

# Turbines for Solving the DO Dilemma

*Increasing the dissolved oxygen levels in water discharged from hydroelectric stations is a significant challenge. Research and development on re-aerating turbines promises to provide effective solutions.*

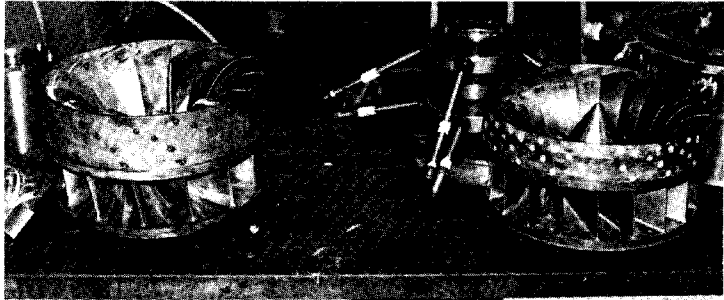
By Patrick A. March, Thomas A. Brice, Mark H. Mobley, and Joseph M. Cybularz

The hydroelectric industry has experimented with adding air to water flowing through a turbine as a means of improving water quality—including increasing dissolved oxygen levels—for nearly 40 years. In the late 1950s, H. Wagner reported on his experiments in West Germany with artificial aeration of river water.<sup>1</sup> Also in the 1950s, turbine aeration was introduced in the U.S. to minimize the effects on river water quality caused by waters discharged from pulp and paper mills and municipal sewage systems.<sup>2</sup> By 1961, turbine aeration systems were operating at 18 hydro plants on the Flambeau, Lower Fox, and Wisconsin rivers.<sup>3</sup> In recent years, several federal agencies, private researchers, and turbine manufacturers have conducted a comprehensive analysis of aeration techniques. This analysis has led to the development of a turbine runner that can provide needed aeration and, at the same time, can increase the hydro unit's efficiency and capacity. The new design offers opportunities for hydro plant owners to improve water quality and optimize operations. The new design is especially promising for situations involving plant rehabilitation.

## Justifying the Need For an Aerating Turbine

Environmental concerns broadly affecting the electric power industry

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This photograph shows the model of the new auto-venting turbine runner (left) and the model of the existing runner (right) at the Norris hydroelectric facility. TVA plans to procure, install, and evaluate two auto-venting turbines at the Norris plant. The new runner should provide a capacity increase of 7 percent and an efficiency increase of 1.8 percent.

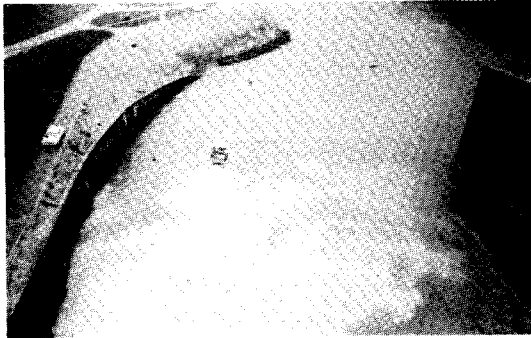
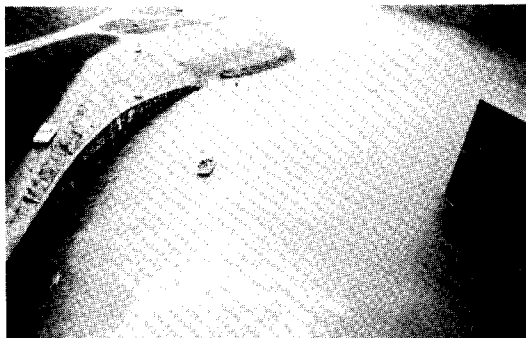
include the depletion and disruption of fossil fuel supplies, the potential for global climatic changes, and uncertainties about long-term nuclear waste management. As a result of such concerns, the electric power industry is focusing attention on renewable, non-polluting energy technologies, including hydroelectric power. Hydro uses a clean, renewable "fuel"—water; is inexpensive to generate; provides a reliable domestic power source; and does not significantly pollute the air, land, or water. However, hydropower facilities can affect aquatic habitat. For many facilities, the primary concern regarding fish protection is the quality of the water discharged from the turbines, specifically the dissolved oxygen (DO) levels in the water. Low DO levels are potentially harmful to aquatic life.

Relicensing or rehabilitating a hydroelectric facility offers an opportunity to address concerns over DO levels and other water quality issues.

The auto-venting turbine (AVT), a hydro turbine designed to aerate the turbine discharge with minimal effect on operating efficiency, represents a promising technology for cost-effectively improving the quality of the water released from hydro plants. A recent U.S. Department of Energy (DOE) assessment of renewable energy technologies notes, "...requirements of the Electric Consumers Protection Act and cumulative environmental impacts will, in many cases, require dramatic water quality improvements before many (hydro) plants may be relicensed after their current license expires. The development of new design replacement turbine runners with improved efficiency and air ingestion capabilities should be desirable."<sup>4</sup>

## A Primer on Dissolved Oxygen

In many hydropower reservoirs, organic material washes into the reservoir during spring rains and settles



One conventional alternative for increasing DO levels in hydropower releases is to install baffles on the turbine hub to create localized low pressure areas and aspirate air directly into the turbine dis-

charge. Removable hub baffles are installed at TVA's Norris hydro plant. These photographs show the Norris tailrace without (left) and with (right) aeration through the hub baffles.

to the bottom. During the summer months, thermal stratification of the reservoir forms a surface layer of less dense, warm water with relatively high levels of dissolved oxygen. The DO in the colder water on the bottom layer reacts with the organic sediments, reducing the overall DO level. Hydroturbine intakes typically withdraw water from this oxygen-depleted layer, which creates the problem of low DO levels in the water released from the turbine.

Numerous factors, such as terrain, size and type of watershed, seasonal temperature variations, intensity and frequency of rainfall, amount of inflow, intake structure design, reservoir system operations, and hydropower operations affect the DO levels in hydropower releases. The experiences of three federal hydropower producers illustrate the site-specific nature of DO levels. A survey assessing the prevalence of DO problems in federal water resource facilities found some degree of DO concerns at 8 percent of the 52 U.S. Bureau of Reclamation projects, located primarily in the West and Southwest; at 18 percent of the

75 U.S. Army Corps of Engineers projects, located throughout the country; and at 42 percent of the 30 TVA projects, located in the Southeast.<sup>5</sup>

### Understanding Is Not Enough: How Do You Solve the Problem?

Conventional methods for increasing DO levels in hydropower releases include selective withdrawal intakes, weirs, surface pumps, diffusers, compressors, and hub and draft tube baffles (obstruction devices). All of these techniques have been tried at hydroelectric facilities, with varying degrees of cost effectiveness and reaeration performance.<sup>5,6,7</sup> For alternatives involving air injection or aspiration directly into the hydroturbine, about 1 percent of air by volume is typically required to increase DO by 1 milligram per liter (mg/L).

Figure 1 shows measured losses in power generating efficiency during turbine generating efficiency during turbine aeration with a variety of techniques for 15 Francis units installed at eight TVA hydro plants and one U.S. Army Corps of Engineers plant. Reducing these efficiency losses is a major objective in development of the auto-venting turbine. [Much of the past work on aeration of hydroturbine releases to improve downstream water quality is summarized in a report prepared by TVA for the U.S. Army Engineer Waterways Experiment Station, *Techniques for Reaeration of Hydropower Releases*.<sup>7</sup>—Ed.]

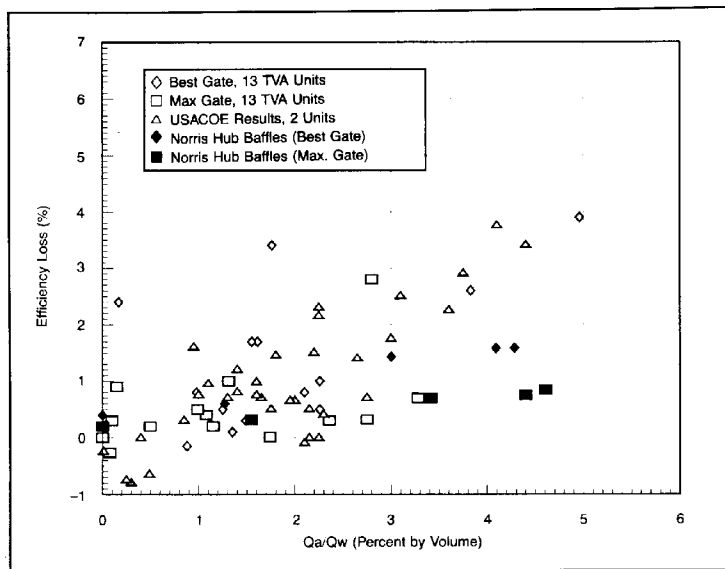


Figure 1: This graph plots measured losses in power generating efficiency during turbine aeration with a variety of techniques for 15 hydro units at eight TVA plants and one Corps of Engineers plant. For this data, the percent reduction in efficiency is generally lower than the percent ratio of volumetric air flow to volumetric water flow (Qa/Qw).

### Developing the AVT: A Collaborative Approach

In 1987, TVA initiated a program to

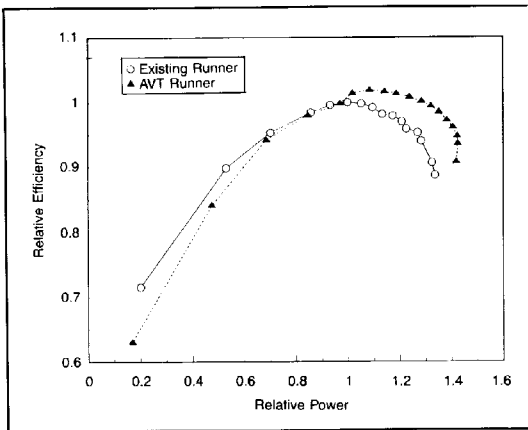


Figure 2: This graph gives efficiency results (without aeration) from model tests of the existing Norris runner with hub baffles and of the proposed auto-venting Norris runner.

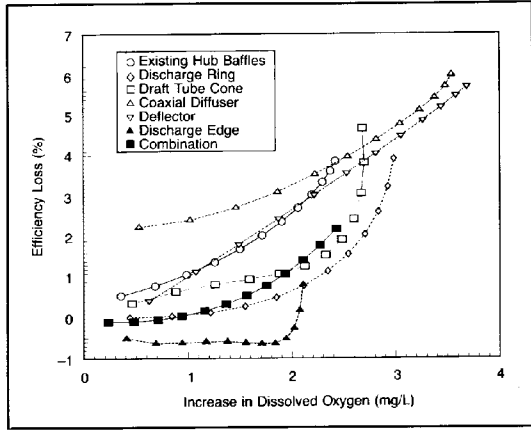


Figure 3: This graph presents typical efficiency loss and aeration results from model tests for a net head of 190 feet and maximum gate opening (100 percent).

develop physical modeling and numerical modeling tools for auto-venting turbine design and to demonstrate auto-venting turbine technology with a full-scale installation. The goal of the program was to provide up to 6 mg/L of dissolved oxygen in hydropower releases, while minimizing the effect of aeration on generating efficiency, capacity, and reliability. The approaches used in developing auto-venting turbine technology include numerical modeling, physical modeling, and prototype evaluation. In addition to TVA, the U.S. Army Corps of Engineers, the University of Iowa's Institute of Hydraulic Research, the U.S. Bureau of Reclamation, the Iowa Investors-Owned Utilities, and Voith Hydro have been involved in the research, development, and demonstration of auto-venting technology.

The Corps of Engineers' Waterways Experiment Station (WES) has provided TVA with a mean properties model for correlating laboratory and field data on DO increases. Data include mean air concentrations, air/water contact time, and DO deficit. WES also plans to use a numerical turbulence model to investigate turbulence effects on bubble size distribution, gas transfer, and model/prototype scaling.

Researchers at the University of Iowa's Iowa Institute of Hydraulic Research (IIHR) are adapting an existing numerical flow model developed for the U.S. Navy. This model will compute pressures, velocities, and turbulence levels throughout a turbine's flow passageway. These data will help

in selecting locations within a turbine where aeration can be most satisfactorily accomplished. The model will be useful for predicting the mixing and distribution of entrained air and for scaling of model results to prototype behavior. Experimental tests with swirling air/water mixtures flowing in a vertical test loop are also underway at IIHR. TVA, the Bureau of Reclamation, and the Iowa Investors-Owned Utilities Research Program have provided funding for the IIHR work.

In the development of auto-venting turbine technology, TVA is initiating and coordinating the research efforts of various organizations. TVA's specific research efforts include:

- Preparing a comprehensive re-aeration database and analyzing existing data on air flow rates, oxygen increases, and efficiency degradation;
- Applying WES's mean properties model to predict DO increases;
- Developing scaling techniques to predict aeration performance and efficiency performance of a full-scale auto-venting hydroturbine from model test results;
- Testing turbine models and analyzing data;
- Investigating methods to maximize oxygen transfer after air is introduced into the flow;
- Developing numerical formulations for simple air/water flows;
- Integrating two-phase flow formulations into the IIHR model to create a comprehensive numerical model for air/water flow in a hydroturbine; and
- Evaluating prototype performance.

In 1988, TVA funded two hydroturbine manufacturers, Voith Hydro, Inc. and American Hydro, both of York, Pennsylvania, to use their existing numerical models to compute the performance of two 50-MW Francis turbine units at TVA's Norris Hydroelectric Facility. (DO levels at Norris fall below 1 mg/L during late summer and early fall. Removable baffles are installed on the turbines to create localized low pressure areas and aspirate air directly into the turbine discharge. The baffles are effective, typically raising the DO levels to 3.5 to 4 mg/L. However, when operating, the baffles cause efficiency losses—about 0.5 percent loss due to the baffle itself and another 1 percent loss due to the air.) TVA asked the manufacturers to propose and evaluate alternatives for increased aeration and to estimate the performance of aerating replacement runners. Of the alternatives tested, TVA selected several for additional evaluation, including air injection through: a redesigned turbine hub, or deflector; discharge edges of the turbine blades; coaxial diffuser; discharge ring; draft tube cone; and combinations of these.

### A Closer Look at AVT Model Tests

As part of the research effort in development of an auto-venting turbine, in 1991 TVA and Voith Hydro co-funded extensive physical model studies to investigate effects of aeration alternatives on performance of a medium-head Francis turbine. Model

tests were conducted for the turbines at the Norris hydro plant, which are scheduled for runner replacement in 1994. The testing included efficiency, cavitation, runaway speed, pressures and pressure pulsations, air flow, and DO measurements. The tests were performed on a model of the existing runner and for a model of a replacement runner designed to provide improved efficiency, increased capacity, and additional aeration using the alternatives identified by Voith and American Hydro in the earlier numerical investigations.

A turbine test stand at Voith's Hydraulic Laboratory in York was used for the design studies. The laboratory has two test stands, which share a 120,000-gallon underground reservoir, two service pumps, and a central control room. Each test stand includes a head tank, penstock, test section, tail tank, and dynamometer. The service pumps and a vacuum pump on the tail tank control the flow rates and pressures during operation.

Figure 2 gives results (without aeration) from model tests of the existing Norris runner with hub baffles and of the proposed auto-venting runner. At a net head of 190 feet, the auto-venting runner provided a capacity increase of 7 percent and an efficiency increase of 1.8 percent.

Figure 3 presents typical efficiency and aeration results for a variety of aeration alternatives from the model tests for a net head of 190 feet and maximum gate opening (100 percent). Aeration through the discharge edges of the turbine blades improved efficiency over a range of air flows, presumably due to reduced flow separation at the high head/high gate condition. The discharge ring, draft tube cone, and combination of discharge edge and draft tube cone provided a reasonable balance between efficiency losses and aeration performance. The largest efficiency losses, as expected, were observed with the coaxial diffuser. Based on the model tests, most of the alternatives, when installed on a full-scale turbine, will pull air in without the requirement of external compressors.

### What about the Future?

TVA's current plans call for the procurement, installation, and evaluation of auto-venting turbines for both units at the Norris plant. One unit will

include aeration through the deflector, the runner discharge edges, and the draft tube cone. The other unit will include aeration through the deflector, the runner discharge edges, and the discharge ring. TVA also is considering installing new auto-venting turbines at its Wilson and Tims Ford plants.

The selection of an aeration alternative for turbine discharges is complex and site specific. Aeration alternatives must be compared on the basis of aeration performance, capital costs, operating costs, reliability, and maintenance costs. Model test results indicate that the multiple objectives of efficiency increases, capacity increases, and aerated releases are attainable. Consequently, an auto-venting turbine represents an attractive option, particularly if the installation is carried out in combination with a planned uprating or rehabilitation. □

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### Notes:

<sup>1</sup> Wagner, H., "Experiments with Artificial River Water Aeration," *Voith Forschung und Konstruktion*, Heft 4, November 1958.

<sup>2</sup> Lueders, B.C., "Turbine Venting for Stream Reaeration." Presentation to paper company officials, Mead Hotel, Wisconsin Rapids, Wisconsin, August 15, 1956.

<sup>3</sup> Wiley, A.J., B.F. Lueck, R.H. Scott, and T.F. Wisniewski, "Commercial Scale Stream Reaeration," *Journal of the Water Pollution Control Federation*, Volume 34, April 1962.

<sup>4</sup> *The Potential of Renewable Energy: An Interlaboratory White Paper*, Report No. SERI/TP-260-3674, Solar Energy Research Institute, Golden, Colorado, March 1990, page A-10.

<sup>5</sup> *Assessment and Guide for Meeting Dissolved Oxygen Water*

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<sup>6</sup> Buck, C.L., D.E. Miller, and A.R. Sheppard, "Prediction of Oxygen Uptake Capabilities in Hydroelectric Turbines Utilizing Draft Tube Aeration Systems," Alabama Power Company, Environmental and Research Services Section, August 1980.

<sup>7</sup> Bohac, C.E., J.W. Boyd, E.D. Harshbarger, and A.R. Lewis, *Techniques for Reaeration of Hydropower Releases*, Technical Report E-83-5, prepared by Tennessee Valley Authority for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 1983.

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