Justifying, Specifying, and Verifying Performance of Aerating Turbines

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Abstract

Owners of hydropower facilities face increasing demands to reduce or eliminate environmental concerns arising from the impoundment and control of once-natural stream flows. These demands, which are rooted in a complex mélange of technical, political, social, legal, and economic factors, are typically applied through regulatory criteria for mitigating the impact of hydro projects on aquatic habitat. The improvement of low dissolved oxygen (DO) in reservoir releases is a major environmental concern for projects with moderate to heavy amounts of organic sediments. When applicable, turbine aeration often is the most cost-effective technology for providing DO improvements. However, opportunities to solve DO-related water quality problems by turbine methods are often overlooked. In some cases this is due to ambiguous accountability for the low DO problem. In other cases, it is due to limited awareness of aerating turbine capabilities, limited support for research and development, or a lack of industry-accepted procedures for the analysis and design of these turbines. This paper presents a brief summary of guiding principles used for justifying, specifying, and verifying the performance of aerating turbines. Examples are given for Tennessee Valley Authority (TVA) hydro projects using turbine aeration. A defensible project justification for turbine aeration requires a reliable determination of the site-specific environmental and hydraulic capabilities of aerating turbines and the ability to express these capabilities in economic terms. Specification requirements must define the desired environmental and hydraulic guarantees to be achieved by an aerating turbine, including the operating conditions for the evaluation. Verification is also needed to determine conformance to proposed environmental and hydraulic guarantees, and measurement uncertainty can have a significant impact.

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Introduction

Hydropower projects likely to experience problems with low DO include those with a reservoir depth greater than 15 m, power capacity greater than 10 MW, reservoir volume greater than 61×10^6 m^3, densimetric Froude number less than 7, and a retention time greater than 10 days (EPRI, 1990). In general, these include projects with watersheds yielding moderate to heavy amounts of organic sediments and located in a climate where thermal stratification isolates bottom water from oxygen-rich surface water. At the same time, organisms and substances in the water and sediments consume and lower the DO in the bottom layer. For projects with bottom intakes, this low DO water creates problems both within and downstream of the reservoir, including damage to aquatic habitat.

Before about 1980, detailed studies of the potential impacts of hydropower on water quality, including low DO, generally were not required prior to licensing. In 1986, however, the Electric Consumers Protection Act (ECPA) defined a process by which the development of hydropower shall be balanced with concerns for the protection of environmental site characteristics. As a result of ECPA, and based on criteria by the U.S. Environmental Protection Agency (USEPA, 1986), specifications for monitoring and maintaining DO levels have become a regular part of license agreements for affected hydro projects.

Among the largest owners of affected hydro projects, however, are federal agencies, which are exempt from the licensing protocol of the Federal Energy Regulatory Commission (FERC). In the Southeast and Ohio Valley, which contain the largest concentration of low DO projects in the United States (USEPA, 1989), the primary federal owners are the Tennessee Valley Authority (TVA) and U.S. Army Corps of Engineers (USACE).

Based on its corporate goal to support a thriving river system, TVA currently provides DO levels commensurate with that of FERC-mandated water quality criteria through its self-imposed Reservoir Releases Improvement (RRI) Program (Brock and Adams, 1997). As summarized in Table 1, this includes the implementation of special DO enhancement technologies at sixteen projects. Turbine aeration is used either in sole operation or in combination with other technologies at ten of these projects. Two types of aerating turbines are used, including the auto-venting turbine (AVT), which aspirates air naturally into the flow, and the forced-air turbine (FAT), which injects air into the flow using compressors or blowers. Almost all are Francis-type units.

The aerating capabilities for most of the relevant turbines in Table 1 have been provided as retrofit arrangements to conventional, non-aerating units. As part of TVA's Hydro Modernization (HMOD) Program, all sixteen projects are to be upgraded with new turbines. This has presented a unique opportunity to integrate objectives for improving DO with those for improving turbine efficiency and capacity. For major rehabilitations where the turbine runner and related equipment are replaced, this also presents an opportunity to consider new options for turbine aeration that would be considered unfeasible in retrofit situations. If properly designed, such options are likely to improve aeration performance beyond that of conventional turbines, retrofit or otherwise. However, this may require additional, site-specific analysis, research, and development. TVA's HMOD program will increase the number of projects with turbine aeration capabilities (see Table 1) from ten to thirteen. To date, four of TVA's projects have been upgraded with turbine aeration technologies - Douglas (Units 2 and 4), Norris, Nottely, and Tims Ford (Hopping et al., 1997).

Table 1. TVA Projects with Technologies for DO Enhancement

Project	Turbines		Approx. Average Discharge (cfs)	Current DO Enhancement Technology [3]	Plans for AVT Technology in New HMOD Turbines	
	No.	Type			Schedule	AVT Options [4]
Apalachia	2	Francis	2,800	AVT	2003-2004	CEN
Blue Ridge [1]	1	Francis	1,800	FOD	2010	CEN, PER
Boone	3	Francis	11,500	AVT	2008-2010	CEN
Chatuge	1	Francis	1,400	IAW	2002	CEN
Cherokee	4	Francis	17,500	FOD, SWP, AVT	2003-2006	CEN, PER
Douglas 1&3	2	Francis	8,250	FOD, SWP, AVT	2001-2002	CEN
Douglas 2&4	2	Francis	8,250	FOD, SWP, AVT	1997-1998	CEN, PER
Fontana	3	Francis	8,000	AVT	1999-2001	CEN
Ft. Loudoun	4	Kaplan	28,000	SUO, FOD	2002-2010	None
Ft. Patrick Henry	2	Kaplan	8,000	UPI	1995-1996	None
Hiwassee 1 [2]	1	Francis	8,000	FOD	2001	CEN
Norris	2	Francis	8,000	AVT	1995-1996	CEN, DIS, PER
Nottely [1]	1	Francis	1,500	FAT	1997	None
South Holston	1	Francis	2,600	AVT, LAW	2009	CEN
Tims Ford [1]	1	Diagonal	3,600	POD, FAT	1992	None
Watauga	2	Francis	2,900	AVT	2009-2010	CEN
Watts Bar	5	Kaplan	45,000	SUO, FOD	2003-2007	None

Notes: (1) Project also includes a small, minimum flow turbine.
(2) Project also contains a pump-turbine.
(3) AVT=Auto-Venting Turbine, FAT=Forced-Air Turbine, FOD=Forebay Oxygen Diffuser, IAW=Infuser Aerating Weir, LAW=Labyrinth Aerating Weir, POD=Penstock Oxygen Diffuser, SUO=Selective Unit Operation, SWP=Surface Water Pump, and UPI=Upstream Project Improvements.
(4) CEN = Central aeration through deflector, DIS = Distributed aeration through discharge edge of buckets, and PER = Peripheral aeration through draft tube cone.

The USACE, like TVA, is active in implementing DO improvement technologies at affected hydro projects. Unlike TVA, however, the USACE's DO improvements do not follow from a power-funded, agency-wide commitment. The level of effort for DO enhancements varies among the different projects depending on the goals and objectives of regional stakeholder groups, the initiative of individual District Engineers, project managers, and technical staff, and congressional funding priorities. Retrofit turbine aeration has been provided at many USACE plants (Harshbarger et al., 1999), and efforts are underway to encourage the incorporation of objectives for DO improvement, when appropriate, into USACE hydro modernization projects.

Justification

Under FERC re-licensing, projects containing low levels of DO typically must provide a method to improve and monitor DO levels in the turbine releases. For non-FERC projects, owners are often obliged to do the same based on corporate values and/or demands by Federal and State fish and wildlife agencies, water quality agencies, and other public and private interest groups. For projects outside of ECPA authority, stakeholders can bring to bear environmental laws such as the National Environmental Policy Act, Clean Water Act, Endangered Species Act, and so on.

A wide range of technologies is available for DO enhancement. Although somewhat dated, USDOE (1991) and EPRI (1990) provide descriptions of many of these technologies. More recent innovations and improvements also exist (see the proceedings for WaterPower '93, WaterPower '95, and WaterPower '97). Justification for one or a combination of these technologies depends, primarily, on cost. A recent example of an economic analysis for the selection of a DO enhancement system is given by Hibbs et al. (1997). In general, the cost of a DO enhancement strategy is site-specific, depending on many factors:

- Physical design factors (geometry of forebay, powerhouse, and tailrace);
- Environmental factors (seasonal variation of flow, water temperature, and DO);
- Biological factors (current and desired aquatic habitat);
- Hydraulic factors (turbine design, headwater/tailwater ranges and flow patterns);
- Operational factors (guide curves for reservoir releases, plant operating modes);
- Market factors (power demand and costs); and
- Statutory factors (ownership and/or access to shorelines and neighboring areas).

In general, an economic analysis requires a determination of both capital and O&M costs. The "no-action" scenario provides the baseline for comparing the cost of enhancement alternatives. In this case, license requirements would dictate that during periods of low DO, hydro operations would need to be curtailed, and perhaps totally suspended, in favor of existing methods to oxygenate the flow, such as spilling or sluicing. If low level outlets do not exist, it may be necessary to siphon high DO water over the dam. The cost of the no-action scenario will depend primarily on the seasonal variation of low DO, required amount of power curtailment, energy cost, and capital and O&M costs, if any, for supplying and operating other equipment. The no-action scenario usually represents the most costly method to satisfy DO requirements, and provides the basic motivation to supply systems that allow reservoir releases exclusively by turbine operations. For TVA, the no-action scenario for the projects in Table 1 would cost the agency tens of millions of dollars per year.

If hydraulic conditions are favorable, turbine aeration usually provides the least cost method to improve DO in hydro releases. This is especially true for turbines containing areas of subatmospheric pressure, which allow the use of AVT technology. In many cases AVT capabilities can be provided in existing units merely by retrofitting the turbines with a vacuum breaker bypass and/or hub baffles, often at a capital cost of no more than $20K-$30K per unit (Carter, 1995). In HMOD situations, multiple AVT alternatives can provide greater amounts of air. For example, with the new HMOD turbines at TVA's Norris Hydro Project, airflows have been more than doubled by providing aeration through the deflector, the runner discharge edge, and the draft tube cone (Hopping et al., 1997). The costs for HMOD-type aeration alternatives typically are higher than those for simple retrofit arrangements, ranging anywhere between $50K and $500K. These alternatives often can be justified based on the reduced cost of additional systems that may be needed for "DO peaking," such as forebay oxygen diffusers.

The determination of size and, subsequently, cost of an AVT alternative requires reliable estimates of the environmental and hydraulic performance of the aerating turbine. The environmental performance is measured by the DO uptake, $\Delta DO=DO_{tw}-DO_{sc}$, where DO_{tw} and DO_{sc} are the DO concentration in the tailwater and scrollcase. The hydraulic performance is measured by the aeration-induced turbine efficiency change $\Delta\eta=\eta_a-\eta_0$, where η_a and η_0 are the turbine efficiency with and without aeration.

Turbine environmental performance is usually determined by the aeration efficiency

$$E = \frac{DO_{tw} - DO_{sc}}{DO_{es} - DO_{sc}}, \tag{1}$$

where DO_{es} is the effective saturation concentration along the path of flow (see Thompson et al., 1997). The aeration efficiency is usually expressed in terms of the air void ratio $\phi=Q_a/Q_w$. Hence, for given values of the scrollcase and saturation concentrations, the DO uptake is given by

$$\Delta DO = (DO_{es} - DO_{sc})E_{\phi}. \tag{2}$$

The efficiency change also is usually expressed in terms of ϕ,

$$\Delta\eta = \Delta\eta_{\phi}. \tag{3}$$

Due to the complex behavior of two-phase flow and gas transfer in hydroturbines, the determination of E_ϕ and $\Delta\eta_\phi$ relies heavily on empirical relationships developed from aeration performance tests conducted in model and prototype units. E_ϕ and $\Delta\eta_\phi$ are also site-specific and depend on turbine operating conditions (i.e., head, gate, and location of aeration outlets in the turbine). From the projects in Table 1 and from a variety of projects owned by the USACE and other customers, TVA has developed a database of E_ϕ and $\Delta\eta_\phi$ values for a wide range of turbine design and operating conditions.

The primary unknown in the relationships represented by Equations (2) and (3) is the air void ratio (i.e., the airflow Q_a). For a given operating condition (i.e., head and gate), ϕ can be estimated using "pressure curves" for the draft tube and air supply passageway, as illustrated in Figure 1. The curve for the air supply is determined based on the energy loss along the path of flow from the air intake to the outlets in the turbine. The "driving force" for airflow is the subatmospheric pressure at the outlets. A larger subatmospheric pressure produces a larger airflow through the aeration outlets. Because air velocities can approach sonic conditions, evaluations need to consider the effects of fluid compression. The curve for the draft tube is based on the energy loss between the aeration outlets and tailwater. The draft tube curve is determined using an appropriate procedure that accounts for the aeration-induced energy losses in the draft tube (Almquist et al., 1991). In general, larger airflows create higher losses in the draft tube and increase "backpressure" on the turbine (i.e., reduce the subatmospheric pressure). The intersection of the air supply and draft tube curves gives the airflow for the auto-venting turbine.

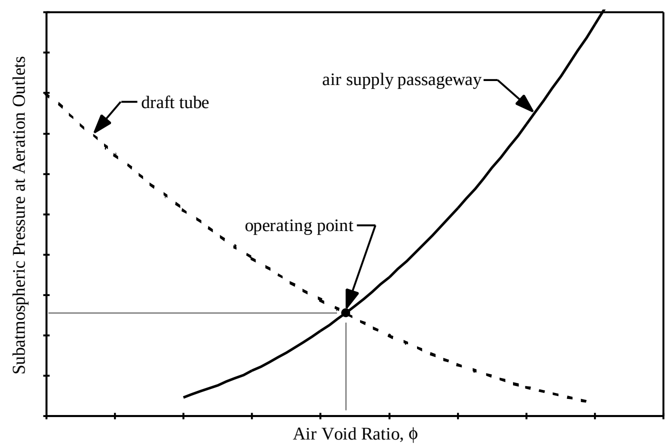

Figure 1. Determination of AVT Air Void Ratio

Knowing ϕ, and subsequently the environmental and hydraulic performance, the annual operations and maintenance (O&M) cost due to turbine aeration-induced energy losses can be determined by:

$$\text{O\&M Cost} = \sum \Delta\eta P C_e \Delta t\,, \tag{4}$$

where $\Delta\eta$, P, and C_e are the average efficiency change, power output (MW), and energy cost ($/MW) in time interval Δt. For analyses in TVA, Δt is selected to capture significant time-dependent changes in $\Delta\eta$, P, or C_e - usually about one week. The summation in Equation (4) occurs throughout the duration of the low DO season. In retrofit situations that include hub baffles as permanent equipment, a "baffle loss" will exist throughout the year. In contrast to retrofit situations, aeration-induced efficiency losses for new HMOD auto-venting turbines are minimal, typically limited only to those periods when aeration alternatives are in service. TVA experience has shown that non-aerating goals for efficiency and capacity improvements in new, upgraded runners can usually be achieved if the AVT alternatives are included as an integral part of the turbine design.

Current TVA plans for AVT technology in new HMOD turbines are also summarized in Table 1. A total of 24 units at 11 projects are to be fitted with one or more aeration alternatives. The economic justification for investment in these technologies is based primarily on two factors—cost savings in reduced use of existing methods of DO improvement, primarily forebay oxygen diffusers, and cost savings in reduced energy losses due to hub baffles. Based on an analysis period of 30 years, the present worth savings for the plan in Table 1 is about $7.6 million. In addition to direct savings, other less-tangible benefits also help provide justification. Local economies can be stimulated by increased fisherman visits to tailwaters, as has been reported for several TVA projects (Brock and Adams, 1997). DO improvements also draw strong support and recognition from stakeholders, which can enhance business relationships with customers and other influential public and private organizations.

Specification

For conventional hydraulic turbines, test codes PTC-18 and IEC 41 are available to help define performance specifications. For aerating turbines, however, no code-accepted performance test procedures currently exist. To help fill the need for such, general guidelines to help owners formulate specifications for aerating turbines were recently proposed by Franke et al. (1997) for the U.S. Department of Energy (USDOE) Advanced Hydropower Turbine (AHT) Project. The main aspects of these guidelines are as follows:

- Specifications for aerating turbines should include target objectives for DO improvement in the project hydro releases. Depending on the aquatic habitat, specification limits also should perhaps include limits for total dissolved gas (TDG). The targets for DO and TDG comprise the desired environmental performance of the aerating turbine. The conditions under which these targets and limits apply should be identified (i.e., head, gate, tailwater elevation, incoming DO concentration, flow).
- Specifications for aerating turbines should include maximum acceptable levels for the aeration-induced efficiency loss, $\Delta\eta$. These requirements comprise the desired hydraulic performance of the aerating turbine. As before, the conditions under which the efficiency losses apply should be identified.
- Specifications for aerating turbines should place upon the contractor the burden of proposing the detailed design arrangements by which aeration will be provided. The manufacturer should clearly identify the aeration features to be used, the guaranteed environmental and hydraulic performance of these features, and the conditions under which the guarantees apply. Note that based on site-specific limitations, design arrangements proposed by the contractor may not provide the environmental and hydraulic performance desired by the owner. In such cases, other DO enhancement technologies, used alone or in combination with turbine aeration, may be required to achieve the target levels of DO and limits for TDG and efficiency loss.
- Specifications should include a description of penalties for non-conformance to environmental and hydraulic guarantees. These should include compensation for the cost of correcting the non-conformance, including expenses for implementing an alternative DO enhancement technology, and/or the cost of lost power from excessive aeration-induced efficiency losses.
- Because there is not yet a code-accepted procedure for testing aerating turbines, the exact methods by which DO, TDG, and $\Delta\eta$ will be measured and evaluated in the model and prototype units should be specified as part of the performance guarantees.
- Successful implementation of aeration technology requires special expertise in turbine analysis, fabrication, installation, and testing. To maximize the probability of success, specifications should require the contractor to have a demonstrated ability to supply aerating turbines. Staff capabilities and previous experience of the contractor should be confirmed. Methods to predict environmental and hydraulic performance should be provided (i.e., assumptions, data, computations, and references). The owner also should consider an independent review of contractor

bid specifications and work, including the design, fabrication, installation, and testing of the aerating turbines.

Verification

Aeration tests are provided to verify conformance to proposed environmental and hydraulic guarantees of aerating turbines. As shown in Figure 2, testing of aerating turbines can be broadly divided into two categories, aeration and non-aeration performance testing. Non-aeration testing is performed with all aeration systems off, and it is the same as that for testing the mechanical performance of conventional turbines. Key parameters include turbine efficiency, maximum power, cavitation level, vibration, shaft runout, and thrust load. Test codes PTC-18 and IEC 41 apply and include procedures to measure flowrate, head, and power output to calculate the turbine efficiency. Testing of an aerating turbine encompasses additional evaluations for both environmental performance and hydraulic performance. As previously defined, environmental performance is measured by the DO uptake, and perhaps the level of TDG and other water quality parameters. Airflow is needed to verify gas transfer characteristics of individual aeration options. The hydraulic performance is measured by the aeration-induced efficiency change $\Delta\eta$. In computing $\Delta\eta$, both η_a and η_0 are found using the procedures of PTC-18 or IEC 41. Airflow and pressures at the aeration outlets are needed to verify hydraulic characteristics of individual aeration options. Aeration can affect other mechanical aspects of turbine operation, so measurements for cavitation and vibration can also be a part of aeration performance testing. Because changes in performance, rather than absolute performance, are of primary interest, index testing often is adequate for aeration performance tests.

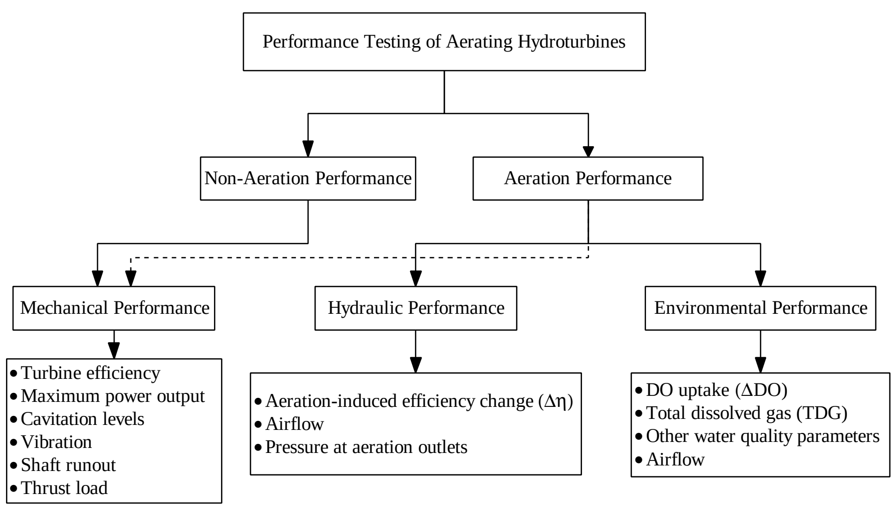

Figure 2. Flowchart for Testing Aerating Hydroturbines

To help owners and contractors define the exact procedures by which ΔDO, TDG, $\Delta\eta$, and other parameters will be measured and evaluated, a draft test code for aerating turbines is given in the USDOE Advance Hydro Turbine Project report by Franke et al. (1997). This draft test code gives guiding principles for determining the environmental and hydraulic performance of aerating turbines. Included are recommendations for methods of measurement, instrumentation, test procedures, and analysis of data.

Recent evaluations of data collected in aeration tests performed by TVA show that the error in the measurement of dissolved oxygen contributes significant uncertainty to the determination of environmental performance (i.e., DO uptake). This primarily is due to spatial variations of DO in the turbine penstock and tailwater. Variations in the penstock result from DO stratification in the reservoir, while variations in the tailwater are due to incomplete mixing of air in the turbine discharge and an uneven distribution of flow in the tailrace. Due to these variations, the estimated confidence interval for measured values of DO uptake can easily vary between 0.5 mg/L and 1.0 mg/L. This, in turn, creates large uncertainty in the computed oxygen transfer efficiency (see Equation 1). The uncertainty in the measured DO uptake also tends to be larger when the ΔDO is small, as emphasized by the sensitivity coefficients for ΔDO shown in Figure 3. The sensitivity coefficients provide a measure of the relative error in ΔDO due to relative errors in DO_{tw} or DO_{sc}. Note that as the ratio DO_{sc}/DO_{tw} approaches unity, or as the DO uptake approaches zero, the relative change in ΔDO increases dramatically.

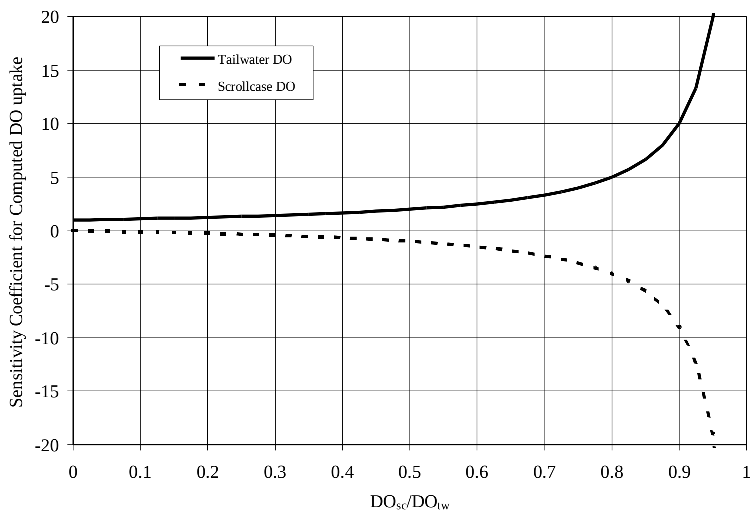

Figure 3. Sensitivity Coefficients for Effects of DO_{tw} and DO_{sc} on ΔDO

The effect of large uncertainty in measured DO uptake can be costly, not only in determining conformance to environmental performance guarantees, but also in terms of supplying and operating DO enhancement systems. With a large uncertainty, a conservative approach must be taken in selecting and operating these environmental systems. Depending on site conditions, the expense for over-design and over-use can be substantial.

To increase accuracy in the measurement of turbine environmental performance, TVA has adopted test procedures requiring multiple DO readings in the turbine penstock and tailwater. Uncertainty in the scrollcase DO is reduced by obtaining independent, continuous DO measurements from each of four taps upstream from the turbine. In the tailwater, multiple, continuous DO measurements are obtained at several points across the turbine discharge. The optimum number of tailwater sensors depends on the magnitude of DO spatial variations and the size of the tailrace. At TVA's Norris Dam, six continuous DO sensors were used to measure tailwater DO. Due to the high cost of deploying multiple sensors, it is important to perform a pre-test evaluation of velocity and DO patterns in the tailrace. This will allow DO sensors to be strategically located to avoid redundant measurements in areas of flow stagnation or recirculation. Pre-test, mid-test, and post-test calibrations of DO sensors in a common bath to a common standard also are performed to increase accuracy.

Additional guidance for increasing the accuracy of measured DO uptake is provided by the sensitivity coefficients in Figure 3. Since errors in DO_{tw} and DO_{sc} have a much greater impact when ΔDO is small, aeration tests should be conducted when the DO entering the turbine scrollcase is as low as possible (i.e., ΔDO will be larger when the deficit DO_{es}-DO_{sc} is large - see Equation 1). Testing under these conditions, however, can be problematic. To properly evaluate the aerating turbine, tests to establish baseline conditions for DO and TDG sensors must be conducted with all aeration systems off. This will result in pulses of low DO water in the turbine discharge, which may injure sensitive aquatic species. To perform such tests, therefore, it may be necessary to obtain regulatory approval to release low DO water, and also to monitor fish stress throughout the duration of the test. To reduce the costs and avert potential problems associated with low DO testing, research is needed to develop new methods to measure DO in reservoir releases.

Conclusions

Turbine aeration technologies provide a cost-effective method for improving water quality in hydro releases. Sound procedures exist for justifying, specifying, and verifying the performance of aerating turbines. These procedures currently are being used by TVA to guide implementation of turbine aeration in its Hydro Modernization Program. For such projects, TVA experience has shown that goals for the improvement of turbine efficiency and capacity can usually be achieved in conjunction with environmental goals if the objectives for DO enhancement are included as an integral part of the turbine design process. Overall, there continues to be a strong need for the hydro industry to develop code-accepted standards for aerating turbines. Until these standards are implemented, the comments and references summarized in this paper should provide guidance in utilizing aerating turbines in applicable projects.

References

Almquist, C.W., P.N. Hopping, and P.A. March, "Energy Losses Due to Air Admission in Hydroturbines," *Proceedings, National Conference on Hydraulic Engineering*, ASCE, 1991.

Brock, W.G., and J.S. Adams, "A Review of TVA's Aeration and Minimum Flow Improvements on Aquatic Habitat," *Proceedings, Waterpower '97*, ASCE, 1997.

Carter, J.C., Jr., "Recent Experience With Turbine Venting at TVA," *Proceedings, Waterpower '95*, ASCE, 1995.

Electric Power Research Institute (EPRI), "Assessment and Guide for Meeting Dissolved Oxygen Water Quality Standards for Hydroelectric Plant Discharges," *Final Report*, EPRI GS-7001, Project 2694-8, 1990.

Franke, G.F., D.R. Webb, R.K. Fisher, Jr., D. Mathur, P.N. Hopping, P.A. March, M.R. Headrick, I.T. Laczo, Y. Ventikos, and F. Sotiropoulos, "Development of Environmentally Advanced Hydropower Turbine System Design Concepts," *Report No. 2677-0141*, Voith Hydro Inc., 1997.

Harshbarger, E.D., J.C. Carter, Jr., B. Herrold, and G. Robbins, "Turbine Venting for Dissolved Oxygen Improvements at Table Rock, Bull Shoals, and Norfork Dams," *Proceedings, Waterpower '99*, ASCE, 1999.

Hibbs, D.E., J.S. Gulliver, and T.L. Biggs, "Cost Comparison of Dissolved Oxygen Enhancement Systems at the El Vado Dam," *Proceedings, Waterpower '97*, ASCE, 1997.

Hopping, P.N., P.A. March, T.A. Brice, and J.M. Cybularz, "Update on Development of Auto-Venting Turbine Technology," *Proceedings, Waterpower '97*, ASCE, 1997.

Thompson, E.J., J.S. Gulliver, "Oxygen Transfer Similitude for Vented Hydroturbine," *Journal of Hydraulic Engineering*, ASCE, Vol. 123, No. 6, 1997.

USDOE, "Environmental Mitigation at Hydroelectric Projects, Volume 1. Current Practices for Instream Flow Needs, Dissolved Oxygen, and Fish Passage," USDOE Report DOE/ID-10360, 1991.

USEPA, "Dam Water Quality Study," USEPA Report 506/2-89/002, 1989.

USEPA, "Ambient Water Quality Criteria for Dissolved Oxygen," USEPA Report 440/5-86-003, 1986.