# Best Practice Catalog

*Francis Turbine Aeration*

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Prepared by

Hydro Performance Processes Inc.
Doylestown, PA 18901-2963

and

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
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# Contents

# 1.0 Scope and Purpose

This best practice for Francis turbine aeration addresses the technology, condition assessment, operations, and maintenance best practices with the objective to maximize the unit performance and reliability. The primary purpose of a Francis turbine aeration system is to provide air into the turbine as a way of increasing the downstream dissolved oxygen (DO) level for environmental enhancement.

Hydropower plants likely to experience problems with low DO include those with a reservoir depth greater than 50 feet, power capacity greater than 10 MW, and a retention time greater than 10 days [3, 6]. In general, these include plants 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 plants with bottom intakes, this low DO water often creates problems downstream from the reservoir, including possible damage to aquatic habitat. Most of the hydropower plants experiencing problems with low DO have Francis turbines. Typically, the most cost-effective method for increasing the downstream DO level is to use some form of Francis turbine aeration [9, 11].

A Francis turbine aeration system's design, operation, and maintenance provide the most significant impact to the efficiency, performance, and reliability for a hydro unit utilizing the system. Aerating Francis turbines can experience insignificant to moderate (approx. 0.2% - 1%) efficiency losses even without aeration due, for example, to baffles or thicker blades compared to conventional, non-aerating technology. Aerating Francis turbines can experience significant (3% to 10% or more) efficiency losses with aeration, depending on the amount of air introduced into the turbine and the locations where the air is introduced [1, 2, 3, 4]. Francis turbines aerating through existing vacuum breaker systems and Francis turbines retrofitted for aeration using hub baffles typically experience restrictions in both capacity and flexibility that can significantly reduce generation [1, 2, 3, 4, 5, 6, 9, 11, 12].

## 1.1 Hydropower Taxonomy Position

Hydropower Facility → Powerhouse → Power Train Equipment → Turbine → Francis Turbine → Aeration Devices (Francis Turbine Aeration System)

### 1.1.1 Components of a Francis Turbine Aeration System

A Francis turbine aeration system can be either active or passive in design. An active design includes some type of motorized blower or compressor to force air into the turbine for mixing with water in the turbine and/or draft tube. The far more common passive design emphasized in this best practice typically includes either (1) additions or modifications to the turbine runner or draft tube to create zones of localized low pressure and draw atmospheric air into the turbine (see hub baffles in Figure 1) or (2) a turbine runner specifically designed for aeration (see Figure 2). The components of a Francis turbine aeration system affecting performance and reliability typically consist of air intakes, air flow instrumentation, sound mufflers, control valves, and air supply piping, as shown in Figure 3.

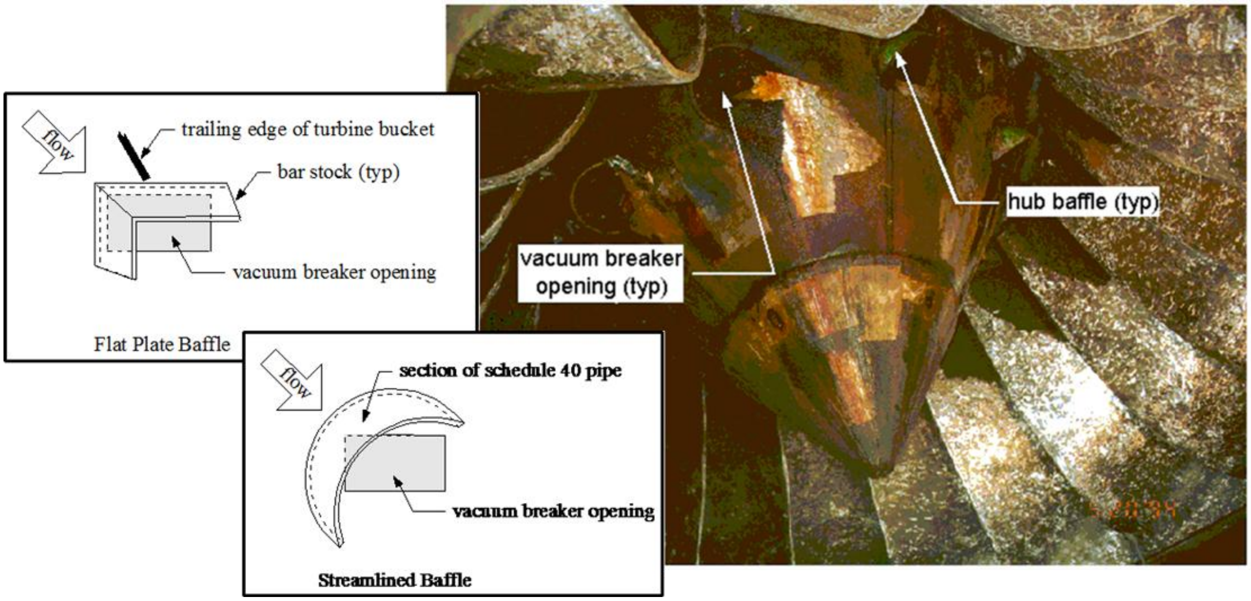


**Figure 1: Photograph of Francis Turbine with Hub Baffles and Diagrams Showing Streamlined and Flat Plate Baffles [6]**

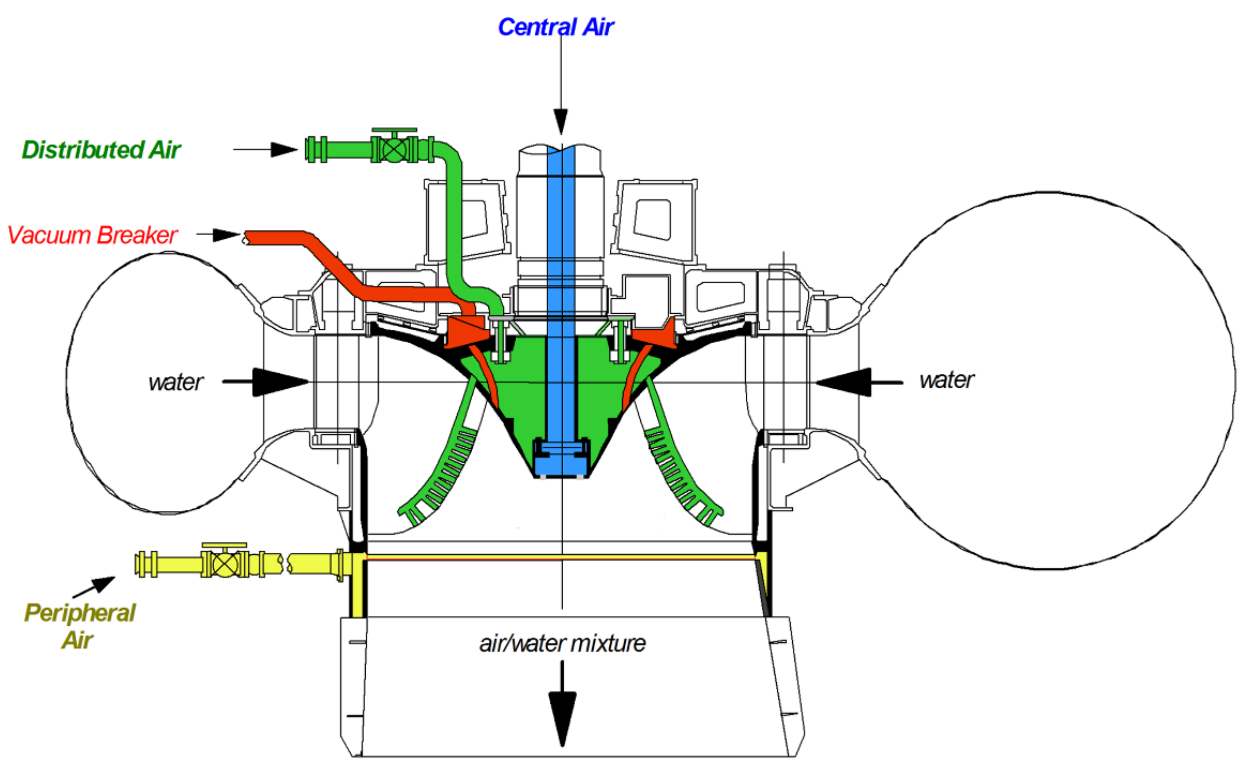


**Figure 2: Sectional View of Francis Turbine with Central Aeration (Red, Vacuum Breaker; Blue, Shaft), Peripheral Aeration (Yellow), and Distributed Aeration (Green) [9]**

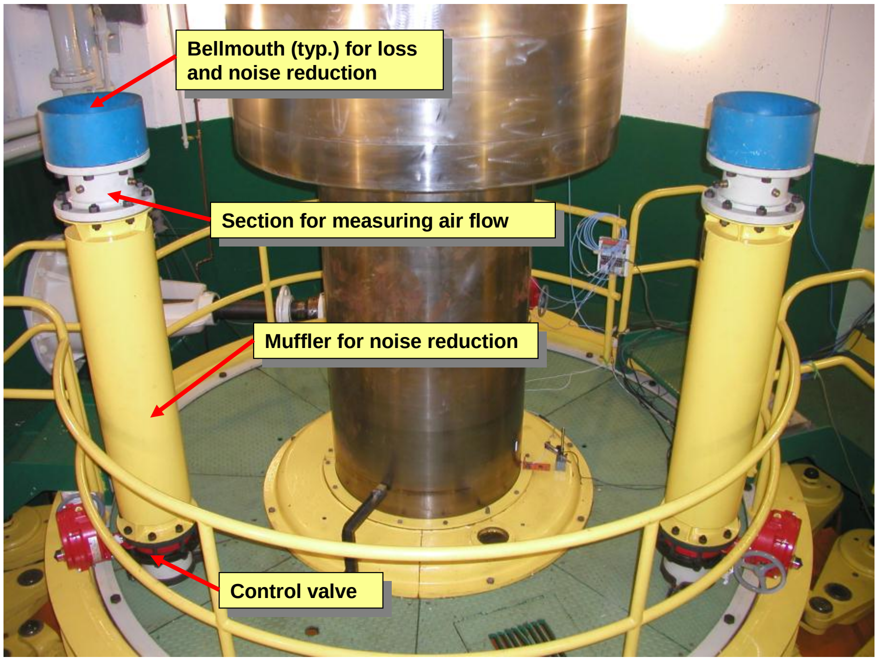


**Figure 3: Typical Configuration for a Francis Turbine Aeration System [7]**

Air Intakes: Properly designed air intakes, typically bellmouths, reduce the noise levels associated with the air flow and reduce pressure losses in the aeration system, which increases air flow through the aeration system. If a standard nozzle design is used for the intake or if the intake is properly calibrated, the intake can also be used for air flow measurement (see Figure 4), which is discussed in the following section.

Air Flow Instrumentation: A variety of technologies can be used for air flow measurements, including bellmouth inlets, Venturi meters, orifice plates, air velocity traverses (typically using a Pitot-static tube or hot-film anemometer), calibrated elbow meters (calibrate off-site with appropriate upstream piping or calibrate in place with velocity traverses), and calibrated single-point velocity measurements (calibrate off-site with appropriate upstream piping or calibrate in place with velocity traverses). The following instruments may also be required for air flow measurements, depending on the type of air flow meters selected for the aeration system:

- Electronic differential pressure cells (preferred), manometers, or mechanical differential pressure gages;
- Thermometers, thermistors, RTDs, or thermocouples for air temperature measurements at primary flow elements;
- Barometer, mechanical pressure gage, or electronic pressure cell for air pressure measurements at primary flow elements; and
- Psychrometer or other means to determine relative humidity at primary flow elements.

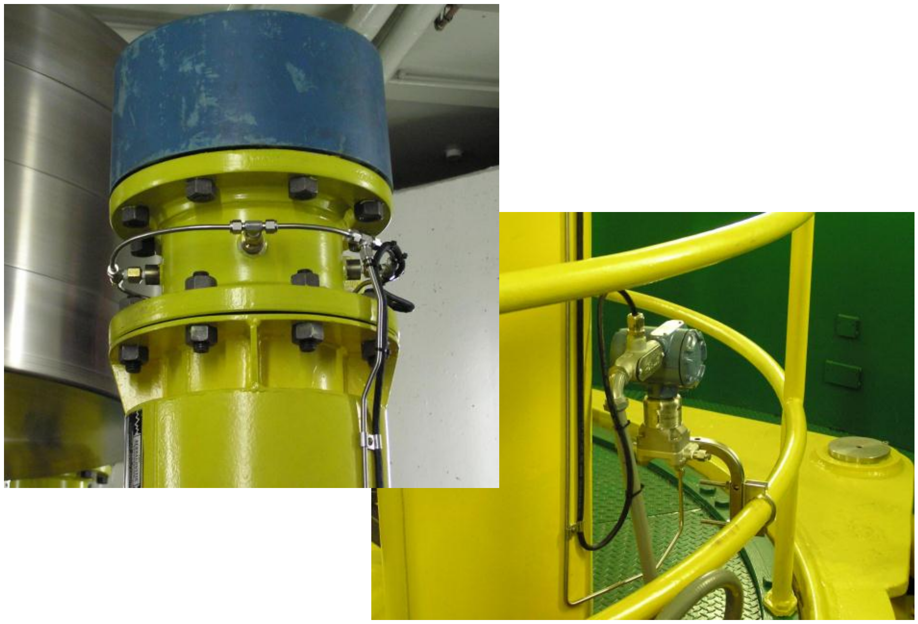

**Figure 4: Inlet nozzle and differential pressure cell for determining air flow [7]**

Detailed instructions, equations, and charts useful for understanding air flow measurements are provided in ASME 1983 [14] and Almquist et al. 2009 [15]. Although the performance test code for turbines and pump-turbines, ASME PTC 18-2011 [16], does not currently include turbine aeration systems, a revision addressing aeration systems is underway [13].

Sound Mufflers: The function of the sound mufflers is to reduce the noise levels associated with air flows into the Francis turbine aeration system. A properly designed muffler will reduce noise to a safe level without significantly decreasing the air flow.

Control Valves: The control valves are used to turn on or shut off the air flows into a Francis turbine aeration system or to regulate the amount of air flow in the system. Control valves may be manually operated, remotely operated, or integrated into the plant's control system.

Air Supply Piping: The Francis Turbine Best Practice discusses the role of the vacuum breaker system for drawing in atmospheric air at low gate openings to reduce vibration and rough operation. Due to the air piping sizes in typical vacuum breaker systems, a retrofitted vacuum breaker system, even with the addition of hub baffles, rarely supplies enough air to produce a significant increase in downstream DO. Both retrofitted aeration systems and aerating turbines typically require additional air supply piping, as shown in Figures 2 and 3.

## 1.2 Summary of Best Practices

### 1.2.1 Best Practices Related to Performance/Efficiency and Capability

Best practices related to performance/efficiency and capability are similar to the Francis Turbine Best Practice, with the addition of aerating operation:

- Establish accurate current unit performance characteristics and limits under both aerating and non-aerating conditions through periodic testing [13, 16].
- Disseminate accurate unit performance characteristics under both aerating and non-aerating conditions to unit operators, local and remote control systems, decision support systems, and other personnel and offices that influence unit dispatch or generation performance.
- Conduct real-time monitoring and periodic analyses of unit performance under both aerating and non-aerating conditions at Current Performance Level (CPL) to detect and mitigate deviations from expected efficiency for the Installed Performance Level (IPL) due to degradation or instrument malfunction.
- Periodically compare the CPL under both aerating and non-aerating conditions to the Potential Performance Level (PPL) under both aerating and non-aerating conditions to trigger feasibility studies of major upgrades.
- Maintain documentation of CPL under both aerating and non-aerating conditions and update when modification to the equipment (e.g., hydraulic profiling, unit upgrade) or the aeration system (e.g., additional air piping, modifications to hub baffles or draft tube baffles, aerating unit upgrade) is made.

### 1.2.2 Best Practices Related to Reliability and Operations & Maintenance

- Use ASTM A487 / A743 CA6NM stainless steel to manufacture Francis turbine runners to maximize resistance to cavitation and cavitation-enhanced corrosion.
- Clad aeration discharge areas with stainless steel to mitigate cavitation-enhanced corrosion.
- Monitor trends for air flows under similar operating conditions to detect aeration system problems.
- Routinely inspect air intakes, mufflers, air piping, and air outlets and remove any obstructing debris for optimal performance.

## 1.3 Best Practice Cross-references

- I&C - Automation Best Practice
- Mechanical – Francis Turbine Best Practice

# 2.0 Technology Design Summary

## 2.1 Technology Evolution

In the 1950s, turbine venting through the vacuum breaker system was introduced in Wisconsin to reduce the water quality impact of discharges from the pulp and paper industry and from municipal sewage systems. Research was also conducted in Europe to develop turbine designs that would boost dissolved oxygen levels in water passing through low head turbines. By 1961, turbine aeration systems were operating in the U. S. at eighteen hydroplants on the Flambeau, Lower Fox, and Wisconsin. During the late 1970s and early 1980s, the Tennessee Valley Authority (TVA) developed small, streamlined baffles, called hub baffles, which reduced energy losses while increasing air flows and operating range for aeration. The hub baffles installed at TVA's Norris Project (see Figure 1) provided DO uptakes averaging 2 to 3 mg/L with typical efficiency losses of 1 to 2% [1].

During the mid-1980s, Voith Hydro Inc. and TVA invested in a joint research partnership to develop improved hydro turbine designs for enhancing DO concentrations in releases from Francis-type turbines. Scale models, numerical models, and full-scale field tests were used in an extensive effort to validate aeration concepts and quantify key parameters affecting aeration performance. Specially-shaped geometries for turbine components were developed and refined to enhance low pressures at appropriate locations, allowing air to be drawn into an efficiently absorbed bubble cloud as a natural consequence of the design and minimizing power losses due to the aeration. TVA's Norris Project, which was scheduled for unit upgrades, was selected as the first site to demonstrate these "auto-venting" or "self-aerating" turbine technologies. The two Norris aerating units contain options to aerate the flow through central, distributed, and peripheral air outlets, as shown in Figure 2.

The successful demonstration of multiple technologies for turbine aeration at TVA's Norris Project in 1995 has helped to develop market acceptance for aerating turbines. Major turbine manufacturers who currently offer aerating turbines include ALSTOM, American Hydro, Andritz, and Voith Hydro.

Performance levels for aerating turbine designs can be stated at three levels as follows:

- The Installed Performance Level (IPL) is described by the unit performance characteristics at the time of commissioning, under aerating and non-aerating conditions. These may be determined from reports and records of efficiency and/or model testing conducted prior to and during unit commissioning.
- The Current Performance Level (CPL) is described by an accurate set of unit performance characteristics determined by unit efficiency and air flow testing, under aerating and non-aerating conditions. This requires the simultaneous measurement of water flow, air flow, head, and power under a range of operating conditions, as specified in the standards referenced in this document [14, 15, 16].
- Determination of the Potential Performance Level (PPL) typically requires reference to new aerating turbine design information from the turbine manufacturer to establish

the achievable unit performance characteristics of the replacement turbine under aerating and non-aerating conditions.

## 2.2 State of the Art Technology

For aerating Francis turbines, turbine efficiencies under aerating and non-aerating conditions are the most important factor in an assessment to determine rehabilitation and replacement, as well as proper operation.

When properly designed, hub baffles typically reduce efficiency by 0.5% to 1% without aeration and 5% or more with aeration, depending on the air flows [1, 2, 3, 4, 5, 9]. In the cross-section through an aerating Francis turbine shown in Figure 2, central aeration through the turbine's vacuum breaker system is shown in red, and central aeration through the shaft is shown in blue. Using an existing vacuum breaker system is typically the aeration option with the lowest initial cost. However, central aeration has the largest effect on unit efficiency, and the capacity and operational range for the turbine may be severely limited [1, 2, 3, 11, 12].

Figure 2 also shows peripheral aeration in yellow and distributed aeration through the trailing edges of the turbine blades in green. Distributed aeration often has the smallest effect on unit efficiency and the highest oxygen transfer into the water (i.e., increased DO), followed by peripheral aeration [11, 12]. For example, a recent study compared the central, peripheral, and distributed aeration systems needed to provide a 5 mg/L DO increase for a plant in the southern USA [12]. In the vicinity of the maximum efficiency, the predicted air flow requirements (i.e., void fraction in %) for central, peripheral, and distributed aeration systems were 7.2%, 6.9%, and 6.5%, respectively. The corresponding efficiency decreases (i.e., non-aerating efficiency minus aerating efficiency, in %) were greater than 10%, 7.4%, and 3.4%, respectively. These predictions are consistent with field test results reported for other sites [6, 8, 11].

In another example, aerating and non-aerating performance testing was conducted according to ASME PTC-18 standards [16] at a hydro plant with multiple types of aerating runners, including two eighty-years-old original runners retrofitted for central aeration, two modern runners installed in 2002 and designed for central aeration, and four state of the art runners installed in 2008 with distributed aeration (see Figure 5) through the trailing edges of the runners [11]. Figure 6 shows the aerating and non-aerating turbine efficiencies versus turbine outputs for the three unit types at this plant, operating at a net head of 95 ft. The turbine efficiencies have been normalized to the maximum measured efficiency of the most efficient unit.

In Figure 6, note the relative efficiencies for the three unit types, the relative effects of aeration on efficiency for central and distributed aeration systems, and the relative amounts of air aspirated by the three unit types. Under non-aerating operation, the 2008 replacement runners (distributed aeration) have the highest peak efficiency, with both the original turbines (retrofitted central aeration) and the 2002 replacement runners (designed central aeration) about 4% lower.

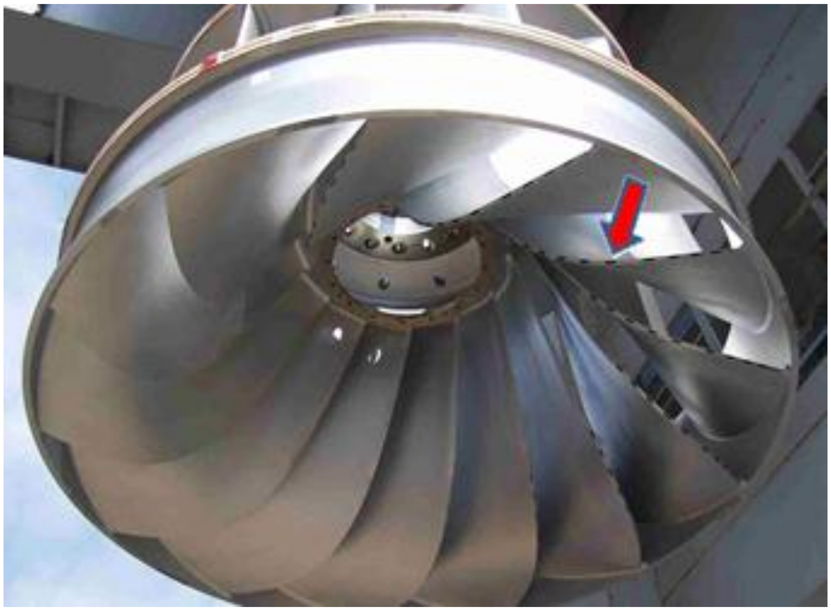

**Figure 5: State of the Art Aerating Turbine with Distributed Aeration**

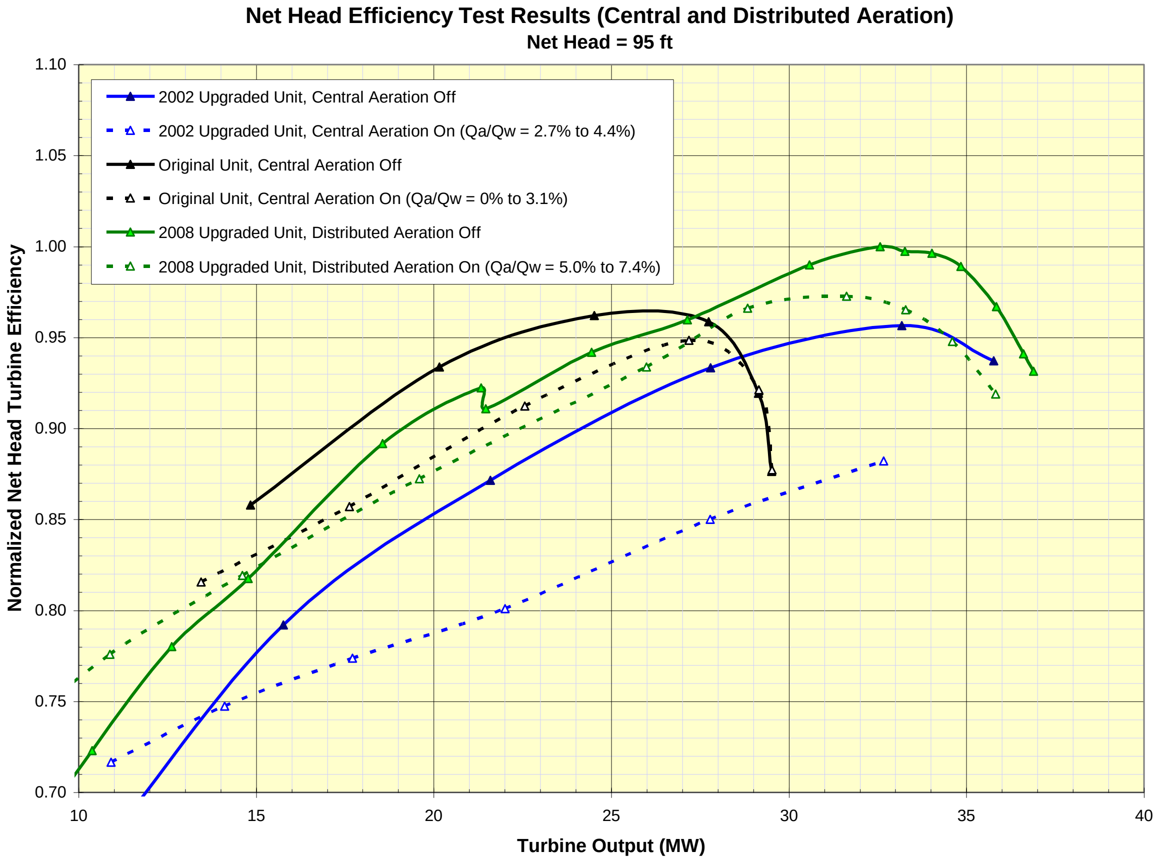


**Figure 6: Normalized Turbine Efficiencies versus Turbine Output for Three Unit Types [11]**

Under aerating operation, peak efficiencies for the 2008 replacement runners, the 2002 replacement runners, and the retrofitted original units drop by about 2.5%, 7%, and 2% (with very low air flows for the retrofitted original units), respectively. Air flow to water flow ratio ranges under aerating operation for the 2008 replacement runners, the 2002 replacement runners, and the retrofitted original runners are 5.0% to 7.4%, 2.7% to 4.4%, and 0% to 3.1%.

The operational challenges for efficient power operation and effective environmental operation of the plant's eight units under non-aerating and aerating conditions, over a range of heads, and with rapid load swings are apparent, emphasizing the importance of proper control system design [11].

# 3.0 Operation & Maintenance Practices

## 3.1 Condition Assessment

After the commercial operation begins, how an aerating Francis turbine is operated and maintained will have a major impact on reducing efficiency losses and maintaining reliability. Materials for turbine runners are usually cast iron, steel, or stainless steel. As a best practice, the most common material being used today for new state of the art runners is ASTM A487 / A743 CA6NM stainless steel (see Francis Turbine Best Practice).

Aeration systems for Francis turbines can take the form of more complex and more energy-consumptive active systems, such as motorized blowers, to the less complex passive systems, such as baffles and aerating runner designs. Focusing on the most common aeration system designs (i.e., passive systems), a simple condition assessment includes inspections of the air intakes, the air discharge passages in the turbine, the dissolved oxygen monitoring equipment, and any observable cavitation or corrosion-related damage that might affect normal operation. A decrease in the expected dissolved oxygen uptake in the waterway downstream from the plant is a good indicator of degradation in the condition of the aeration device.

A comprehensive condition assessment for a Francis turbine aeration system requires information on:

(1) the plant's environmental and regulatory environment, including

- incoming DO, TDG, and water temperature levels throughout the year
- measurement locations and methods for incoming DO, TDG, and temperature (typically, multiple locations in penstock or spiral case)
- regulatory requirements for downstream DO, TDG, and temperature
- measurement locations and methods for downstream DO, TDG, and temperature
- record of compliance and non-compliance;

(2) the plant's operational environment, including

- daily and seasonal operational patterns
- typical tailwater range during periods of aeration
- other restrictions affecting operations (e.g., rough zones, special requirements for functioning of aeration systems);

(3) details of the specific aeration system, including

- type of aeration system (e.g., vacuum breaker, hub baffles, central, peripheral, distributed, multiple methods)
- diameters and lengths of aeration piping
- control valve characteristics;

(4) environmental and hydraulic performance of the specific aeration system, including

- pressures at aeration outlets over the operational range
- head losses for the aeration piping
- air flows through the aeration piping as a function of tailwater elevation, water flow, and control valve position
- turbine efficiency without aeration as a function of power and head
- turbine efficiency with aeration as a function of power, head, and air flow
- DO uptake over the range of operational conditions
- Corresponding TDG levels over the range of operational conditions.

### 3.2 Operations

Because aerating Francis turbines typically have a narrow operating range for peak efficiency (see Figure 6, for example), it is extremely important to provide plant operators or automated control systems with accurate operating curves for the units under aerating and non-aerating conditions. The curves usually originate from the manufacturer's model test data and from post-installation performance testing. Because turbine performance can degrade over time, periodic performance testing must be carried out to determine unit efficiencies and to update the performance curves used for operational decisions. The ten-year testing cycle recommended in the Francis Turbine Best Practice is typically appropriate.

Francis turbine aeration systems may be operated manually or the operation may be integrated into a plant's control system. The detailed aeration instrumentation and controls are site-specific. Aeration systems are often operated conservatively to ensure that environmental requirements for DO levels are maintained. However, this can lead to higher levels of total dissolved gases (TDG), as well as unnecessary efficiency losses due to excessive air flows into the turbine. Some sites have TDG environmental requirements in addition to DO requirements, and the TDG requirements can have an additional negative impact on plant operation and further reduce overall plant efficiency [11].

### 3.3 Maintenance

For Francis turbine aeration systems, all air flow intakes and passageways must be clean and free from obstructions to operate properly. Normal maintenance of a Francis turbine aeration system includes periodic inspection (during routine inspections) and testing of components to ensure that the aeration system is operating according to design. Areas adjacent to the air discharge locations in the turbine or draft tube must be monitored for damage due to cavitation-influenced corrosion. As a best practice, the area surrounding the air discharge locations should be clad with stainless steel to mitigate damage.

The associated instrumentation for Francis turbine aeration systems, including incoming DO levels, compliance point DO levels, air flow rates, air valve control, and air valve positions, must be calibrated and maintained in good working order. Instrumentation for hydraulic performance data, including unit water flow rates, headwater elevations, tailwater elevations, and unit powers, must also be calibrated and maintained in good working order. Data on incoming DO levels, air valve positions, air flow rates, and air temperatures should be recorded at time intervals that can be correlated with other relevant plant data. As a best practice, hydraulic performance data and environmental performance data (incoming DO levels, compliance point DO levels, compliance point TDG levels, unit air flow rates, air temperatures) should be simultaneously recorded and stored in a common database.

# 4.0 Metrics, Monitoring, and Analysis

## 4.1 Measures of Performance, Condition, and Reliability

The fundamental performance measurement for a hydro turbine is described by the efficiency equation, which is defined as the ratio of the power delivered by the turbine to the power of the water passing through the turbine. The general expression for this efficiency ($\eta$) is

$$\eta = \frac{P}{\rho g Q H}$$

where P is the output power, $\rho$ is the density of water, g is the acceleration of gravity, Q is the water flow rate through the turbine, and H is the head across the unit [16].

The condition of an aerating Francis turbine can be monitored by the Condition Indicator (CI) as defined according to the HAP Condition Assessment Manual [10].

Unit reliability characteristics, as judged by the unit's availability for generation, can be monitored by use of the North American Electric Reliability Corporation (NERC) performance indicators, such Equivalent Availability Factor (EAF) and Equivalent Forced Outage Factor (EFOR), which are used universally by the power industry [17]. However, hydro plant owners typically do not designate whether or not their Francis turbines are aeration-capable and do not differentiate between aerating and non-aerating operation.

## 4.2 Data Analyses

The key measurements for hydraulic performance include headwater elevation, $H_{HW}$ (ft); tailwater elevation, $H_{TW}$ (ft); water flow rate through Unit N without aeration, $Q_N$ (cfs); power output for Unit N without aeration, $P_{ON}$ (MW); and $T_H$, the measurement timestamp for hydraulic data. The key measurements for environmental performance include incoming DO level for Unit N, $L_{DON}$ (mg/L); incoming TDG level for Unit N, $L_{TDGN}$ (%); incoming water temperature, $F_{WTN}$ (degrees F); downstream DO level for plant at the compliance location, $L_{DOC}$ (mg/L); downstream TDG level, $L_{TDGC}$ (%) at the compliance location; and downstream water temperature, $F_{WTC}$ (degrees F), at the compliance location; air flow rate through Unit N, $Q_{AN}$ (cfs); water flow rate through Unit N with aeration, $Q_{NA}$ (cfs); power output for Unit N with aeration, $P_{ONA}$ (MW); and $T_E$, the measurement timestamp for environmental data. Measurements can be near real-time or periodic (hourly, daily), depending on the site details, license requirements, and operational requirements.

The unit efficiency $\eta_N$ (nondimensional) for operation without aeration is:

$$\eta_N = P_{ON}/[K\rho g Q_N(H_{HW} - H_{TW})/(1{,}000{,}000)]$$

where K is a dimensional constant, $\rho$ is the density of water at Unit N, and g is the acceleration of gravity at Unit N. For most cases, using $K\rho g = 84.5$ provides satisfactory results.

The unit efficiency $\eta_{NA}$ (nondimensional) for operation with aeration is:

$$\eta_{NA} = P_{ONA}/[K\rho g Q_{NA}(H_{HW} - H_{TW})/(1{,}000{,}000)]$$

References provide detailed guidance on performing the key hydraulic measurements [16] and the key environmental measurements [14, 15].

The unit efficiency loss due to aeration is equal to $\eta_N$ minus $\eta_{NA}$ for a given power level. However, detailed data analyses are required to determine what portion of these efficiency losses are avoidable, due to over-aeration, suboptimization, etc., and to compute the associated revenue losses. In general, aeration-induced efficiency losses greater than 2% to 3% warrant further investigation. The costs associated with the aeration-induced efficiency losses, capacity losses, and reductions in operational flexibility should be established for comparison with the associated revenue losses and used to optimize aeration operations and to evaluate and justify new aeration systems, including turbine replacements.

The condition assessment of an aerating Francis turbine is quantified through the CI, as described in the HAP Condition Assessment Manual [10]. The overall CI is a composite of the CI derived from each component of the turbine. This methodology can be applied periodically to derive a CI snapshot of the current turbine condition so that it can be monitored over time and studied to determine condition trends that can impact performance and reliability.

The reliability of a unit as judged by its availability to generate can be monitored through reliability indexes or performance indicators as derived according to NERC's Appendix F, *Performance Indexes and Equations* [17].

### 4.3 Integrated Improvements

Data on lost efficiency, lost capacity, and operational restrictions due to Francis turbine aeration systems can be used to quantify lost revenues from generation and ancillary services, and the economic losses can be used to evaluate and justify funding for aeration system improvements, including turbine replacement.

The periodic field test results should be used to update the unit operating characteristics and limits. Optimally, the updated results would be integrated into an automated control system. If an automated control system is not available, hard copies of the updated curves and limits should be made available to all relevant personnel, particularly unit operators, and the importance of the updated results should be emphasized, discussed, and confirmed.

## 5.0 Information Sources:

*Baseline Knowledge:*


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4. Carter, J., "Recent Experience with Hub Baffles at TVA," *ASCE Proceedings of Waterpower 95*, San Francisco, California, July 25-28, 1995.

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*Standards:*

14. ASME, *Fluid Meters: Their Theory and Application*, New York, New York: American Society of Mechanical Engineers (ASME), 1983.

15. Almquist, C. W., P. N. Hopping, and P. J. Wolff, “Draft Test Code for Aerating Hydroturbines,” TVA Report No. WR98-1-600-125, Norris, Tennessee: Tennessee Valley Authority (TVA), August 1998.

16. ASME, *Performance Test Code 18: Hydraulic Turbines and Pump-Turbines*, ASME PTC 18-2011, New York, New York: American Society of Mechanical Engineers (ASME), 2011.

17. NERC, *Appendix F: Performance Indexes and Equations*, January 2011.

*It should be noted by the user that this document is intended only as a guide. Statements are of a general nature and therefore do not take into account special situations that can differ significantly from those discussed in this document.*

For overall questions
please contact:

Brennan T. Smith, Ph.D., P.E.
Water Power Program Manager
Oak Ridge National Laboratory
865-241-5160
smithbt@ornl.gov

or

Qin Fen (Katherine) Zhang, Ph. D., P.E.
Hydropower Engineer
Oak Ridge National Laboratory
865-576-2921
zhangq1@ornl.gov