Best Practice Catalog

Francis Turbine

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1.0 Scope and Purpose

This best practice for a Francis turbine addresses its technology, condition assessment, operations, and maintenance best practices with the objective to maximize its performance and reliability. The primary purpose of the turbine is to function as the prime mover providing direct horsepower to the generator. It is the most significant system in a hydro unit. How the turbine is designed, operated, and maintained provides the most impact to the efficiency, performance, and reliability of a hydro unit.

1.1 Hydropower Taxonomy Position

Hydropower Facility → Powerhouse → Power Train Equipment → Turbine → Francis Turbine

1.1.1 Francis Turbine Components

Performance and reliability related components of a Francis turbine consist of a spiral case, stay ring/stay vanes, wicket gates, reaction type runner, vacuum breaker, aeration device, and draft tube.

Spiral Case: The function of the spiral case (or scroll case) is to supply water from the penstock to the stay vanes while maintaining near uniform water velocity around the stay vanes and wicket gates as achieved by its unique shape and continual cross sectional area reduction.

Stay Ring/Vanes: The function of the stay vanes (and stay ring) is to align the flow of water from the spiral case to the wicket gates. They also usually function as support columns in vertical units for the static weight of the unit's stationary components and hydraulic thrust during turbine operation.

Wicket Gates: The function of the wicket gates is primarily to control the quantity of water entering the turbine runner, thereby controlling power output. Secondarily, the gates control the angle of the high tangential velocity water striking the runner bucket surface. The optimum angle of attack will be at peak efficiency. The wicket gates also function as a closure valve to minimize leakage through the turbine while it is shutdown. Leakage can also originate from water passing by the end seals on the gates between the top end of the gates and head cover and the bottom end of the gates and bottom ring.

Runner: The function of the runner is to convert the potential energy of pressure (head) and flow of water into mechanical energy or rotational horsepower which is supplied directly to the turbine shaft. There are various types of designs such as horizontal or vertical orientations, single discharge, double discharge, and overhung designs. The most prevalent type is a vertical unit.

Vacuum Breaker: The function of the vacuum breaker is to admit air to a zone near the turbine runner [2]. It is usually an automatic device either spring loaded or cam operated off the wicket gate shifting ring. For reaction turbines it is used for drawing in atmospheric air at low gate openings, such as synchronizing and speed no load, to reduce vibration and rough operation. While this reduces rough operation, it also reduces turbine efficiency by introducing vacuum and air vortices beneath the runner.

Aeration Device: The function of an aeration device is for the inlet of air into the turbine to provide for an increase in dissolved oxygen in the tailrace waterway for environmental enhancements. The device can be either active or passive in design with the passive designs being more common. An active design would include some type of motorized blower or compressor to force air into the turbine for mixing with water in the turbine and/or draft tube. A passive design would consist of some type of addition or modification to a turbine runner to naturally draw in atmospheric air into the turbine. This in its most basic form is done through adding baffles to vacuum breaker air discharge ports in the crown or nose cone of the turbine runner and blocking the vacuum breaker open. The latest and most efficient method is an aerating turbine runner designed and built to discharge the air through internal porting in the runner and out the blade tips.

Draft Tube: The function of the draft tube is to gradually slow down the high discharge velocity water capturing the kinetic energy from the water, which is usually below atmospheric pressure. In most cases, it has an elbow in order to minimize excavation for the unit. The head recovery from the draft tube is the difference between the velocity head at the runner discharge and the draft tube discharge overall, increasing the head across the turbine. The larger the head differential is across the turbine, the higher the turbine power output. The draft tube should be steel lined from the discharge ring to the point where the water velocity reduces to about 20 ft/s, which is considered below concrete scouring velocity [1].

Non-performance but reliability related components of a Francis turbine include the wicket gate mechanism/servomotors, head cover, bottom ring, turbine shaft, guide bearing, and mechanical seals/packing.

Wicket Gate Mechanism/Servomotors: The function of the wicket gate mechanism and servomotors is to control the opening and closing of the wicket gate assembly. The mechanism includes arms, linkages, pins, shear pins, turnbuckles or eccentric pins for closure adjustment, operating ring (or shift ring, and bearing pads), and bushings either greased bronze or greaseless type. Servomotors are usually hydraulically actuated using high pressure oil from the unit governor. In some limited cases a very small unit may have electro-mechanical servomotors.

Head Cover: The head cover is a pressurized structural member covering the turbine runner chamber that functions as a water barrier to seal the turbine. It also serves as a carrier for the upper wicket gate bushings, upper seal surface for the wicket gate vanes, support for the gate operating ring, carrier for the runner stationary seal rings, and support for the turbine guide bearing.

Bottom Ring: The bottom ring serves as a carrier for the bottom wicket gate bushings, bottom seal surface for the wicket gate vanes, and a carrier for the bottom runner stationary seal ring.

Turbine Shaft: The function of the turbine shaft is to transfer the torque from the turbine runner to the generator shaft and generator rotor. The shaft typically has a bearing journal for oil lubricated hydrodynamic guide bearings on the turbine runner end or wearing sleeve for water lubricated guide bearings. Shafts are usually manufactured from forged steel, but some of the largest shafts can be fabricated.

Guide Bearing: The function of the turbine guide bearing is to resist the mechanical imbalance and hydraulic side loads from the turbine runner thereby maintaining the turbine runner in its centered position in the runner seals. It is typically mounted as close as practical to the turbine runner and supported by the head cover. Turbine guide bearings are usually either oil lubricated hydrodynamic (babbitted) bearings or water lubricated (plastic, wood, or composite) bearings.

Mechanical seals/packing: Sealing components in the turbine include the seal for the turbine shaft and the wicket gate stem seals. Shaft seals are typically either packing boxes with square braided packing or for high speed units a mechanical seal is required. Wicket gate stem packing is usually either a square braided compression packing, a V type or Chevron packing, or some type of hydraulic elastomer seal. Although in the truest sense, any sealing components on a turbine could be a performance issue, since any leakage that by-passes the turbine runner is a loss of energy, the leakage into the wheel pit is considered insignificant to the overall flow through the turbine.

1.2 Summary of Best Practices

1.2.1 Performance/Efficiency & Capability - Oriented Best Practices

Performance levels for 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. 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 testing, which requires the simultaneous measurement of flow, head, and power under a range of operating conditions, as specified in the standards referenced in this document.

Determination of the Potential Performance Level (PPL) typically requires reference to new turbine design information from manufacturer to establish the achievable unit performance characteristics of replacement turbine(s).

- Periodic testing to establish accurate current unit performance characteristics and limits.
- Dissemination of accurate unit performance characteristics to unit operators, local and remote control and decision support systems, and other personnel and offices that influence unit dispatch or generation performance.
- Real-time monitoring and periodic analysis of unit performance at CPL to detect and mitigate deviations from expected efficiency for the IPL due to degradation or instrument malfunction.
- Periodic comparison of the CPL to the PPL to trigger feasibility studies of major upgrades.
- Maintain documentation of IPL and update when modification to equipment is made (e.g., hydraulic profiling, draft tube slot fillers, unit upgrade).
- Trend loss of turbine performance due to condition degradation for such causes as metal loss (cavitation, erosion, and corrosion), opening of runner seal, opening of wicket gate clearances, and increasing water passage surface roughness. Adjust maintenance and capitalization programs to correct deficiencies.
- Include industry acknowledged "up to date" choices for turbine components materials and maintenance practices.

1.2.2 Reliability/Operations & Maintenance - Oriented Best Practices

- Use ASTM A487/A743 CA6NM stainless steel to manufacture Francis turbine runners, wicket gates, and water lubricated bearing shaft sleeves. This martensitic grade of stainless steel is a good compromise between its performance properties (resistance to wear, erosion and cavitation) versus the austenitic grade stainless steels (300 series) which carry an inhibitive higher cost. [19, 20]
- Bushing clearances greater than two times the design are considered excessive and warrants replacement.
- Wicket gate shear pins (mechanical fuse) are an engineered product designed to prevent failures of more costly components in the mechanism. When replacing pins or spare pins, it is best practice, to purchase the pin material from one manufacturer to ensure material properties remain consistent. Prototype sample pins are manufactured and tested to finalize the diameter for the final pin shop drawing.
- Turbine shaft areas near the shaft seal that are exposed to water should be sealed with a robust coating such as an epoxy paint to prevent corrosion of the shaft.
- Damage from erosion and cavitation on component wetted surfaces are repaired using 309L stainless steel welding electrodes. This austenitic grade stainless steel

enables the avoidance to post heat treatment of repaired components and increases damage resistance.

- When turbine runner seal clearances reach twice the design value, one should consider rehabilitating or replacing the runner due to efficiency loss.
- Francis turbines with heads above 100 feet should be considered candidates for embedded wicket gate vane end seals and wicket gates fabricated from stainless steel to mitigate leakage and wear.
- Adequate coating of the turbine wetted components not only prevents corrosion but has added benefits of improved performance.
- Vacuum breakers should be inspected routinely and adjusted for optimal performance.
- Discharge areas on a turbine runner for aeration devices should be clad with stainless steel to mitigate cavitation.
- Wicket gate mechanism linkage bushings should be of the greaseless type to reduce grease discharge to the wheel pit and ultimately the station sump. Use greaseless bushings in other applications if possible; however, care must be taken in any retrofit to ensure that the servomotors are strong enough to operate even after a 25% increase in long term friction.
- For applications above 200 feet of head, stainless steel wearing plates embedded into the head cover and bottom ring immediately above and below the wicket gate vanes are recommended.
- Kidney loop filtration should be installed on turbine guide bearing oil systems.
- Automatic strainers with internal backwash should be installed to supply uninterrupted supply of clean water to water lubricated turbine guide bearings.
- Monitor trends of decrease in condition of turbine (decrease in Condition Indicator (CI)), decrease in reliability (an increase in Equivalent Forced Outage Rate (EFOR), and a decrease in Effective Availability Factor (EAF)). Adjust maintenance and capitalization programs to correct deficiencies.

1.3 Best Practice Cross-references

- I&C – Automation
- Mechanical – Lubrication System
- Electrical – Generator
- Mechanical – Governor
- Mechanical – Raw Water System

2.0 Technology Design Summary

2.1 Material and Design Technology Evolution

Francis turbine runners are typically manufactured as one piece, either as a casting or as a welded fabrication. Very old runners, from the early 1900's or before, were cast from cast iron or bronze and later replaced with cast carbon steel. Today runners are either cast or fabricated from carbon steel or stainless steel. Just as materials have improved for modern turbine runners, so has the design and manufacturing to provide enhanced performance for power, efficiency, and reduced cavitation damage.

Best practices for the turbine begins with a superior design to maximize and establish the baseline performance while minimizing damage due to various factors, including cavitation, pitting, and rough operation. The advent of computerized design and manufacturing occurred in the late 1970's and 1980's and made many of the advancements of today possible. Modern Computational Fluid Dynamics (CFD) flow analysis, Finite Element Analysis techniques (FEA) for engineering, and Computer Numerically Controlled (CNC) in manufacturing have significantly improved turbine efficiency and production accuracy.

2.2 State of the Art Technology

Turbine efficiency is likely the most important factor in an assessment to determine rehabilitation or replacement. Such testing may show CPL has degraded significantly from IPL. Figure 1 is an example of the peak efficiency of a Francis unit with a percentage point drop in peak efficiency of greater than 3 in a 35 year period since it went into commercial operation. Regardless of whether performance has degraded or not, newer turbine designs are usually more efficient than those designed 30 to 40 years ago. Also, a new turbine can be designed using actual historical operations rather than original design data providing a turbine more accurately suited for the site.

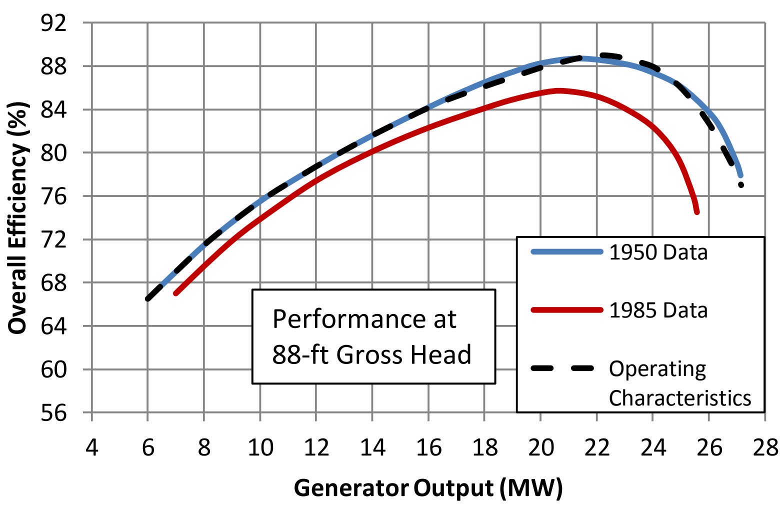

Figure 1: Example - Original vs. Degraded Performance Curves [8]

Newer state of the art turbine designs can not only achieve the PPL but also provide decreased cavitation damage based on better hydraulic design and materials [3]. Figures 2 and 3 show an original runner and its state of the art stainless steel replacement runner, as a comparison. Figure 6 shows a state of the art aerating runner which discharges the air from the bucket tips.

Figure 2: Original Runner

Figure 3: New Stainless Steel Replacement Runner

3.0 Operation and Maintenance Practices

3.1 Condition Assessment

After the commercial operation begins, how the turbine is operated and maintained will have a huge impact on loss prevention of the IPL and CPL 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 [19, 20]. It is cavitation resistant, fairly easy to cast and fabricate, and can usually be weld repaired without post heat treatment. The same is true for wicket gate materials.

The other wetted turbine components such as stay vanes, spiral cases, and draft tubes are usually constructed from steel due to strength requirements. Some components have stainless steel cladding overlaid in critical areas. The most significant contributor to performance loss for all wetted components is any metal loss due to cavitation, as shown in Figure 4, abrasive erosion, surface finish degradation, and the poor quality of past repairs which can distort the hydraulic design contours of components.

Condition assessment of those flow components must address any past damage, location of damage, repeat damage, and resulting increase in surface roughness. Evaluating the overall condition of a turbine and all its components may show that a new state of the art turbine runner with enhanced power and efficiency may provide sufficient benefits to justify its replacement, including rehabilitating related components, as compared to maintaining current turbine with existing efficiency [3].

Figure 4: Typical Cavitation Damage to Runner Blade

The vacuum breaker or air inlet valve is usually mounted directly to turbine head cover and will probably require disassembly for a thorough condition assessment. A condition assessment would include observing operation of the vacuum breaker during startup. Loose operation or banging of the seals would indicate a misadjusted or worn device requiring maintenance. Unit performance can also be checked with the valve opened, closed, and in normal operating position to measure and contrast any difference in unit performance that would indicate a problem with the valve.

Aeration devices for the turbine can take the form of more complex active systems, such as motorized blowers, to the less complex passive systems, such as baffles and self aspirating runner designs. The passive designs are the most common practice, as shown in Figures 5 and 6.

Focusing on the most common designs, the condition assessment would include inspections of the air discharge passages in the turbine and any observable cavitation or erosion damage that might affect its normal operation. A decrease of normal dissolve oxygen uptake in the waterway downstream could be an indicator of degradation of the condition of the aeration device.

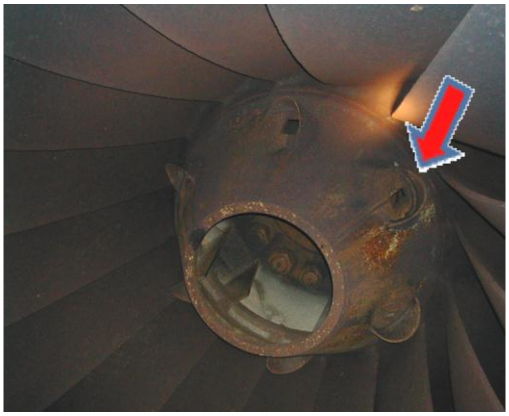

Figure 5: Aeration Baffles on Nose Cone

Figure 6: Aerating Runner (through bucket tips)

The wicket gate mechanism (Figure 7) and the actuating servomotors provide for the regulation and control of the turbine. The condition assessment of the components would include measurements of wear or looseness in the arms, linkages, pins, shear pins, turnbuckles (or eccentric pins), linkage bushings, operating ring (and bearing pads), and wicket gate stem bushings. It is important to note that excessive wear in the components is additive and can result in losing off-line regulating control of the wicket gates making it more difficult to synchronize the unit. This is an indication that rehabilitation of the components is necessary. Measurement of wear is difficult without disassembly; however, extreme wear can be observed as loss of motion in gate movements.

In some turbine designs it is possible during dewatered outages, to measure the clearance between the wicket gate stem journals and the inside diameter of the bushings with feeler gauges. Abnormal water leakage around the wicket gates in the turbine wheel pit after an attempt to adjust the stem packing is an indicator of excessive wicket gate stem bushing wear. As a best practice, bushing to journal clearance greater than two times the design is considered excessive. An increase in the number of shear pin failures over a given period is an indication of either a problem with the design and material used to manufacture the pins or a problem with binding in the mechanism.

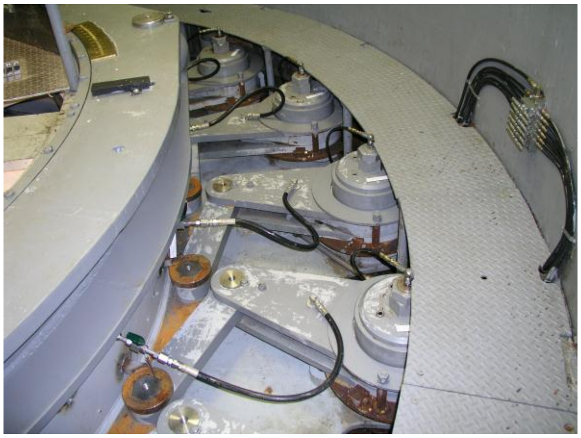

Figure 7: Wicket Gate Mechanism

Hydraulic servomotors (Figure 8) are usually very reliable, with the most common problem being oil leakage from the seal on the actuating rod. The amount of acceptable leakage is dependent on the seal design and site maintenance requirements. Hydraulic seals will leak very little whereas a square braided compression packing will leak more. A condition assessment would include observation of the leakage and discussion with the plant maintenance technicians as to the amount of daily or weekly maintenance required. Excessive maintenance would require the change of the seal or packing. It is important to note and observe if the actuating rod is smooth and without any scoring or grooves which would prevent sealing. If the rod is damaged it will require repair or replacement.

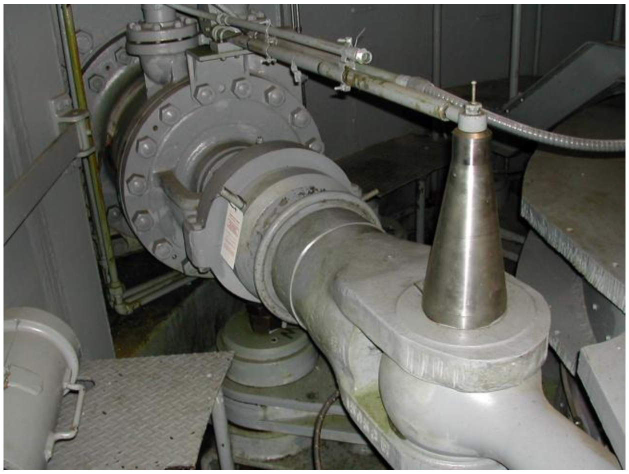

Figure 8: Wicket Gate Servomotor

The condition assessment of the head cover and bottom ring consists mainly of visually inspecting the wetted surfaces for erosion and cavitation. Cracking in either component or deep erosion in the water barrier of the head cover is a major concern and must be addressed immediately. Excessive corrosion of the joint bolting (stay ring flange or split joints) or failure of the bolting is a major concern and must be addressed immediately. The assessment would also include observation of any galling between the ends of the wicket gate vanes, the head cover, bottom ring and damage to embedded end seals.

The condition assessment of the turbine shaft (Figure 9) would include observation of corrosion and defects on the exposed surface. Any cracking as identified by the Nondestructive Examination (NDE) methods is a major concern and must be addressed immediately.

Bearing journals and sleeves must be smooth and free of defects (only accessible with bearing removed) to ensure the reliability of the turbine guide bearing. As a best practice for water lubrication turbine bearings, wearing sleeves are usually manufactured from ASTM A487/A743 CA6NM stainless steel either as a forging or centrifugally cast [19, 20]. Areas near the shaft seal that are exposed to water should be sealed with a robust coating such as an epoxy paint to prevent corrosion of the shaft.

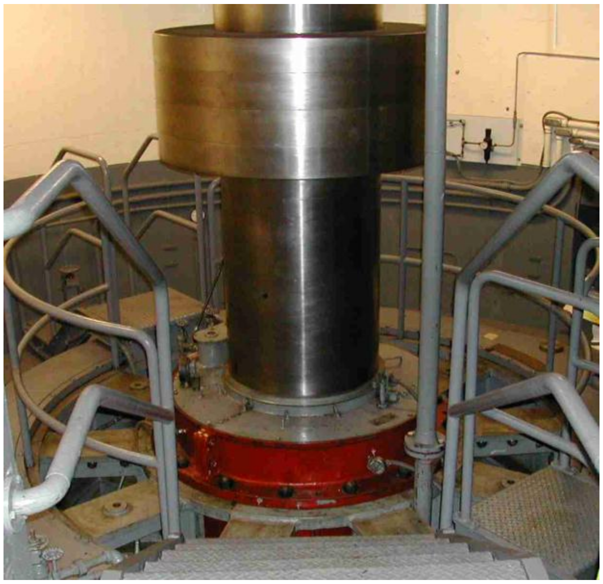

Figure 9: Turbine Shaft / Wheel Pit

Turbine guide bearings are usually either oil lubricated hydrodynamic bearings (Figure 10) or water lubricated bearings (Figure 11), with the latter being found only in low head slow speed units. The condition assessment of the oil lubricated type includes vibration measurements (i.e. shaft throw) and temperature of the bearing in operation. Abnormal indications of those could be a sign of failure of the babbitted surface (wipe), un-bonding of the babbitt from the bearing housing, or contamination of the oil. The condition assessment of a water lubricated type centers mainly on vibration measurements and success of subsequent bearing adjustments if the design permits. An indication of a loose wearing sleeve on the shaft is excessive shaft throw (vibration) even after adjusting the bearing. Non-adjustable water lubricated bearings, or bearings worn beyond adjustment will require the wearing liner (either wood, plastic, or composite) to be replaced.

Figure 10: Babbitted Oil Journal Bearing

Figure 11: Water Lubricated Bearing

The condition assessment of the wicket gate stem seals or shaft seals usually includes the observation of excessive water leakage in the turbine wheel pit area which can be viewed visually or estimated by sump pump operation (if available). Excessive leakage, even after adjustments (if possible by design), is an indication that the seals or packing must be replaced.

3.2 Operations

Since Francis turbines have a very narrow operating range for peak efficiency (Figure 12), it is extremely important for plant operations to have an accurate operating curve for the units. The curves originate from the manufacturer's model test data and post installation performance testing. The performance of the turbine can degrade over time due to cavitation and/or erosion damage and resulting weld repairs, etc. Therefore to maximize unit efficiency, periodic performance testing either as absolute or relative testing must be carried out to update operational performance curves. An example of relative testing would be index testing (using Winter Kennedy taps).

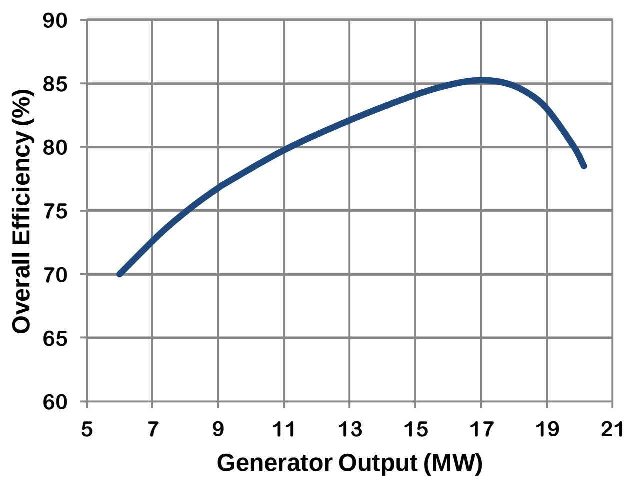

Figure 12: Typical Francis Performance Curve

"Frequent index testing, especially before and after major maintenance activities on a turbine, should be made to detect changes in turbine performance at an early stage and establish controls [9]." Plants should, as best practice, perform periodic performance testing (such as index testing according to PTC 18 [14]) to assure the most accurate operating curves are available to optimize plant output. Routinely, this should be done on a 10 year cycle as a minimum.

3.3 Maintenance

It is commonly accepted that turbines normally suffer from a progressive deterioration in performance over time (in default of restorative action) [4]. Usual causes include cavitation damage, abrasive erosion wear, galvanic corrosion, impact damage from debris passing through, and errors in welding repairs to original runner blade profile and surface finish. Performance related maintenance techniques involve mainly those weld repairs for cavitation damage, abrasive erosion damage, and galvanic corrosion on the turbine components such as the runner, wicket gates, stay vane, spiral case and draft tube. The usual best practice is to perform cladding with a 309L stainless steel welding electrode to provide some cavitation resistance. In some cases, original blade contour templates are available at the plant to facilitate returning the blade back to Original Equipment Manufacturer (OEM) specifications. A good reference for turbine maintenance is the USBR's FIST Volume 2-5, *Turbine Repair* [6] and *Hydro Wheels: A Guide to Maintaining and Improving Hydro Units* [14].

Francis turbine runners usually have replaceable seal rings or wear rings on the outside diameter of the crown and band or provisions for adding such in the future. It is essential to maintain adequate sealing to prevent excessive hydraulic thrust loads on the generator thrust bearing (bearing carrying the unit's axial load, i.e., static weight plus hydraulic thrust) and prevent excessive water leakage by-passing the runner.

The generator thrust bearing is designed to handle hydraulic loads from the seals worn to twice the design value [1]. Therefore, as a best practice, when runner seal clearances reach twice the design value, one should consider rehabilitating or replacing the runner. Seal ring clearances are usually measured with feeler gauges during routine maintenance and documented for trending over time. For high head units, leakage by these seal rings may affect the overall efficiency of the turbine by 1 to 3% [5].

Worn wicket gate end clearances can also contribute to a decline in unit performance since leakage contributes to power generation loss, particularly by those units with a low service factor (i.e., gates in closed position for a significant period of time). In a new unit, the leakage through properly designed wicket gates may be markedly less than 1% of full gate discharge; however, over years of operation this could be doubled due to eroded end clearances, worn stem journal bushings, and improperly adjusted toe to heel closures [5]. As a best practice, turbines with heads above 100 feet should be considered as candidates for embedded wicket gate vane end seals and wicket gates fabricated from stainless steel to mitigate leakage and wear.

Investigations by the US Army Corps of Engineers (USACE) show minor modifications to the stay vane - wicket gate system which could result in an operation efficiency increases of 0.5 to 0.7% for the units studied [11]. As shown in reference [11], the modification takes the form of profile change on the stay vane leading and trailing edges modifying the wake relative to the wicket gate. These changes have to be studied in a Computational Fluid Dynamics (CFD) model and/or physical model. In addition, such modifications can reduce fish injury as one environmental benefit.

In some cases, Von Karman vortices can trail off the wicket gates during high flow operation, impinging on the runner band and blades with resulting cavitation damage. Flow profile modifications, including a narrowing of the lower trailing edges (as shown in Figure 13) of the wicket gates, can reduce the formation of vortices, and thus allow higher flow rates and power output. The exact profile change should be designed based on CFD and/or physical modeling.

Figure 13: Wicket Gate Modification

Further studies by the USACE to improve turbine efficiency have found some relationship between surface roughness of the turbine components, and degradation of the unit performance [10]. It is commonly known that surface roughness on flow surfaces robs a moving fluid of energy; similar to what is found in piping systems. A higher relative roughness will increase the friction loss usually expressed in the head.

Since the power generated by a turbine is directly related to head, logically, any loss in head by frictional losses of the water flowing through the turbine will be a loss in performance. Improvements in surface finish include grinding and coating (painting) the surfaces. In some cases, the USACE tests found efficiency improvements of 0.1 to 0.8% comparing pre-coated versus post-coating performance [10]. However, the level of uncertainty of field testing measurement can range up to 1%, which makes it difficult to quantify results within testing error. Common maintenance best practice of providing adequate coating of the turbine components to prevent surface corrosion does have added benefits of improved performance, however unquantifiable.

By design, a vacuum breaker introduces atmospheric air into the sub-atmospheric area below the runner reducing the pressure across the runner, thereby reducing efficiency. The vacuum breaker should be able to work at the smallest possible gate setting to avoid vibration and rough operation, but not admit air at the higher operating gate settings. Best practice for the vacuum breaker includes periodic maintenance (during routine inspections) to assure proper operation and evaluation of the condition of the main seals to prevent leakage. It is important that any stroke dampening devices built into the vacuum breaker be checked and adjusted annually to avoid excessive cycling (banging) of the seal during operation. The vacuum breaker, being a mechanical device subject to frictional wear, will require major maintenance (overhauling) based on number of cycles of operation, but typically every 10 to 20 years.

Maintenance of any aeration device on the turbine includes periodic inspection (during routine inspections) and testing of components to ensure the device is operating according to design. Areas adjacent to the air discharge in the turbine must be monitored for damage due to erosion or cavitation. As a best practice, those areas if not stainless steel already should be clad with stainless steel to mitigate damage.

Pressures in the draft tube increase as the water flows from the elbow to the exit. If the top of the draft tube gate slots (close to the elbow) is submerged (under tail water), water can be drawn down into the draft tube due to the lower pressure there, increasing the total flow in the draft tube from that point to the exit, thereby increasing the head loss and reducing the unit efficiency. The closer the gate slot is to the centerline of the unit, the greater the effect. The use of slot fillers to plug the upper openings of the gate slots have been shown to remedy this problem and in some cases improving efficiency by as much as 1%.

The wicket gate mechanism consists of arms, linkages, pins, shear pins, turnbuckles (or eccentric pins), linkage bushings, operating ring (and bearing pads), and wicket gate stem bushings. For greased bushing designs, it is essential that the greasing system is functioning to original specification with metered grease flowing to all points. It is important to grease the wicket gate stem bushings and observe if the grease is entering the bushing clearance and visually discharging. If not, this will have to be repaired immediately.

Greaseless bushing designs require less routine maintenance than the greased designs; however, the most common maintenance issue is broken or loose anti-rotation devices on the pins. The greaseless bushings will wear at a more rapid rate than the greased bushings, requiring replacements more frequently, such as on a 10 to 20 year cycle in contrast to a 30 to 40 year cycle for greased bushings.

As a best practice, the bushings on the wicket gate linkages are usually the greaseless type in order to reduce the amount of grease discharging into the wheel pit area and ultimately flowing into the powerhouse sump. Bushing applications in other turbine areas, such as wicket gate stem bushings, operating ring pads, and servomotors, are usually chosen based on the owner's preference when comparing bushing life and reliability versus the owner's desire to minimize the use of grease lubrication. However, it is important that each greaseless bushing is designed correctly for the application.

In some cases the friction in greaseless bushings increases over time due to trapped wear debris and incursion of silt and debris from the water, as compared to the greased bushings which are flushed by the movement of the grease. An increase in long term operating friction in greaseless applications, means the wicket gate servomotors must be over designed (particularly in retrofits) with excess capacity of at least 25% in order to ensure reliable operation [12].

Major maintenance of the wicket gate mechanism includes replacement of the pins, pads, bushings, and true machining of wear surfaces. This will be required every 10 to 40 years depending on the design and operating conditions. Shear pins (mechanical fuse) are an engineered product designed to prevent failures of more costly components in the mechanism. It is best practice to purchase the pin material from one manufacturer to ensure material properties remain constant. Prototype sample pins are manufactured and then broken in a test stand to determine actual shear properties. This test data is used to finalize the shear area diameter for the final pin shop drawing.

Routine maintenance of wicket gate servomotors is minimal and usually only requires changing of the actuating rod seals or packing when leakage become excessive. Major maintenance includes an overhaul of the servomotor, requiring disassembly, and replacement of bushings, seals, and piston rings.

Head cover and bottom ring routine maintenance is usually to ensure that the protective coating on the wetted surfaces is intact and any erosion or cavitation is repaired before it progressively worsens. Any galling damage at or near the ends of the wicket gate vanes must be removed by grinding to prevent further galling or damage to the wicket gate vane end seals. For higher head units with heads above 200 feet and/or poor water quality units, it is best practice to embed stainless steel wearing plates in the head cover and bottom ring immediately above and below the wicket gate vane ends to mitigate erosion and cavitation damage.

It is also common to install wicket gate vane end seals (either elastomer or bronze) into these areas to minimize leakage. Unfortunately, it is also best practice to manufacture wicket gates from stainless steel. Since stainless steel in contact with stainless steel can experience a high degree of galling, it is imperative that the design of wicket gate up thrust device be robust to resist the axial movement of the gate and prevent these surfaces from contacting. Wicket gate up thrust is generated either by the hydraulic pressure of water under the bottom stem and/or grease application pressure. Major maintenance of the head cover and bottom ring includes blasting and Nondestructive Examination (NDE) for cracking inspection, recoating, replacing wear plates and runner stationary seal rings, and replacing wicket gate bushings.

Routine turbine shaft maintenance consists of minimizing the corrosion of the shaft surface with a light coat of oil in the non-water contact areas and periodic re-coating of areas that come in contact with water with a robust paint such as epoxy. Major maintenance includes refurbishment on bearing journals, replacement of wearing sleeve, and re-truing coupling faces during a major unit overhaul.

Turbine guide bearings are usually either oil lubricated hydrodynamic bearings or water lubricated bearings. Maintenance of an oil lubricated bearing and its reliability are directly connected to the quality of the supplied oil used for lubrication and cooling. Any contamination of the oil either with debris or water will increase the likelihood of a bearing failure. A best practice is to install a kidney loop filtration system capable of continuously removing debris and water from the bearing oil supply. Maintenance of a water lubricated bearing and its reliability are also directly connected to the quality of the supplied water used for lubrication and cooling. Although in this case, with the viscosity of the water being so low, the water functions more as a coolant than as a lubricant. A best practice is to install an automatic strainer with internal backwash for uninterrupted supply of clean water to the bearing without need of routine maintenance to change or clean the filters. An uninterrupted supply is essential since any loss of water flow during turbine operation will quickly overheat the anti-friction contact surface of the internal liner (plastic, wood, or composite) of the bearing resulting in a rapid failure.

Since water lubricated bearings inherently wear which results in an increase in shaft vibration (shaft throw), periodic maintenance is required to adjust the bearing to tighten the running clearance. Some poorly designed bearings are non-adjustable and require the internal lining to be replaced to tighten clearances. Extreme shaft vibration (shaft throw) can cause contact of the turbine runner's seal rings, resulting in wear and the possible failure of the seal rings and extended unit outage. Major maintenance of either bearing type requires the refurbishment of the bearings, such as re-babbitting of an oil bearing or re-lining the water lubricated bearing. In addition, for water lubricated bearing, the shaft wearing sleeve may have to be machined true or replaced.

Sealing components in the turbine include the wicket gate stem seals and the seal for the turbine shaft. Routine maintenance will vary according to the type of seal and the operating conditions. Generally the hydraulic type seals, such as PolyPak seals, on wicket gate stems are maintenance free, however, like o-ring seals, once they leak there are no adjustments and must be replaced. Adjustable seal designs, such as with packing, can be tightened to reduce the leakage. Excessive leakage, even after adjustment, is an indication that the seals or packing must be replaced.

Seals for the turbine shaft vary from simple packing in a packing box around the shaft to higher speed applications with mechanical seals. It is important to note that a certain amount of leakage is required in a turbine shaft seal for cooling the seal (or packing), therefore zero leakage is not the objective. Routine maintenance includes replacement of the packing in the packing box or replacement of the composite (sacrificial) wearing component in the mechanical seal. Major maintenance of all the applications consists of the routine maintenance replacements and additional replacement of any opposing hard face wear elements such as wear sleeves for packing and hard face wear elements for the mechanical seals.

4.0 Metrics, Monitoring and Analysis

4.1 Measures of Performance, Condition, and Reliability

The fundamental process 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 (η): $\eta = \frac{P}{\rho g Q H}$ [15]

Where: · **η** is the hydraulic efficiency of the turbine

· **P** is the mechanical power produced at the turbine shaft (MW)
· **ρ** is the density of water (1000 kg/m^3)
· **g** is the acceleration due to gravity (9.81 m/s^2)
· **Q** is the flow rate passing through the turbine (m^3/s)
· **H** is the effective pressure head across the turbine (m)

Turbine performance parameters for Francis units are defined in ASME PTC-18 [16] and IEC 60041 [17], and typically include the following: Generator Output, Turbine Discharge, Headwater and Tailwater Elevations, Inlet Head, Discharge Head, Gate Position, and Water Temperature.

Typical vibration measurements may include: shaft displacement (x and y) at turbine and generator bearings, and headcover and thrust bridge displacements (z). Acoustic emission (on the draft tube access door or liner) may be measured to track relative cavitation noise.

The condition of the Francis turbine can be monitored by the Condition Indicator (CI) as defined according to HAP Condition Assessment Manual [13].

Unit reliability characteristics, as judged by its availability for generation, can be monitored by use of the North American Electric Reliability Corporation's (NERC) performance indicators, such Equivalent Availability Factor (EAF) and Equivalent Forced Outage Factor (EFOR). These are used universally by the power industry. Many utilities supply data to the Generating Availability Data System (GADS) maintained by NERC. This database of operating information is used for improving the performance of electric generating equipment. It can be used to support equipment reliability and availability analysis and decision-making by GADS data users.

4.2 Data Analysis

Analysis of test data is defined in ASME PTC-18 [16] and IEC 60041 [17]. Basically, determine unit efficiency and available power output relative to turbine discharge, head, gate opening position, and determine operating limits based on vibration and acoustic emission measurements (CPL). Compare results to previous or original unit test data (IPL), and determine efficiency, capacity, annual energy, and revenue loss. Compare results to new unit design data (from turbine manufacturer), and determine potential efficiency, capacity, annual energy, and revenue gain (PPL). For the latter, calculate the installation/rehabilitation cost and internal rate of return to determine upgrade justification. Separately, determine the justification of draft tube profile modification using turbine manufacturer's data.

Trend runner seal clearances (top and bottom) relative to OEM design values. If rehabilitation is required (resulting in complete unit disassembly), consider the value of installing new design unit.

Trend wicket gate end clearances (top and bottom) and toe to heel closures relative to OEM design values. If rehabilitation is required (resulting in complete unit disassembly), consider the value of installing new design unit. If the turbine does not already have wicket gate end seals (either spring loaded bronze or elastomer), analytically determine the annual energy and revenue gain associated with their use. Calculate the implementation cost and internal rate of return.

Monitor the operation of vacuum breaker based on routine maintenance program and performance testing. Consider rehabilitating the vacuum breaker if it is leaking.

Analytically or using field test data, determine the efficiency, annual energy, and revenue gain associated with the use of draft tube gate slot fillers. Calculate the implementation cost and internal rate of return.

The condition assessment of a Francis turbine is quantified through the CI as derived according to HAP Condition Assessment Manual [13]. 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 such 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* [18].

4.3 Integrated Improvements

The periodic field test results should be used to update the unit operating characteristics and limits. Optimally, these would be integrated into an automatic system (e.g., Automatic Generation Control), but if not, hard copies of the curves and limits should be made available to all involved personnel (particularly unit operators) and their importance emphasized.

Justified projects (hydraulic re-profiling, slot fillers, unit upgrade) and a method to constantly monitor unit performance should be implemented.

As the condition of the turbine changes, the CI and reliability indexes are trended and analyzed. Using this data, projects can be ranked and justified in the maintenance and capital programs to bring the turbine back to an acceptable condition and performance level.

5.0 Information Sources:

Baseline Knowledge:

1. Thomas C. Elliott, *Standard Handbook of Powerplant Engineering*, McGraw Hill Publishing, 1989
2. NEMA *Standard for Hydraulic Turbines and Governors*, Pub. No. HT1-1949
3. US Corps of Engineers, *Hydro Plant Risk Assessment Guide*, September 2006
4. EPRI, *Increased Efficiency of Hydroelectric Power*, EM 2407, June 1992
5. *Hydroelectric Handbook*, William P. Creager, John Wiley & Sons, 1950
6. USBR, FIST Volume 2-5, *Turbine Repair*, September 2000
7. *Hydro Life Extension Modernization Guide, Volume 2: Hydromechanical Equipment*, EPRI, Palo Alto, CA: 2000. TR-112350-V2.

State of the Art

8. March, P.A. and Wolff, P.J., *Component Indicators for an Optimization-Based Hydro Performance Indicator: HydroVision 2004*, Montreal, Quebec, Canada, August 2004.
9. Brice, T.A. and Kirkland, J.E., *Checking Turbine Performance by Index Testing*, Hydro Review, Vol. V, No. V, Winter, 1986
10. USACE, *Turbine Surface Roughness Improvement*, HDC-P, December, 2003
11. USACE, *Stay Vane and Wicket Gate Relationship Study*, CENWP- HDC-P, January 19, 2005
12. J.C. Jones, *Wicket Gates – Grease vs. Greaseless*, USBR O&M Workshop, April 10, 2001
13. ORNL, *HAP Condition Assessment Manual*
14. Spicher, T., *Hydro Wheels: A Guide to Maintaining and Improving Hydro Units*, HCI Publications, 3rd Edition 2004
15. Cateni, A., Margri, L., Grego, G.: *Optimization of Hydro Power Plants Performance importance of Rehabilitation and Maintenance in Particular for Runner* – 2008

Standards:

16. ASME 2011, *Hydraulic Turbines and Pump-Turbines*, PTC 18-2011
17. IEC, 1991, *Field Acceptance Tests to Determine the Hydraulic Performance of Hydraulic Turbines, Storage Pumps and Pump-Turbines*, IEC-60041
18. NERC, Appendix F, *Performance Indexes and Equations*, January, 2011
19. ASTM A487, *Standard Specification for Steel Castings Suitable for Pressure Service*

20. ASTM A743, *Standard Specification for Castings, Iron-Chromium, Iron-Chromium-Nickel, Corrosion Resistant, for General Application*

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.

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