JUN 17 1997

A PROGRESS REPORT ON DOE'S ADVANCED HYDROPOWER TURBINE SYSTEMS PROGRAM

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Abstract. Recent hydropower research within the U.S. Department of Energy (DOE) has focused on the development of new turbine designs that can produce hydroelectricity without such adverse environmental affects as fish entrainment/impingement or degradation of water quality. In partnership with the hydropower industry, DOE's advanced turbine program issued a Request for Proposals for conceptual designs in October 1994. Two contracts were awarded for this initial program phase, work on which will be complete this year. A technical advisory committee with representatives from industry, regulatory agencies, and natural resource agencies was also formed to guide the DOE turbine research. The lack of quantitative biological performance criteria was identified by the committee as a critical knowledge gap. To fill this need, a new literature review was completed on the mechanisms of fish mortality during turbine passage (e.g., scrape/strike, shear, pressure change, etc.), ways that fish behavior affects their location and orientation in turbines, and how these turbine passage stresses can be measured. This year, new laboratory tests will be conducted on fish response to shear, the least-well understood mechanism of stress. Additional testing of conceptual turbine designs depends on the level of federal funding for this program.

BACKGROUND

The U.S. Department of Energy (DOE) has been supporting research and development on hydroelectric energy for more than 20 years. A major emphasis of DOE's efforts has been finding ways to make hydropower more environmentally acceptable, so that this important source of renewable energy can co-exist with other water resource uses and remain a significant contributor to the nation's energy portfolio. Recent products of these efforts have included two Environmental Mitigation Study reports (Sale et al. 1991; Frankfort et al. 1994). The Department's contributions are summarized in regular biennial reports (e.g., Rinehart et al. 1995).

Beginning in 1994, DOE's hydropower activities began to focus on the development of a new generation of turbine technology that would reduce environmental impacts (Brookshier et al. 1995). Fish passage had been identified by various sources as one of hydropower's most constraining environmental issues [Mattice 1991; Sale et al. 1991; HCI 1992; and the Hydro Working Group of the Electric Power Research Institute's (EPRI)]. The intent of this new initiative is to enable development of turbines that will make the hydropower industry more environmentally acceptable and therefore more competitive. Advanced Hydropower Turbine Systems (AHTS) were envisioned as any "black box" replacing traditional turbine-generator units and having one or more of the following qualities:

- reduce or eliminate the mortality and injury of fish passing through the unit,
- increase the dissolved oxygen (DO) concentration in water discharged from the unit,
- produce hydroelectricity efficiently over a wide range of flows (e.g., variable speeds),
- be constructed from durable, lightweight, cavitation-resistant materials, and
- reduce contaminants by employing greaseless bearings or other measures.

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In contrast to most of the papers presented at this workshop that are oriented at keeping fish out of turbines, the DOE-sponsored research is directed at making the path through the turbine safer for fish. We recognize that there are benefits and costs associated with this research approach. If successful, advanced turbines may allow more river flows to be available for hydroelectric production and avoid some of the expensive passage facilities that may or may not work. However, the overall energy efficiency of the new turbines may suffer. In balance, our goal is to make hydroelectric production more environmentally acceptable and yet remain economically competitive with other energy sources.

PROGRAM DEVELOPMENT

The original concept for advanced turbine development 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. (HRFI) to support this kind of research. Later in 1993, NHA and HRFI assembled financial contributions from nine utility members and the Electric Power Research Institute 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 program was envisioned as a phased effort with three parts to be completed over multiple years:

- Phase I — conceptual design (completed by April 1997)
- Phase II — detailed design and model testing (1996-1998)
- Phase III — construction and testing of prototypes (1998-2004)

The program is jointly managed by DOE, represented by the Idaho Operations Office, and HRFI. A unique aspect of the AHTS Program is the collaborative management structure that has been set up. 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 eight 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 and Oak Ridge National Laboratory serve as *ex officio* members of the Committee and provide other support to DOE. The Committee drafts Requests for Proposals (RFPs), evaluates RFP responses, and provides guidance to Program management. The Committee structure reflects DOE's commitment to independent peer review and interagency cooperation in all of its research and development activities.

An RFP for Phase I work, funded jointly by DOE and the HRFI contributions, was issued on October 21, 1994 (Brookshier et al. 1995).

PHASE I RESULTS

Responses to the Phase I RFP were received in February 1995, and two awards were made in October 1995. The winning proposals came from: (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. 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 Hidrostaal pump impeller. The Voith proposal took as its starting point existing technology and planned to make incremental improvements on three different designs.

A final report on the Alden team's conceptual design has been completed (Cook et al. 1997). It represents an excellent example of the spirit of AHTS program (i.e., identification of biological design criteria, followed by new conceptual design of hydroelectric generating equipment aimed at operating within those constraints). Alden's

Table 1. Biological criteria used by Alden Research Laboratory in their conceptual design of an advanced hydropower turbine system (Cook et al. 1997).

<i>Criterion</i>	<i>Goal</i>
Velocity of runner tip	Less than 40 ft/sec
Minimum pressure	Greater than 10 psia
Pressure gradient	Less than 80 psi/sec
Velocity gradient	Less than 15 ft/sec/inch
Clearance within flow passage	Less than 2 mm
Flow passage width	Maximize
Number/length of runner blades	Minimize

first step was to identify biological performance goals that would avoid adverse effects to fish (Table 1). Using these design criteria and the general Hidrosta 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.

The Voith project is more broad than the Alden project, but a final report is not available at the time of this workshop. This work has been organized into 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 three design concepts that the Voith team is working on are:

- improvements to Kaplan turbines for improved fish survivability
- improvements to Francis turbines for improved fish survivability
- augmentation of DO in Francis turbines

All three of these objectives are oriented at rehabilitation of existing turbines with heads of 10 to 50 feet. The Voith efforts will also examine how advanced instrumentation and control systems can be used to improve operation for both hydraulic and environmental performance. A final report is expected by the time of this workshop.

BIOLOGICAL DESIGN CRITERIA

As work progressed on the Phase I work, we began a parallel activity to evaluate the quality of biological design criteria applicable to hydropower turbines. The results of this literature review were released in March (Cada et al. 1997). Phases I and II of the AHTS Program will involve considerable CFD modeling and engineering design studies to develop novel designs for fish-friendly turbines, i.e., turbines in which mortality of entrained fish is small. To accomplish this, the designers need quantitative criteria for biological damages as input. That is, the engineers need specification of several hydrodynamic and fluid flow parameters that define a "safety zone" for fish.

If one of these injury mechanisms has over-riding importance compared to others, the designers could focus their efforts to "design out" this stress in the new generation of turbines. Because the relative importance of each of these stresses is difficult to discern from field studies, a critical review of biological and engineering literature was needed. Published laboratory bioassays and similar studies of the responses of fish to the component stresses of turbine passage were reviewed, with the goal of deriving biological criteria for the turbine designers. In many cases there were few or no data to support quantitative biological criteria, so laboratory and field experimental techniques that could be used to fill gaps in existing information were addressed in this review. The published literature on fish behavior was also examined to determine whether particular species or sizes of fish are likely to exhibit predictable, directed movements at the turbine intake that might subsequently influence their position or orientation as they pass through the turbine. This knowledge needs to be incorporated into the CFD models and in turbine design.

The most important conclusions that were reached in this literature review are the following:

- of the major injury mechanisms (pressure, cavitation, shear/turbulence, and mechanical damage), shear and turbulence are the least well understood – more laboratory level studies are needed to quantify fish response to shear stresses and to understand the relative contributions of these effects compared to other injury mechanisms;
- indirect mortality, such as increased susceptibility to predation or disease following turbine passage, have not been studied quantitatively and warrant further evaluation; pre-existing stress levels may also affect observed mortality rates in turbines;
- the first priority for a fish-friendly turbine system on rivers with anadromous fish should be designs that direct as many downstream-migrating fish as possible along their natural, surface-oriented path, not through deep turbine intakes;
- CFD modeling can be a valuable tool for understanding the dynamics of fish passage through turbines; simulation of most non-salmoides as passive objects within the turbine system is acceptable, but the effects of buoyancy and active orientation should be examined, at least with sensitivity analysis; and
- more work is needed to describe and understand the distribution and orientation of fish as they enter turbine intakes, using hydro acoustic and underwater photography.

FUTURE DIRECTIONS

The next step in the Program was intended to be more complete engineering design and model testing of concepts generated in Phase I. We are currently trying to work out funding arrangements to continue prototype testing of the conceptual designs from Phase I. DOE funding for the program has been relatively flat at around \$1 million for the past few years. This level of funding is not high enough to support the full Phase II work as originally planned. No new industry funding has been available from HRFI beyond their original contribution. We are looking for creative ways of leveraging existing funds, including coordinated research with programs such as the Corps of Engineers and EPRI, but there are no firm plans as yet. Progress on subsequent phases is being influenced by available federal funding.

Additional work is being planned on biological performance criteria for advanced turbine designs. Our literature review (Cada et al. 1997) concluded that among the injury mechanisms associated with turbine passage (water pressure changes, cavitation, shear, turbulence, strike and grinding), the effects of shear and turbulence were least understood. The contribution of the other injury mechanisms to fish passage mortality are at least roughly predictable based on past studies and knowledge of the turbine design and fish characteristics. In addition, effects of pressure changes within the turbine passages are presently being studied by other organizations, in coordination with the DOE AHTS Program. However, because of the lack of both existing information and ongoing/planned studies from other groups, collection of experimental data on shear effects has been judged a high priority for the continued development of advanced turbine designs.

Further refinement of advanced turbine designs depends on the development of reliable biological criteria, i.e., the quantitative description of maximum allowable levels of injury that a fish can sustain from specific sources without irreparable damage or loss of life. The objective of these currently planned experiments will be to quantify the responses of fish to levels of turbulence and shear in a complex 3-dimensional velocity field representative of the inside of a hydroelectric turbine, draft tube, and tailback.

The new laboratory testing will be conducted under controlled conditions and will be coupled with physical modeling that will relate test conditions to levels of shear stress encountered within a hydropower turbine's water passage. In order to accomplish this, an experimental apparatus will be designed and constructed which can: (1) create quantifiable and reproducible amounts of shear that are representative of those encountered in a hydropower turbine; (2) expose a variety of fish species and sizes to those levels of shear; (3) as appropriate, record the behavioral response of fish to shear forces during the test; and (4) allow for the post-test assessment of survival, tissue damage, and susceptibility to predation. The independent variables to be studied in these tests include maximum shear, average shear, minimum shear, and representative exposure histories of shear over time. Test results will be used to develop specific biological design criteria for advanced turbines and to derive estimates of shear-related mortality of fish in old and new turbine designs.

CONCLUSIONS

DOE's contributions to the hydropower industry are continuing through the AHTS program. This work is a valuable complement to the fish passage research being conducted by other federal agencies and utilities. We have organized an informal coordinating committee of federal and non-federal hydropower researchers (separate from the AHTS Committee) to facilitate cooperation (INEL 1997). Given today's limited budgets and pressures of deregulation, collaborative research activities such as the AHTS program are more important than ever.

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