research is working to describe. Additional software, the Virtual Fish (VF) model (another product from earlier stages of the AHTS program), will be used with the steady flow simulations to estimate flow-induced loads on test organisms. The VF model encompasses a set of algorithms and numerical techniques that allow the prediction of fish trajectories through a power plant by the numerical solution of the equations of motion of a statistically adequate number of fish. The VF estimates of stress will be compared to the response of live organisms in the DOE shear test flume.



Time-Averaged Turbulent Flowfield for Re = 200,000

Instantanteous Snapshot of the Turbulent Jet for Re = 200,000

Figure 3: Comparison of steady (left side) and unsteady simulations of the DOE shear test flume *(computational fluid dynamics modeling by Fotis Sotiropoulos, Georgia Institute of Technology)***.**

The objective of the work at Voith Hydro is somewhat different from Georgia Tech. The specific objective of this subcontract is to relate velocity field conditions inside existing turbines with the velocity fields in tests being conducted in the DOE shear test flume. The work provided will apply AEA TascFlow software, a commercially available, state-of-the-art 3-D viscous CFD code, to model the experimental flume, and then correlate these computed hydraulic stresses with those predicted in existing analyses for turbines at the Wanapum Dam on the Columbia River in Washington. The VF model will also be used with the 3-D viscous simulations to estimate flow-induced loads on test organisms. This work will be coordinated with parallel research at Georgia Tech to allow comparisons of velocity fields and VF predictions that are based on different CFD methods, thereby providing better understanding of the value of alternative approaches.

FUTURE ACTIVITIES

There is much unfinished business in the hydropower R&D arena. Although DOE's future activities will be subject to Congressional funding and direction, here are some of the areas that may be pursued:

- *Synthesis and integration of AHTS results* -- data and model intercomparisons of results from current studies to extract the best possible design criteria for further development of fish-friendly turbines.

- ***Testing of Low Head/Low Power Fish Friendly Turbine Technology*** -- testing of new low head/low power turbine technology to evaluate its environmental performance. This technology to be tested must be developed to a stage that hardware exists or can readily be constructed, i.e., design has been completed. The effort is to identify new technology with fish passage characteristics that has not been part of the current AHTS program.

- ***Additional Environmental Mitigation Studies for Instream Flow; Fish Passage Through Reservoirs; and Dissolved Oxygen*** -- studies to address instream flow requirements and benefits, fish passage issues through the reservoir system, and dissolved oxygen water quality issues. These items have been identified by the hydropower industry as high priority issues (HCI 1992). Other topics that may be pursued include protection of wetlands and riparian ecosystems, recreation and aesthetics, terrestrial habitat, and dam decommissioning.

- ***Stay Vanes/Wicket Gate Relationship Study*** -- study of the hydraulic relationship of the stay vanes and wicket gates to the turbine design changes. This will assist in the investigations of improving fish passage through Kaplan turbines.

- ***Full Scale Testing of New Fish Friendly Turbine Concepts*** -- full scale testing of new turbine concepts that have been developed outside of the DOE AHTS Program. This effort will be cost shared by DOE and would test the fish friendly characteristics of the turbine technology.

- ***Biological design criteria for draft tubes and tailraces*** – additional biological studies to further define and enhance the biological criteria as the technology progresses.

- ***Next-generation sensor fish technology*** -- continue to improve the sensor fish technology.

CONCLUSION

The combined engineering and environmental R&D of the AHTS program can enable hydropower to remain an important part of the U.S. energy future if it results in enhanced environmental performance of hydropower projects. The DOE AHTS program is a carefully designed, multi-faceted R&D effort that is providing unique new solutions that will enhance hydropower's environmental performance. Hopefully, these contributions will help ensure that hydropower maintains its important role in the U.S. energy future. Communication among federal agencies and others is also critical to success – DOE is helping that too. The end result, we hope, will be to stimulate and challenge the U.S. hydropower industry to design, develop, build, and test environmentally friendly advanced turbine systems through the development of new concepts, application of cutting-edge technology, and exploration of innovative solutions. This program is intended to emphasize innovative concepts, and the designs should be adaptable to existing facilities. These designs would clearly demonstrate that valuing and incorporating environmental design parameters can lead to the development of commercially viable turbine systems that successfully balance the tradeoffs between environmental, technical, operational, and cost considerations.

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