

Best Practice Catalog

Propeller/Kaplan Turbine



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Contents

1.0	Scope and Purpose	4
1.1	Hydropower Taxonomy Position	4
1.1.1	Propeller/Kaplan Turbine Components	4
1.2	Summary of Best Practices	6
1.2.1	Performance/Efficiency & Capability - Oriented Best Practices.....	6
1.2.2	Reliability/Operations & Maintenance - Oriented Best Practices	7
1.3	Best Practice Cross-references	8
2.0	Technology Design Summary.....	9
2.1	Material and Design Technology Evolution	9
2.2	State of the Art Technology	9
3.0	Operational & Maintenance Best Practices	12
3.1	Condition Assessment	12
3.2	Operations	18
3.3	Maintenance	20
4.0	Metrics, Monitoring and Analysis	27
4.1	Measures of Performance, Condition, and Reliability	27
4.2	Data Analysis	27
4.3	Integrated Improvements.....	28
5.0	Information Sources.....	29

1.0 Scope and Purpose

This best practice for a Propeller/Kaplan 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. The Propeller/Kaplan type turbine is typically used in a low head and high flow application. Fixed-blade propeller types have a very narrow range of high efficiency operation, while adjustable-blade types can operate at high efficiency over a wide flow and power output range.

1.1 Hydropower Taxonomy Position

Hydropower Facility → Powerhouse → Power Train Equipment → Turbine → Propeller/Kaplan Turbine

1.1.1 Propeller/Kaplan Turbine Components

Performance and reliability related components of a Propeller/Kaplan turbine consist of a reaction type axial-flow runner with adjustable-blade mechanism, wicket gates and controlling mechanism, spiral case, stay ring/stay vanes, and draft tube.

Spiral Case: The function of the spiral case (or scroll case) is to supply water from the intake to the stay vanes directly to the upstream portion of the turbine 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 to the downstream portion of the turbine.

Stay Ring/Vanes: The function of the stay vanes (and stay ring) is to align the flow of water from the spiral casing to the wicket gates. They also function as support columns in vertical units for supporting 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. Secondly, the gates control the angle of the high tangential velocity water striking the runner blades. The optimum angle of attack will be at peak efficiency. In an adjustable-blade unit, the tilt of the blades and opening of the gates are synchronized to maximize efficiency over as much of the operating range as possible. The wicket gates also function as a closure valve to minimize leakage through the turbine while it is shutdown.

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. The Kaplan runner is comprised of a hub, nosecone, blades, and an internal blade tilting mechanism - typically a hydraulically-driven piston with linkage and seals. Oil pressure is provided by the governor hydraulic system.

Draft Tube: The function of the draft tube, which is initially conically shaped and attached to the turbine discharge, is to gradually slow down the high discharge velocity water, capturing 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 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 throat ring of 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 Propeller/Kaplan turbine include the wicket gate mechanism/servomotors, head cover, bottom ring, turbine shaft, guide bearing, mechanical seals/packing and discharge/throat ring.

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.

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: Water retaining sealing components in the turbine includes 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.

Oil filled Kaplan hubs have seals around the blade trunnions to prevent oil leakage and to prevent water leakage into the oil. These trunnions seals are usually either double opposing or chevron packing type.

Head Cover/Bottom Ring: 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. 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.

Discharge/Throat Ring: The discharge ring serves as the steel housing of the runner which is the transitional piece to the expanding draft tube.

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 manufacturers 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, slot fillers, unit upgrade).
- Trend loss of turbine performance due to condition degradation for such causes of metal loss (cavitation, erosion and corrosion), opening of runner seal and wicket gate clearances, 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 to plant engineering standards.

1.2.2 Reliability/Operations & Maintenance - Oriented Best Practices

- Use ASTM A487/A743 CA6NM stainless steel to manufacture Propeller/Kaplan 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. [18, 19].
- 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 spares 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 component and increases damage resistance.
- Propeller/Kaplan 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.
- 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 of sufficient strength to operate even after a 25% increase in long term friction.
- 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.

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

Propeller/Kaplan turbine blades and internal parts are typically cast; whereas the hub and nose cone are either cast or rolled and welded. 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's casting would involve casting or fabrication from carbon steel or stainless steel. As a best practice, the most common material used for the blades is ASTM A487/A743 CA6NM stainless steel [18, 19]. It is cavitation-resistant, fairly easy to cast and fabricate, and can usually be weld-repaired without post heat treatment.

A best practice 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 today's advancements 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 a condition assessment to determine rehabilitation or replacement. Testing may show performance has degraded significantly. For example the efficiency of a Kaplan unit has experienced steady degradation amounting to a total of 4 percentage points over a 19 year period (Figure 1).

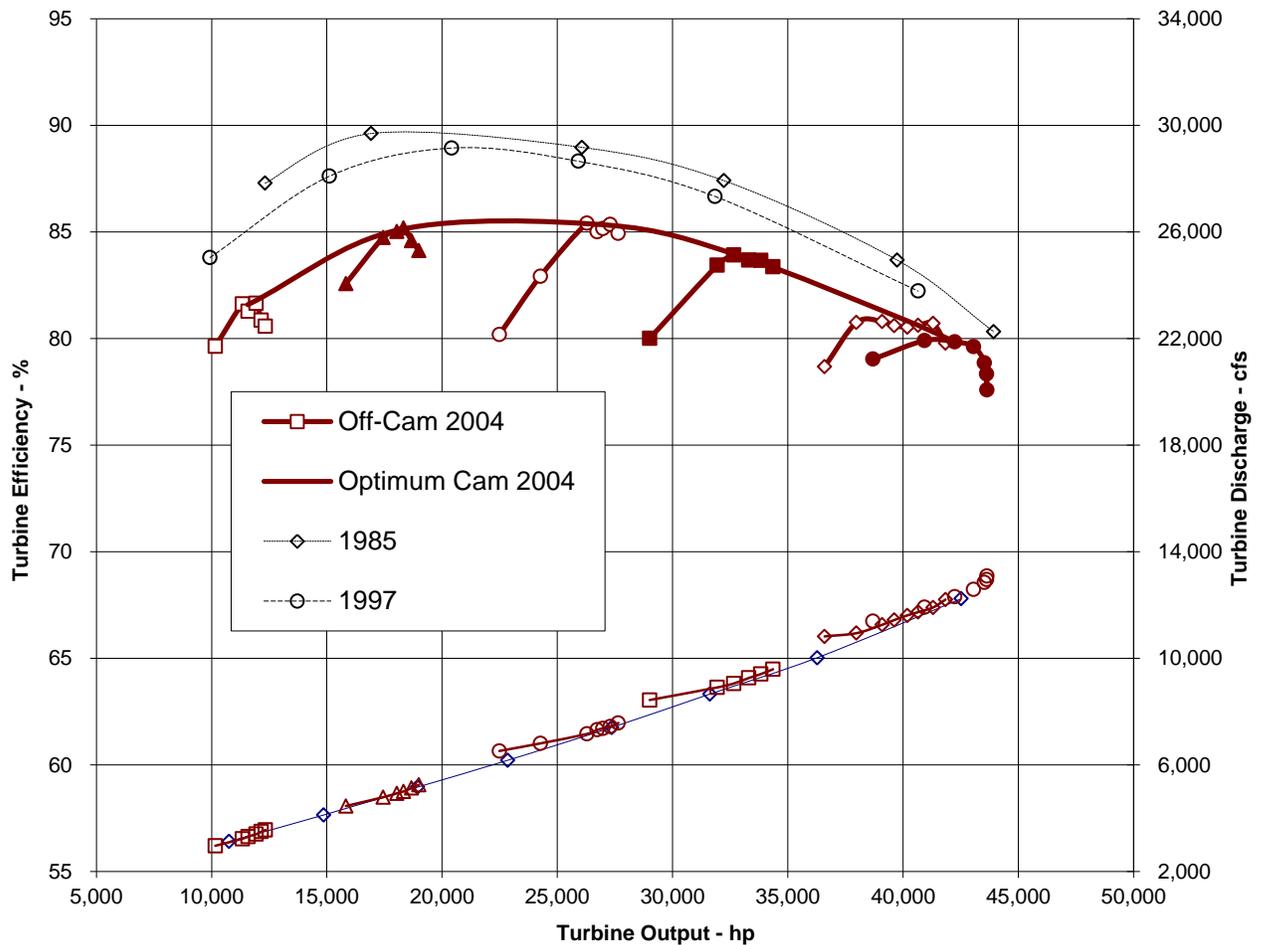


Figure 1: Kaplan Performance Degradation

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 data rather than original design data providing a turbine more accurately suited for the site. Newer turbine designs also provide decreased cavitation based on better hydraulic design and materials [2]. For comparison, Figures 2 and 3 show an original runner and its stainless steel replacement runner.



Figure 2: Original Runner



Figure 3: New Stainless Replacement Runner

3.0 Operational & Maintenance Best Practices

3.1 Condition Assessment

After 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 [18, 19]. 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 hub and nose cone are usually carbon steel, but should have strategically-located stainless steel overlay. The other wetted components such as distributor rings, including stay vanes, are typically constructed from steel due to strength requirements and some with stainless steel cladding overlaid in critical areas.

Spiral cases and draft tubes are usually left as poured concrete except for the high velocity throat ring area. A significant contributor to performance loss in these wetted components is any surface degradation due to cavitation, abrasive erosion, surface finish degradation, and the poor quality of past repairs. Typical locations are shown in Figure 4. These deteriorating factors can distort the hydraulic design contours of components. Condition assessment of those flow components must address all past damage, location of damage, repeat damage, and resulting increase in surface roughness. 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.

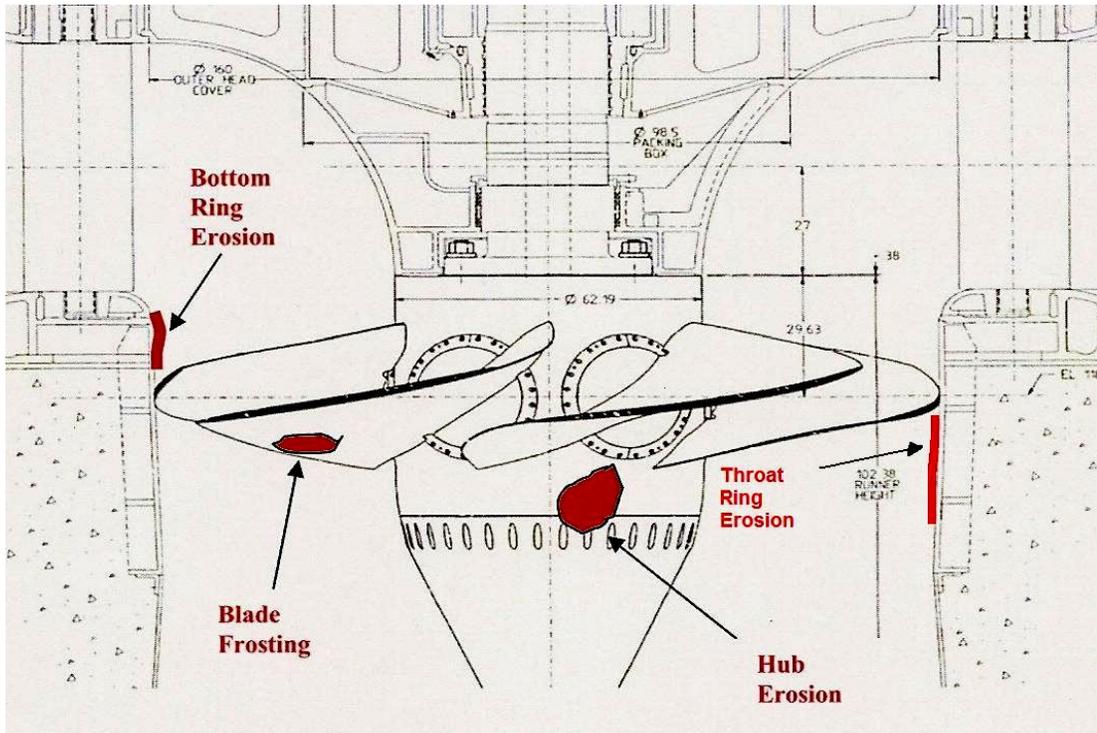


Figure 4: Typical Areas to Check for Cavitation Damage

A certain amount of cavitation is inherent in a Kaplan runner, primarily due to gaps between the blade inner periphery and hub and between the blade outer periphery and throat ring. Most runners manufactured since the 1980's include an "anti-cavitation fin" (located on a portion of the suction side of the blade outer periphery) to serve as a sacrificial element (Figure 5). Periodic inspection of this fin and of the throat ring may assist in identification of excessive operation beyond recommended cavitation limits in an effort to take advantage of the excessive flow and/or head which are otherwise wasted.

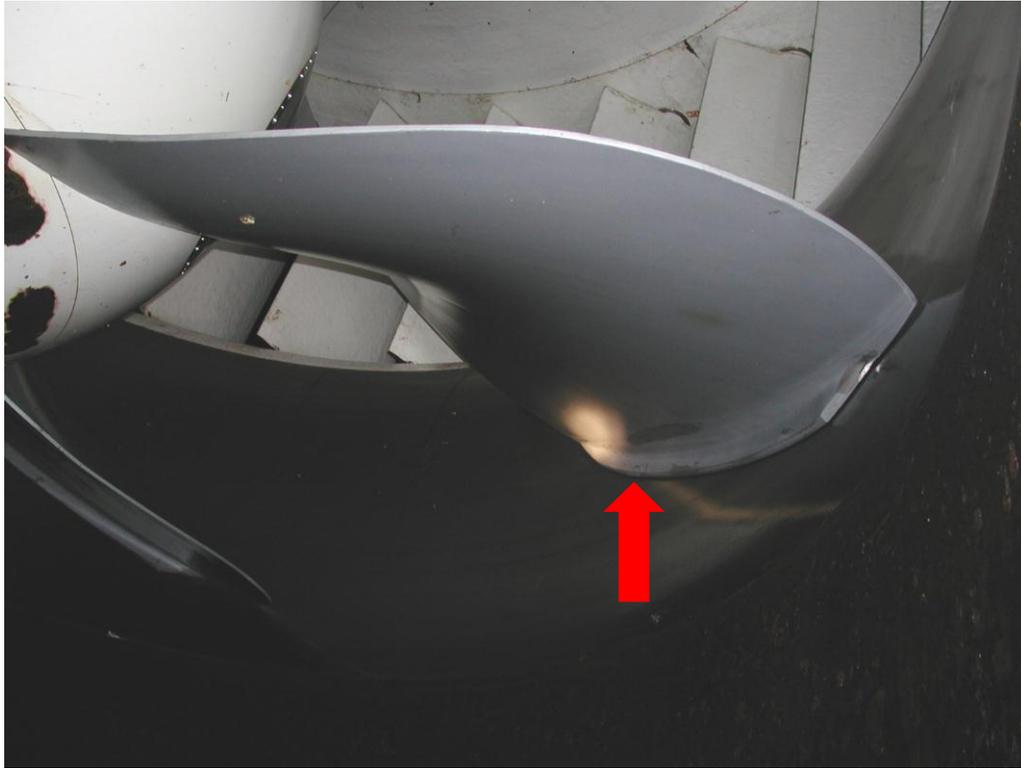


Figure 5: Anti-Cavitation Fin & Throat Ring Overlay

A comparison of the blade tip clearances to original installation measurements will provide an indication of the condition of the mechanism (bushings/bearings) securing the blade trunnions. Increased play in the securing mechanism of the trunnions can result in sagging blade tips which essentially creates a modified hydraulic profile from that designed, and consequent reduction in performance.

Drifting of the blade position over time and excessive oil usage may indicate the need to replace piston rings or other oil seals in the system. Maintaining blade position is paramount for optimizing performance. A periodic check should be made of the blade position on the hub versus the indicated position outside the unit, since original manufacturer's data (usually model) is often required to develop the optimum gate-blade relationship over the full head range.

Evaluating the condition of a turbine and its components may show that a new, state of the art designed runner with enhanced power and efficiency may provide sufficient benefits to justify its replacement, including rehabilitating related components, as compared to maintaining the current turbine with its existing efficiency [2].

The wicket gate mechanism (Figure 6) 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 indicator that rehabilitation on 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 binding in the mechanism.



Figure 6: Wicket Gate Mechanism

Hydraulic servomotors (Figure 7) 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, without any scoring or grooves which would prevent sealing. If the rod is damaged it will require repair or replacement.

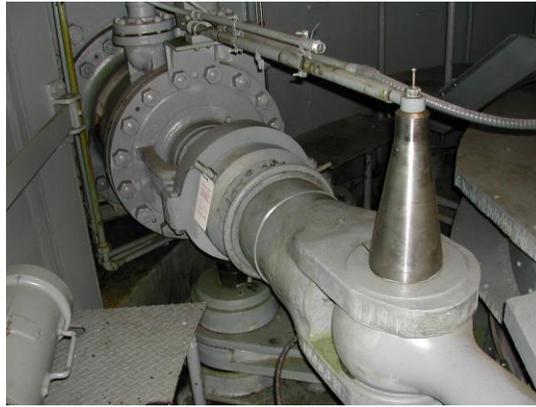


Figure 7: Wicket Gate Servomotor

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 and the head cover and bottom ring and damage to embedded end seals.

The condition assessment of the turbine shaft (Figure 8) 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 bearing wearing sleeves are usually manufactured from ASTM A743 CA6NM [17] stainless steel either forged or centrifugally cast. 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 8: Turbine Shaft / Wheel Pit

Turbine guide bearings are usually either oil lubricated hydrodynamic bearings (Figure 9) or water lubricated bearings (Figure 10), 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), unbonding 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 (design permitting). 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 9: Babbitted Oil Journal Bearing



Figure 10: 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.

Either leakage of oil from the Kaplan blade trunnions seals or leakage of water into the Kaplan hub, oil leakage is an indicator of possible worn Kaplan blade trunnions bushings or bearings. Excessive wear in the blade trunnions bushings allow the blade to move further than the capability of the seal resulting in leakage during operation and long term wear of the seal.

3.2 Operations

Turbine performance can be maximized by utilizing operating characteristic curves and adhering to minimum and maximum output limits (such as vibration and cavitation). Adjustable blade units require the additional necessity of an accurate gate-blade relationship. Curves, limits, and gate-blade relationships should be generated from manufacturer's data and adjusted to field test data.

Operation will only be as good as this information is accurate. Plus, the performance of the turbine can degrade over time due to cavitation and/or erosion damage and resulting weld repairs, etc. Periodic performance checks, through absolute or relative (e.g., index) testing, are necessary for maintaining accuracy and must be made comprehensively at a number of operating heads. If a 2-dimensional (2D) cam is used in the governor for blade tilt control, it must be adjusted periodically to changing head conditions. If an electronic 3-dimensional (3D) cam is used, the database must be updated as needed, and the head inputs must be checked against independent measurements particularly if the permanent measurement location can be affected by trash buildup.

Figure 11 shows typical performance curves for fixed and adjustable-blade units (from the same plant). The very narrow range of high efficiency in the fixed blade units must be defined accurately to optimize performance. In contrast, the adjustable-blade units offer a much wider range of high efficiency; however, the absolute peaks of the individual blade tilt efficiency curves (Figure 1) must be defined accurately in order to develop the optimum gate-blade relationships required to realize optimum performance.

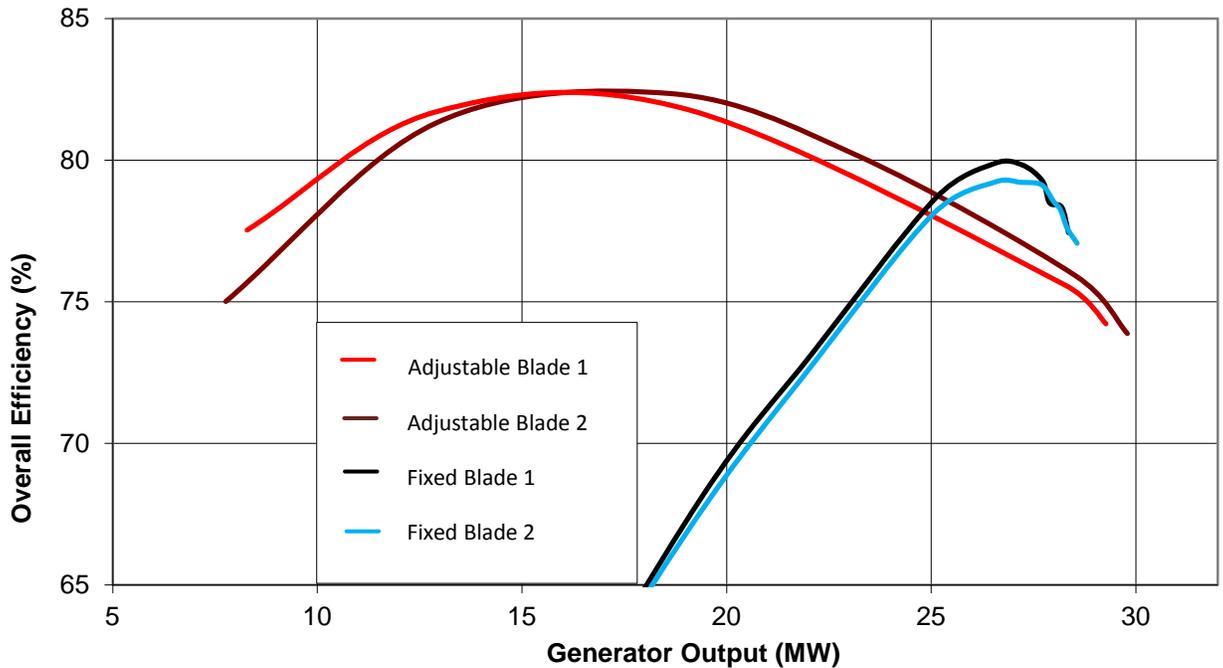


Figure 11: Typical Fixed and Adjustable-Blade Unit Efficiency Curves

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 [6]. Plants should, as a best practice, perform periodic performance testing (such as index testing according to PTC 18 [15]) to assure the most accurate operating curves are available to optimize plant output. This should be done on a 10 year cycle as a minimum.

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 are submerged (under tailwater), water can be drawn down into the draft tube due to the lower pressure increasing the total flow in the draft tube from that point to the exit. Therefore, 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 (Figure 12) have been shown to remedy this problem in one case by as much as 1% efficiency [8].



Figure 12: Draft Tube Gate Slot Fillers

3.3 Maintenance

It is commonly accepted that turbines normally suffer from a progressive deterioration in performance over time (in default of restorative action) [3]. Usual causes include cavitation damage, abrasive erosion wear, galvanic corrosion, striking damage from debris passing through, and errors in welding repairs to original blade profiles and surface finish. Performance-related maintenance techniques involve mainly those weld repairs to cavitation damage, abrasive erosion damage, and galvanic corrosion on the turbine components such as the runner, wicket gates, and distributor ring. A 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 inlet and trailing edges back to OEM specifications. A good reference for turbine maintenance is the USBR's FIST Volume 2-5, *Turbine Repair* [4] and Spicher's *Hydro Wheels* [14].

Typically, Kaplan runner blades are designed with stress relief grooves at the leading and trailing sides of the blade/trunnion intersection (Figure 13). These grooves, located to minimize the possibility of cracking in the high stress areas of the blade, create cavities in the flow profile which cause downstream disturbances in the form of low pressure vortices and can result in cavitation erosion on the hub and nose cone. It has been shown that fillers, attached to the blade or trunnion seal, have been effective in reducing the erosion, especially when paired with strategically-located stainless steel overlay on the hub and nose cone. Figure 14 shows a typical overlay area for a Kaplan runner hub/nose cone. Also, the spherical design of some newer runner hubs, as opposed to the traditional conical design, minimizes the gap between the blades and hub as the blades move to flatter positions (Figures 2 and 3).



Figure 13: Stress Relief Notch & Overlay

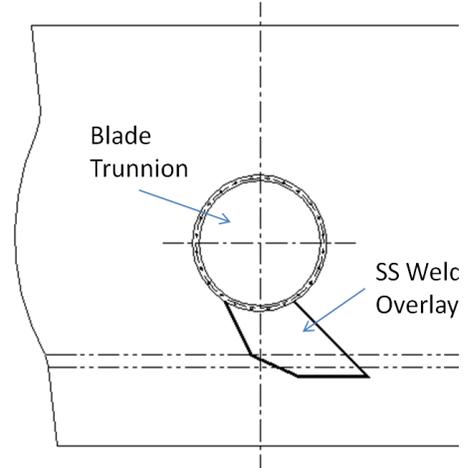


Figure 14: Typical Hub/Nose Cone Stainless Steel Overlay Location

Additional areas for stainless steel overlay include the throat ring to protect against “seal cavitation” at the blade periphery (Figure 5) and sections of the lower distributor ring and bottom ring where Von Karman vortices can trail off the wicket gates during high flow operation (Figure 15).

Flow profile modifications, a narrowing of the lower trailing edges of the wicket gates (Figure 16), can reduce vortices and allow higher flow rates and power output. The exact profile change should be designed based on Computational Fluid Dynamics (CFD) and/or physical modeling.



Figure 15: Bottom Ring Overlay



Figure 16: Modified Wicket Gate

Investigations by the US Army Corps of Engineers (USACE) show minor modifications to the stay vane/wicket gate system could result in an operation efficiency increase of 0.5 to 0.7% for units studied [9]. As shown in the reference, the modification takes the form of profile changes on the stay vane, leading and trailing edges, and modifying the wake relative to the wicket gate. The exact profile change should be designed based on CFD and/or physical modeling. In addition, such modifications can reduce fish injury as one environmental benefit.

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 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.

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 an excess capacity of at least 25% in order to ensure reliable operation [10].

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 a 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.

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 [11]. 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 in the head pressure.

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 [11]. 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.

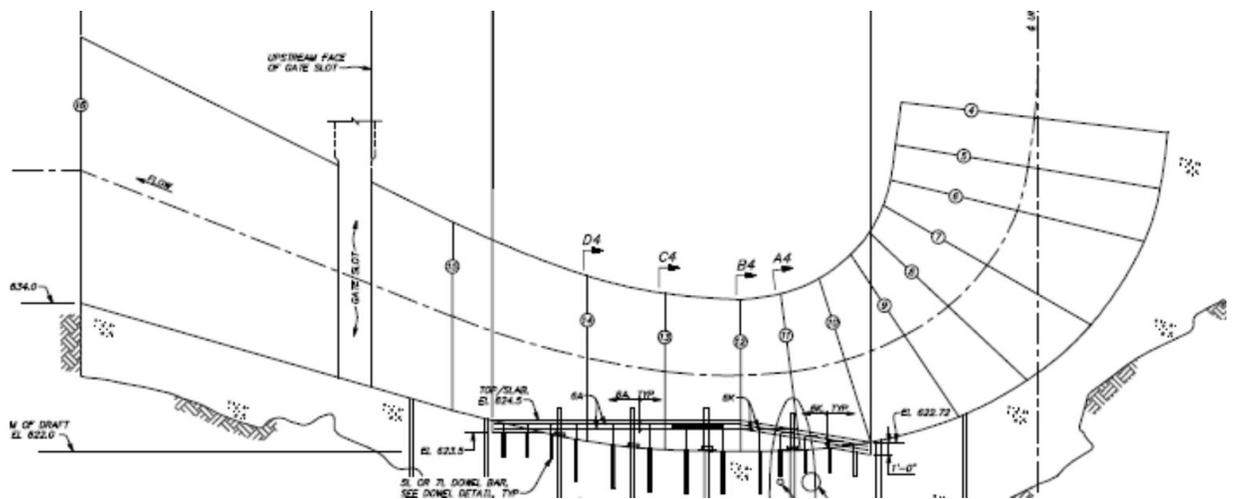


Figure 17: Draft Tube Modification

At certain head and flow rate combinations, flow separation can occur in the elbow section of some draft tubes resulting in unstable operation (stall). This is manifested in scattered data forming steep, peaky efficiency curves for individual blade tilts which make it difficult to determine and maintain an optimum gate-blade relationship. A reduction in the cross-sectional area of the elbow can reduce separation and be accomplished economically by strategically pouring concrete to raise the floor elevation (Figures 17 and 18).

Exact pour locations and depths should be determined using CFD and/or physical modeling. The result is more rounded efficiency curves so that if the gate-blade relationship changes, the operation will shift only slightly lower in efficiency instead of nose-diving. Additionally, model tests for one project showed efficiency and capacity gains of 0.11% and 535 hp.



Figure 18: Draft Tube Mod Pour

In general, any potential modifications to hydraulic profiles should be studied and verified with CFD and/or physical modeling by a competent turbine manufacturer or independent hydraulic laboratory. In the event of model testing for a turbine upgrade, the opportunity should be taken to investigate any modifications that hold performance improvement potential.

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.

It is imperative that the design of the wicket gate up thrust device be robust and capable of resisting the axial movement of the gate and preventing the gate from contacting the headcover. 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 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 is 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 is 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 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 every time. Extreme shaft vibration can cause contact of the turbine runner's seal rings resulting in wear and the possible failure of the seal rings causing 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 the 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, with 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 and opposing hard face wear elements such as wear sleeves for packing and hard face wear elements for the mechanical seals.

Kaplan blade trunnions seals usually require replacing every 15 to 20 years. However, after 40 to 50 years the Kaplan blade trunnions bushing or bearings may be worn to the extent that seal replacements will not retain oil or water. At this point the Kaplan turbine will require refurbishment or replacement.

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, 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): $\eta = \frac{P}{\rho g Q H}$ [12]

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/m³)
- g is the acceleration due to gravity (9.81 m/s²)
- Q is the flow rate passing through the turbine (m³/s)
- H is the effective pressure head across the turbine (m)

Turbine performance parameters for Propeller/Kaplan units are defined in ASME PTC-18 [15] and IEC 60041 [16], and typically include the following: Generator Output, Turbine Discharge, Headwater and Tailwater Elevations, Inlet Head, Discharge Head, Gate Position, Blade 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 man-door or liner) may be measured to track relative cavitation noise.

During unit outages: Blade tip clearances.

The condition of the Propeller/Kaplan turbine can be monitored by the Condition Indicator (CI) as defined according to HAP Condition Assessment Manual [12].

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 as Equivalent Availability Factor (EAF) and Equivalent Forced Outage Factor (EFOR). These are universally used 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 [15] and IEC 60041[16]. Basically, the analysis is used to determine unit efficiency and available power output relative to turbine discharge, head, gate opening, and blade tilt position. 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/rehab cost and internal rate of return to determine upgrade justification. Separately determine justification of any modifications (e.g., draft tube profile) using turbine manufacturer's data.

Determine the optimum gate-blade relationship. Compare the current 2D cam adjustment practice to a seasonal or periodic adjustment, and calculate the associated energy and revenue difference. Compare the current 2D cam adjustment practice to the continuous adjustment of a 3D cam and calculate the associated annual energy and revenue gain. For the latter, calculate the 3D cam installation cost and internal rate of return to determine upgrade justification.

Trend blade tip clearances relative to OEM design values. If rehab is required (resulting in complete unit disassembly), consider value of installing new design unit.

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 Propeller/Kaplan turbine is quantified through the Condition Indicator (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.

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, January 2011 [17].

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, AGC), but if not, hardcopies of the curves and limits should be made available to all involved personnel (particularly unit operators) and their importance emphasized.

If required, 2D cams should be replaced or re-profiled and 3D cam databases updated to reflect the test results. A table or set of curves showing the gate-blade relationship should be available to all involved personnel for periodic checking.

Justified projects (hydraulic 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

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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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