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Advanced, Environmentally Friendly Hydroelectric Turbines For the Restoration of Fish and Water Quality

G.F. Čada[1], P.A. Brookshier[2], J.V. Flynn[3],
B.N. Rinehart[4], G.L. Sommers[4], and M.J. Sale'

[1] Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6036 U.S.A.
[2] Idaho Operations Office, U.S. Department of Energy, 850 Energy Drive, MS 1220, Idaho Falls, ID 83401-1563 U.S.A.
[3] Office of Geothermal Technologies, U.S. Department of Energy, EE-12 Room 5H/048, 1000 Independence Ave. S.W., Washington, DC 20585 U.S.A.
[4] Idaho National Engineering & Environmental Laboratory, 2525 Fremont Ave., Idaho Falls, ID 83415-3830 U.S.A.

ABSTRACT

Hydroelectric power contributes about 10 percent of the electrical energy generated in the United States, and nearly 20 percent of the world's electrical energy. The contribution of hydroelectric generation has declined in recent years, often as a consequence of environmental concerns centering around (1) restriction of upstream and downstream fish passage by the dam, and (2) alteration of water quality and river flows by the impoundment. The Advanced Hydropower Turbine System (AHTS) Program of the U.S. Department of Energy is developing turbine technology which would help to maximize global hydropower resources while minimizing adverse environmental effects. Major technical goals for the Program are (1) the reduction of mortality among turbine-passed fish to 2 percent or less, compared to current levels ranging up to 30 percent or greater; and (2) development of aerating turbines that would ensure that water discharged from reservoirs has a dissolved oxygen concentration of at least 6 mg/L. These advanced, "environmentally friendly" turbines would be suitable both for new hydropower installations and for retrofitting at existing dams. Several new turbine designs that have been developed in the initial phases of the AHTS program are described.

INTRODUCTION

Hydroelectric power plants can provide a multitude of benefits to society, including electricity, flood control, reservoir fisheries and recreation, and a reliable water supply for human consumption and irrigation. Hydropower provides nearly 20 percent of the world's electricity, and it is by far the most important source of renewable energy. As a renewable energy source it can contribute to reduction of greenhouse gases by offsetting conventional carbon-based electricity generation.

However, the potential adverse impacts of hydropower plants are well known (Ackermann *et al* 1973; Petts 1984; Mattice 1991; Rosenberg ef *al* 1997). Reservoirs associated with large dams can inundate large amounts of terrestrial and river habitat and displace human populations. Dams of all sizes can block fish movements and alter water quality and streamflows. It is necessary to minimize these adverse environmental effects in order to maintain the renewable energy production potential and water supply benefits of hydropower. A recent survey of the hydropower industry and its regulators in the United States found that the most important environmental issues limiting hydropower production are obstruction of fish passage and water quality degradation, particularly as manifested as low dissolved oxygen concentrations in water released from the turbines. It is likely that these two issues are also of considerable importance to hydroelectric power development in many other **parts** of the world.

The mission of the U.S. Department of Energy's (DOE) Hydropower Program is to improve the technical, societal, and environmental benefits of hydropower through appropriate research and development, thereby ensuring that hydroelectric generation is an environmentally sound use of water resources. To that end, the costs and benefits of numerous mitigative measures designed to deal with fish passage and water quality problems were analyzed (Sale et ***al*** 1991; Francfort et ***al*** 1994). These environmental mitigation studies identified numerous measures for increasing the levels of dissolved oxygen in hydropower discharges, aiding the upstream movements of fish blocked by dams, and preventing the passage through turbines of downstream-migrating fish. Although many of these measures are effective, uncertainty about the effectiveness of mitigative measures associated with downstream fish passage and protection remains. For example, intake screens have **often** been used to exclude fish from turbine intakes. These screens are expensive to install and operate, yet little is known about their benefits to fish populations (Francfort et ***al*** 1994). In some cases mortality among screened fish has been greater than mortality among turbine-passed fish **(Ferguson** 199 1).

The DOE's Advanced Hydropower Turbine System (AHTS) Program was initiated in 1994 to develop "environmentally **friendly"** turbines, i.e, turbine systems in which environmental attributes such as fish passage survival and water quality improvements are emphasized (Brookshier et ***al*** 1995). The AHTS Program was instituted to explore the possibility that advanced turbines could be used to (1) improve water quality by aerating hydropower discharges, and (2) eliminate the need for intake screens and other such measures by creating turbine passage conditions that are not damaging to fish. It is intended that such turbines could be employed either at new hydropower sites or to replace aging turbines at existing sites. The AHTS Program is cost shared with the hydropower industry and relies on a Technical Committee with representatives from various federal agencies and industry, including the Electric Power Research Institute. This Committee conducts peer reviews of the technology and criteria being developed. The first phase of the AHTS Program was completed in 1997 with the development of preliminary designs for new, environmentally friendly turbines. The characteristics of these turbines, and the subsequent efforts to advance these preliminary designs, are described in this paper.

TURBINES THAT INCREASE THE SURVIVAL OF ENTRAINED FISH

Downstream-moving fish may be drawn into the power plant intake flow (entrained) and pass through the turbine. Entrained fish are exposed to physical stresses (pressure changes, cavitation, shear, turbulence, strike) that may cause disorientation, physiological stress, injury, or mortality. Five percent or more **of the** turbine-passed fish may be killed in the best existing turbines, and mortality in some turbines may exceed 30 percent. A variety of mitigative measures (e.g., intake screens and spill flows) have been employed to reduce the numbers of fish that are entrained and killed by turbine passage, but such measures have had only mixed success (Francfort et ***al*** 1994). Even effective, well-designed intake screening and bypass systems may protect only a portion of the fish entrained in intake flows; the remainder will pass through the turbines. Hence, the DOE AI-ITS Program recognized the need to develop advanced, "fish-friendly" turbines that would increase the survival of entrained fish. One of the goals of Phase I of the AHTS Program was conceptual designs for turbines that would reduce mortality among turbine-passed fish to 2 percent or less. Contracts were awarded to two teams, Alden Research Laboratory, Inc./Northern Research and Engineering Corporation (ARLNREC) and Voith Hydro, Inc. (Voith), to develop these conceptual designs.

ARL/NREC developed a completely new turbine runner, based on a redesign of a pump impeller that is widely used to transport fish and vegetables with minimal damage (Cook et ***al*** 1997). Computational Fluid Dynamics (CFD) modeling was used to investigate flow characteristics within the turbine and to refine the runner design (Figure 1). Based on the CFD modeling, **ARL/NREC** predicts that the full-sized runner would provide safe fish passage (0.0 to 0.5 percent mortality) with an overall turbine power efficiency of about 90 percent. As a next step, the DOE AHTS Program plans to support a phased program of further design, construction, and testing of the ARIJNREC runner.

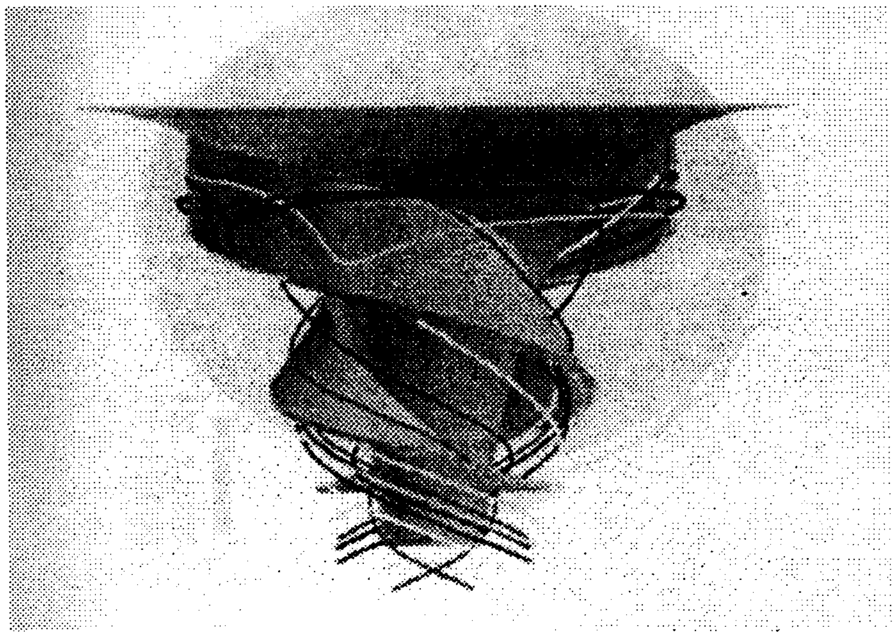

Figure 1. **ARL/NREC** turbine runner. From Cook *et al* **(1997).**

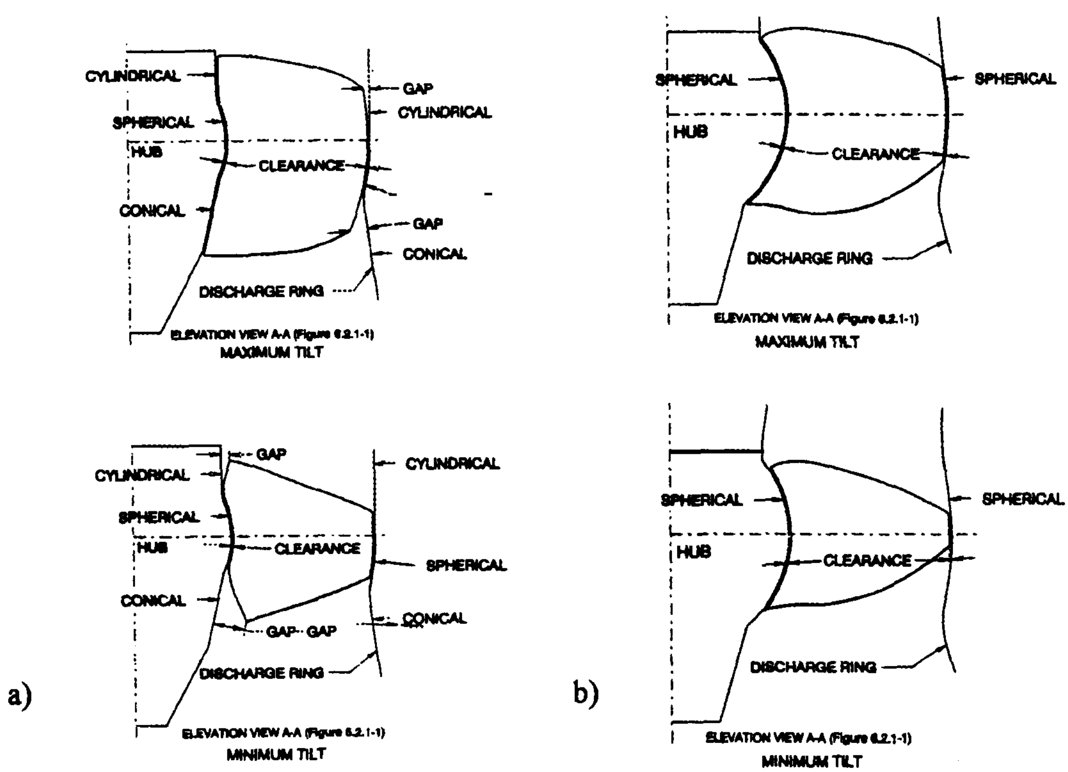

Figure 2. Some of the design features for **(a)conventional** Kaplan runners and **(b)** advanced, minimum gap Kaplan runners. From Franke *et al* **(1997).**

The Voith team, on the other hand, took the approach of modifying existing turbine types (Kaplan and Francis runners) to make them more fish-friendly (**Franke** et *al* 1997). Through a detailed examination of the sources of injury to turbine-passed fish and CFD modeling of the effects of design changes on these injury sources, the Voith team produced a conceptual design for a Kaplan turbine (Figure 2) that included the following features: 1) high efficiency over a wide operating range with reduced cavitation potential, 2) a **gapless** design for the runner **hub,** discharge ring, and blades; 3) a non-overhanging design for wicket gates; 4) environmentally compatible hydraulic fluid and lubricants; 5) greaseless wicket gate bushings; and 6) smooth surface finishes (Fisher ***et al*** 1998). An environmentally enhanced Francis turbine was also developed which includes many of the same features. Although Voith's conceptual designs have not yet been constructed and tested, some elements of the new Kaplan design have been incorporated into replacement turbines at hydroelectric projects on the Columbia River, and fish survival testing will soon be performed.

Further development of fish-friendly turbines requires knowledge of the physical stresses (injury mechanisms) that impact turbine-passed fish and the fish's tolerance to these stresses. There are many possible causes for entrainment injury and mortality (Figure 3). Instrumentation of turbines and the increasing use of CFD modeling can provide information about the levels of each of these potential injury mechanisms that can be expected within existing and advanced turbines. However, data on the responses of fish to these levels of stress are frequently lacking. For example, the sensitivity of fish to the shear and turbulence that occur in a turbine is not well understood, and as a result we do not know what effect altering the amounts of these fluid stresses in a new turbine design will have on survival.

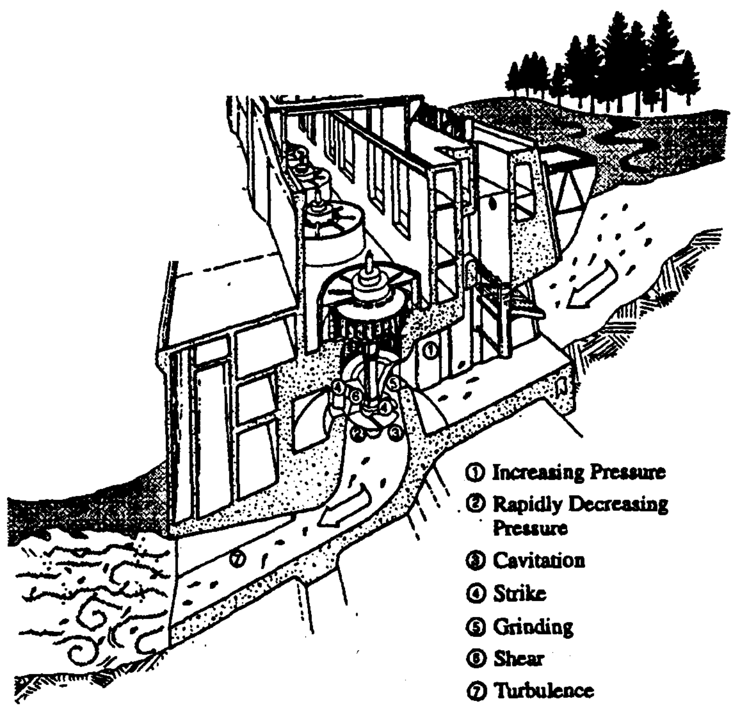

Figure 3. Locations within a hydroelectric turbine at which particular injury mechanisms may be most severe. From **Čada** ***et al*** (1997).

Čada ***et al*** (1997) reviewed published laboratory bioassays and similar studies of the responses of fish to the component stresses ofturbine passage. Provisional biological criteria were developed for maximum and minimum pressures, maximum rate of pressure change, probability of blade strike, and cavitation. On the other hand, although fish are exposed to substantial fluid stresses (shear and turbulence) during passage through the turbine, **draft** tube, and tailrace, very little is known about their sensitivity to these phenomena. As a result of this review and the identification of critical data gaps, the DOE AHTS Program is supporting laboratory studies of shear and turbulence on fish. The goal of these studies is to provide the turbine designers with numbers (biological criteria) that define a **safety** zone for fish within which shear forces and turbulence are at acceptable levels for survival.

TURBINES THAT INCREASE THE CONCENTRATIONS OF DISSOLVED OXYGEN

Water quality problems in the discharges of hydroelectric power plants can result from the seasonal warming and thermal stratification of waters impounded by the dam. Decomposition of organic matter under chemically reducing conditions, brought on by an absence of dissolved oxygen (DO) in the hypolimnion, may result in the buildup of toxic hydrogen sulfide and ammonia, and may mobii iron, manganese, and some heavy metals from the reservoir sediments. Discharges from hydroelectric power plants that have low DO concentrations and elevated levels of contaminants may seriously affect other downstream water uses.

Not all reservoirs stratify or develop water quality problems, however. Stratification and low DO problems are influenced by such factors as reservoir surface area, depth, volume, flushing rate, and the degree of protection from wind. In order to assess the potential for water quality problems, as exemplified by low DO concentrations, to constrain hydropower production in the U.S., Čada et *al* (1983) calculated probabilities of noncompliance (PNCs), i.e., the probabilities that DO concentrations in hydropower discharges would drop below 5 mg/L (Figure 4). Not surprisingly, most regions of the U.S. had higher mean PNCs in summer than in winter, and summer PNCs were greater for large than for small hydropower plants. The Southeastern U.S. and Ohio Valley regions were most likely to experience low DO episodes (high PNCs), probably because they have relatively warm water and deep reservoirs. More recent analyses, summarized in Franke *et al* (1997), have confirmed this pattern.

Numerous techniques for increasing DO concentrations in reservoir releases have been explored (Table 1). These have been categorized by Franke *et al* (1997) as methods for increasing DO when the water is still in the reservoir (Reservoir Techniques), aerating the water as it passes through the intake, turbine, or draft tube (Powerhouse Techniques), aerating the water after it has left the draft tube (Tailwater Techniques), and assorted operational measures (Operational Techniques). Sale *et al* (199 1) provide a description of these measures and the frequency of their use in the U.S.

TABLE 1

TECHNIQUES FOR INCREASING DISSOLVED OXYGEN CONCENTRATIONS IN HYDROPOWER RELEASES. MODIFIED FROM SALE ET AL. (199 1) AND FRANKE ET AL. (1997).

Reservoir Techniques	**Powerhouse Techniques**
Epilimnetic pumps	Intake aeration
Hypolimnetic air or oxygen diffusers	Penstock air or oxygen diffusers
Forebay destratification	Turbine aeration
	Draft tube venting
Tailwater Techniques	**Operational Techniques**
Submerged tailrace diffusers	Sluice or spillway aeration
Surface aerators	Selective withdrawal
Side-stream aeration	Special turbine operations
Aerating weirs	

Aerating turbines are an attractive option for increasing DO concentrations in hydropower discharges because such advanced turbines can improve water quality while generating power, with few additional costs and structures. In its development of conceptual designs for the DOE AHTS Program, the Voith team (Franke *et al* 1997) relied on the considerable experience of the Tennessee Valley Authority (TVA) in developing aerating turbines during the decade of the 90s. For example, under a five-year program aimed at improving water quality in the Tennessee River basin, TVA actively developed many of the techniques listed in Table 1, including self-aerating (auto-venting) designs for Francis turbines. TVA and Voith Hydro, Inc. modeled these designs at various scales and tested auto-venting replacement turbines at the Norris Project (Fisher *et al* 1998; March and Fisher 1999). Results from the Norris Project were encouraging; initial tests showed that up to 5.5 mg/L of DO could be added to the turbine discharge (starting with a concentration of incoming DO of zero). Compared to the original turbines at Norris, these advanced auto-venting turbines also provided overall efficiency and capacity improvements of 3.7 and 10 percent, respectively (March and Fisher 1999).

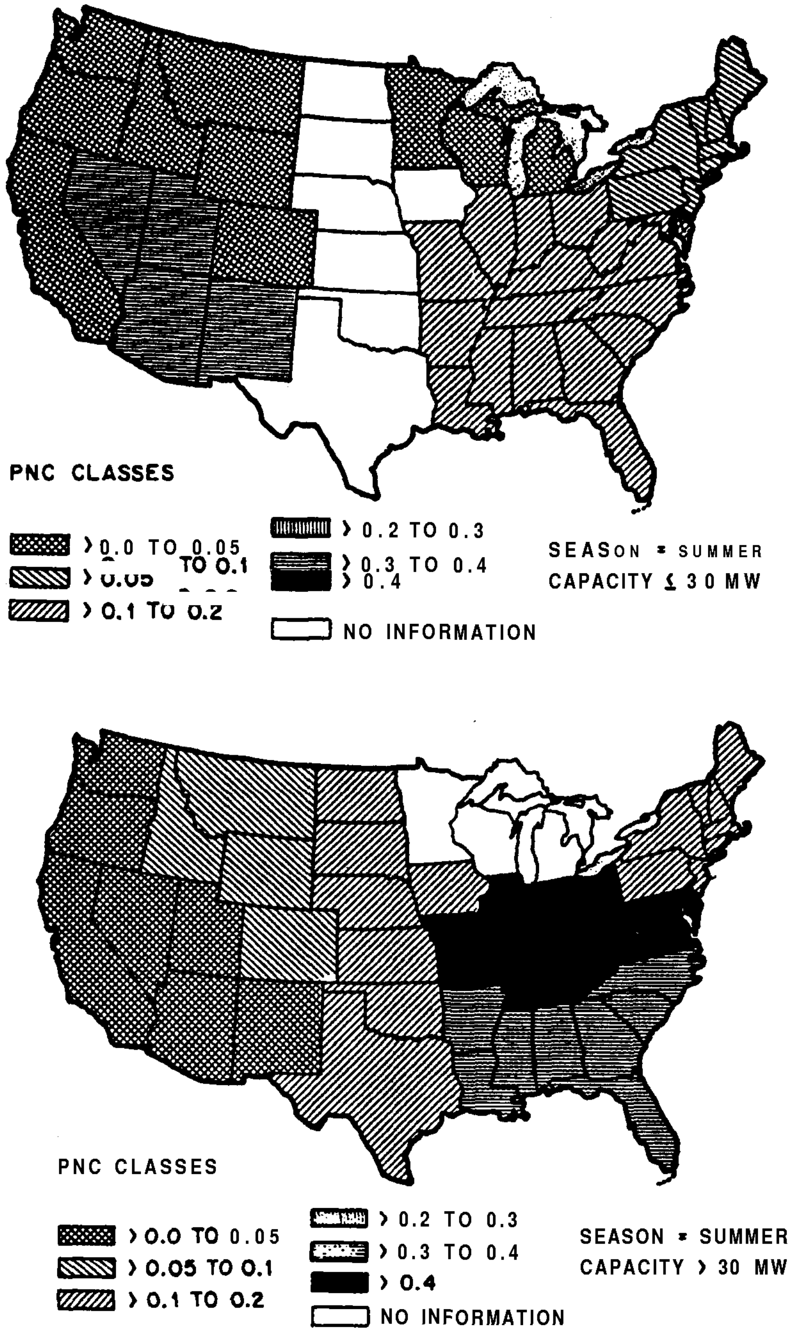

Figure 4. Mean probabilities of noncompliance (PNCs) with a 5 mg/L dissolved oxygen criterion, for small (≤ 30 MW) and large (> 30MW) hydroelectric sites. From Čada *et al* (1983).

CONCLUSIONS

Recent developments in the design of advanced, environmentally friendly turbines indicate that there is a real potential for reducing some of the most common adverse impacts of hydropower. For example, as a result of its success in developing dissolved oxygen enhancing techniques, TVA plans to install 26 auto-venting turbines at 13 hydroelectric projects that presently experience dissolved oxygen deficiencies in the tailwaters (Hopping *et al* 1997). The efficiency improvements of these new turbines, combined with online performance monitoring systems and multi-unit optimization software, are expected to increase the electrical generation of the TVA system while improving water quality in the basin (March and Fisher 1999).

Phase I of the DOE AHTS Program produced conceptual designs for advanced turbines that have a potential to increase the survival of turbine-passed fish. Based on mathematical modeling of these designs and a consideration of biological performance criteria, we expect that the environmental performance of hydroelectric turbines can be improved. The next step is to construct and test prototypes of these new environmentally friendly turbine designs. If the performance of the new turbines is proven, these advanced designs can be added to the suite of mitigative measures that can be considered at hydroelectric projects to ensure reliable, environmentally sound generation of renewable energy.

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