Best Practice Catalog

Pelton Turbine

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Contents

1.0 Scope and Purpose

This best practice for a Pelton turbine addresses its technology, condition assessment, operations, and maintenance best practices with the objective to maximize its performance and reliability. The 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 significant impact on the efficiency and performance of a hydro unit.

1.1 Hydropower Taxonomy Position

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

1.1.1 Pelton Turbine Components

Pelton turbines are impulse turbines used for high head (usually 100 to 1000 m or above) and low flow hydro applications. The Pelton runner normally operates in air or near atmospheric pressure with one to six jets of water impinging tangentially on the runner.

The Pelton turbine units come in two shaft axis arrangements: horizontal (Figure 1) and vertical (Figure 2). This is dictated by the overall hydro plant design. The horizontal shaft turbine (maximum of 4 jets) is simpler to perform maintenance, but the powerhouse is larger in size, whereas the vertical shaft turbine (maximum of 6 jets) is more difficult to perform maintenance but allows a narrower shape of the power station footprint [1].

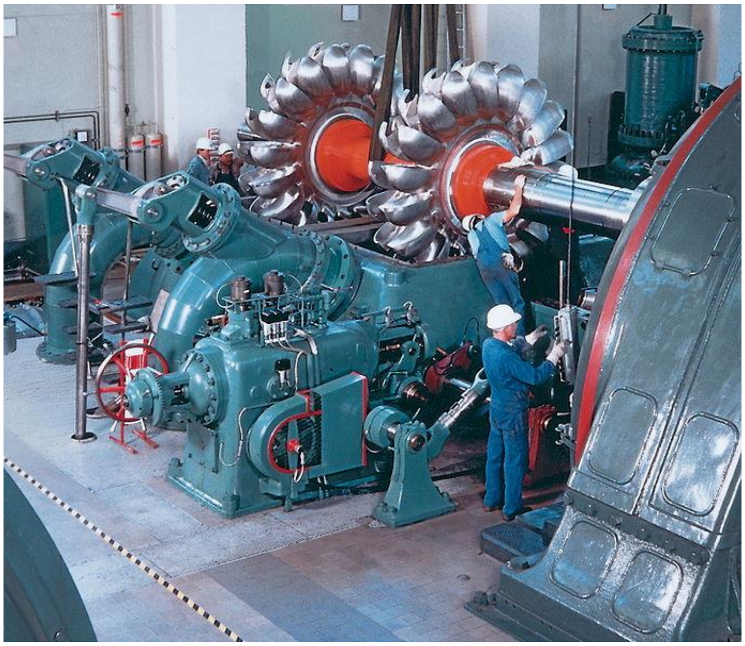

Figure 1: Twin runner horizontal Pelton turbine

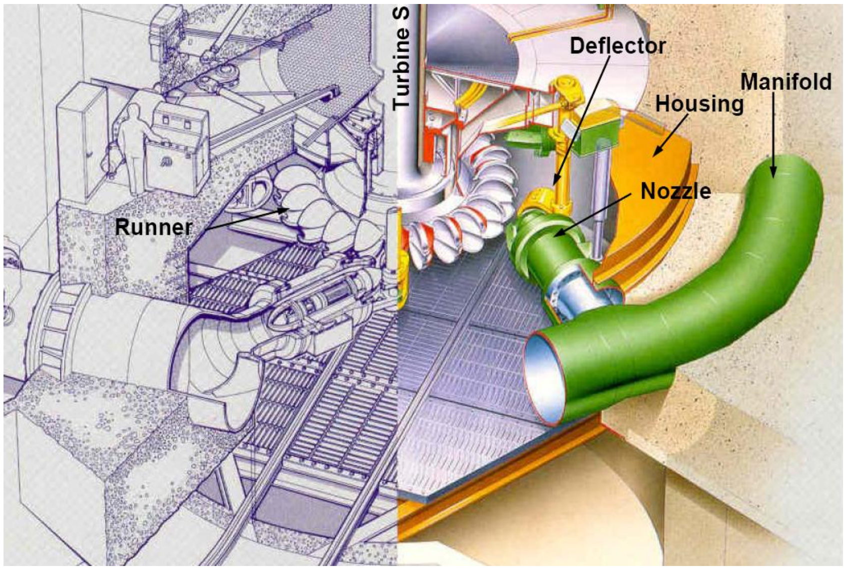

Figure 2: Multi-nozzle vertical Pelton turbine

Performance and reliability related components of a Pelton turbine consist of a distributor/manifold, housing, needle jet/nozzle, impulse runner and discharge chamber.

Distributor/Manifold: The function of the distributor (or manifold) is to provoke an acceleration of the water flow towards each of the main injectors. The advantage of this design is to keep a uniform velocity profile of the flow.

Housing: The function of the housing is to form a rigid unit with passages for the needle servomotor piping, feedback mechanisms, and the deflector shafts. The shape of the wetted side of the housing is important for directing the exit water effectively away from the runner.

Needle Valve/Nozzle: The function of the needle jet (or nozzle) is to regulate the flow of water to the runner in an impulse turbine runner. The needle jet is regulated by the governor via mechanical-hydraulic or electro-hydraulic controls. The shape is designed for rapid acceleration at the exit end and for assuring a uniform water jet shape at all openings. The needle valve/nozzle assembly is placed close to the runner as possible to avoid jet dispersion due to air friction [2].

Runner: The runner consists of a set of specially shaped buckets mounted on the periphery of a circular disc. It is turned by forced jets of water which are discharged from one or more nozzles. The resulting impulse spins the turbine runner, imparting energy to the turbine shaft. The buckets are split into two halves so that the central area does not act as a dead spot (no axial thrust) incapable of deflecting water away from the oncoming jet [2].

Discharge Chamber: The function of the discharge chamber is to enable water existing the runner to fall freely toward the drainage. It also functions as a shield for the concrete work and avoids concrete deteriorations due to the action of the water jets. Correct water level regulation (surge chambers) inside this chamber is critical for maximum efficiency.

Non-performance but reliability related components of a Pelton turbine include the deflector, turbine shaft, and guide bearing.

Deflectors: The deflectors have the function to bend the jet away from the runner at load rejections to avoid too high of a speed increase. Moreover it protects the jet against exit water spray from the runner. The deflector arc is bolted to the deflector support structure frame with the control valve of the needle servomotors. A seal ring around the deflector shaft bearing housing prevents water and moisture from penetrating into the bearing.

Turbine Shaft: The function of the turbine shaft is to transfer the torque from the turbine runner to the generator shaft and rotor. The shaft typically has a bearing journal for oil lubricated hydrodynamic guide bearings on the turbine runner end. Shafts are usually manufactured from forged steel, but some of the larger 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 oil lubricated hydrodynamic (babbitted) bearings.

1.2 Summary of Best Practices

1.1.2Performance/Efficiency and Capability - Oriented Best Practices

- 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 Current Performance Level (CPL) to detect and mitigate deviations from expected efficiency for the Installed Performance Level (IPL) due to degradation or instrument malfunction.
- Periodic comparison of the CPL to the Potential Performance Level (PPL) to trigger feasibility studies of major upgrades.

- Maintain documentation of IPL and update when modification to equipment is made (e.g., hydraulic profiling, unit upgrade, etc.).
- Trend loss of turbine performance due to condition degradation for such causes as metal loss (cavitation, erosion, and corrosion), opening of runner seal, and increasing water passage surface roughness.
- Include industry acknowledged advances for updated turbine component materials and maintenance practices.
- Adjust maintenance and capitalization programs to correct deficiencies.

1.1.3Reliability/Operations and Maintenance - Oriented Best Practices

- Use ASTM A743 CA6NM stainless steel to manufacture Pelton turbine runners, and water lubricated bearing shaft sleeves to maximize resistance to erosion, abrasive wear, and cavitation. [15]
- Damage from erosion and cavitation on component wetted surfaces are repaired using 309L stainless steel welding electrodes to increase damage resistance. The electrodes increase damage resistance.
- Adequate coating of the turbine wetted components not only prevents corrosion but has added benefits of improved performance.
- 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 for the condition of turbine for decreasing Condition Indicator (CI) and decrease in reliability, that is to say 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 Best Practice
- Mechanical - Lubrication System Best Practice
- Mechanical - Generator Best Practice
- Mechanical – Governor Best Practice
- Mechanical – Raw Water Best Practice

2.0 Technology Design Summary

2.1 Material and Design Technology Evolution

Pelton 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, could have been cast from cast iron or bronze, later replaced with cast carbon steel. Today they 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 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 through 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.

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).

2.2 State of the Art Technology

Turbine efficiency is likely the most important factor in an assessment to determine rehabilitation or replacement of the turbine. Such testing may show CPL has degraded significantly from IPL. Figure 3 is an example of the relative efficiency gains of a Pelton unit. 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 "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.

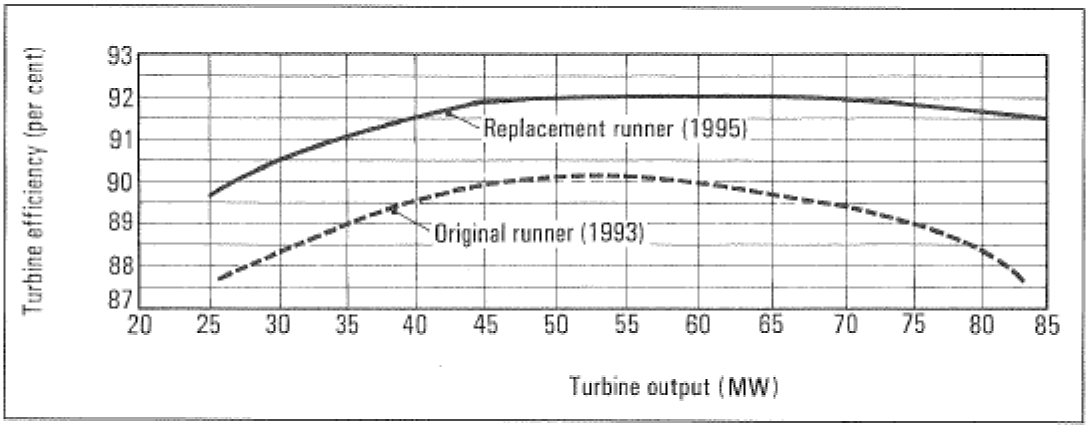

Figure 3: Example - Original vs. New Performance Curves [7]

3.0 Operation and Maintenance Practices

3.1 Condition Assessment

All Pelton turbine arrangements, vertical or horizontal, have four major components that are critical to performance losses.

- The Runner: There are losses due to friction and turbulence by surface deterioration and subsequent hydraulic bucket geometry changes.
- The Housing/Discharge chamber: There are losses due to case splashing, air ventilation and tail-water interference.
- The Needle Valves/Nozzles: There are losses due to unbalanced velocity profiles and turbulent fluctuation causing “bad jet quality” (in the form of jet deviation or jet dispersion).
- The Distributor/Manifold: There are losses due to friction, bends and bifurcations (the split of water into two streams) [5].

The typical losses in a Pelton turbine are approximately as follows:

- Inlet pipe (Distributor) and Injector (Nozzle) - 0.5 to 1.0%
- Runner - 6.5 to 9.0%
- Turbine housing/discharge chamber - 0.5 to 1.0%

A high head multi-jet turbine has relatively lower losses, whereas a low head horizontal unit has relatively higher losses [3].

3.1.1Runner

The surface roughness of the runner bucket surfaces must be assessed. There are two drivers for this surface deterioration; cavitation (Figure 4), and sand/silt erosion (Figure 5). A careful visual inspection can be performed during an outage situation when the unit is in a dry state.

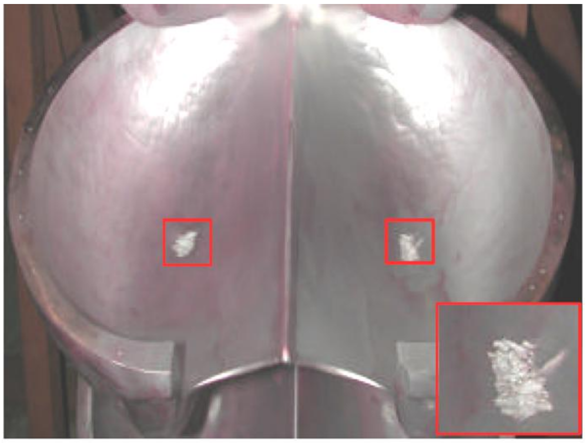

Figure 4: Cavitation damage on runner bucket [14]

Figure 5: Erosion damage on runner bucket [14]

There is also a possibility of the combined effect of sand/silt erosion and cavitation in the hydraulic turbine components. It must be noted that properly hydraulic designed Pelton runners do not cavitate. Yet, even in cavitation-free geometry, surface roughness due to sand erosion at high velocity regions may initiate cavitation erosion. The synergic effect of sand erosion and cavitation can be more pronounced than their individual effects.

Bucket erosion has been found to vary with the jet velocity, as compared to water quality or intake elevation, the jet velocity is the strongest parameter in bucket erosion. As jet velocity is the function of head, the high head turbines are more vulnerable to silt erosion. Based on typical qualitative studies it was found that the sharp edge of the splitter became blunt and the depth of the bucket increased due to sand/silt erosion [14].

The jet loading is also the key to determining the bucket sizing. Most modern runner designs optimize the ratio of bucket width to jet diameter, which is approximately 3.6 to 4.1, depending on the number of jets and rotational speed. Older machines were often designed with a lower overall rotational speed and with larger bucket widths compared with more modern runner designs [7].

An appropriate indicator of efficiency loss due to erosion on a Pelton runner is the width of the splitter as a percentage of bucket width. A 1 % increase in relative splitter width represents approximately a 1 % decrease in efficiency [3].

3.1.2 Housing/Discharge Chamber

Appropriate venting prevents the runner discharge water from building up (in the housing) [7]. The housing ventilation points need to be assessed to ensure that they are clear, allowing full ventilation. The tail water levels below the runner must not interfere with the jet flow. These water levels must remain within the OEM designed range. Jet interference prevents the regular flow in the buckets and results in the sharp deterioration of turbine output power with cavitation and vibration [8]. Figures 6 and 7 illustrate the negative effects of jet interference splash on the turbine performance.

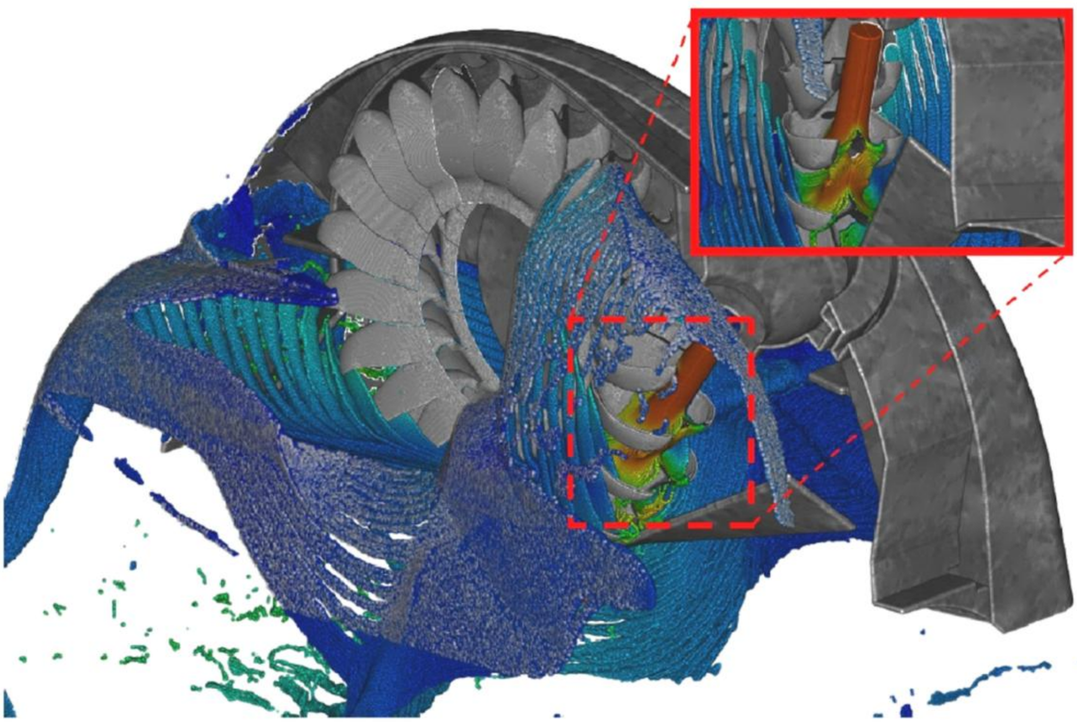

Figure 6: Modeling of jet interference within housing [8]

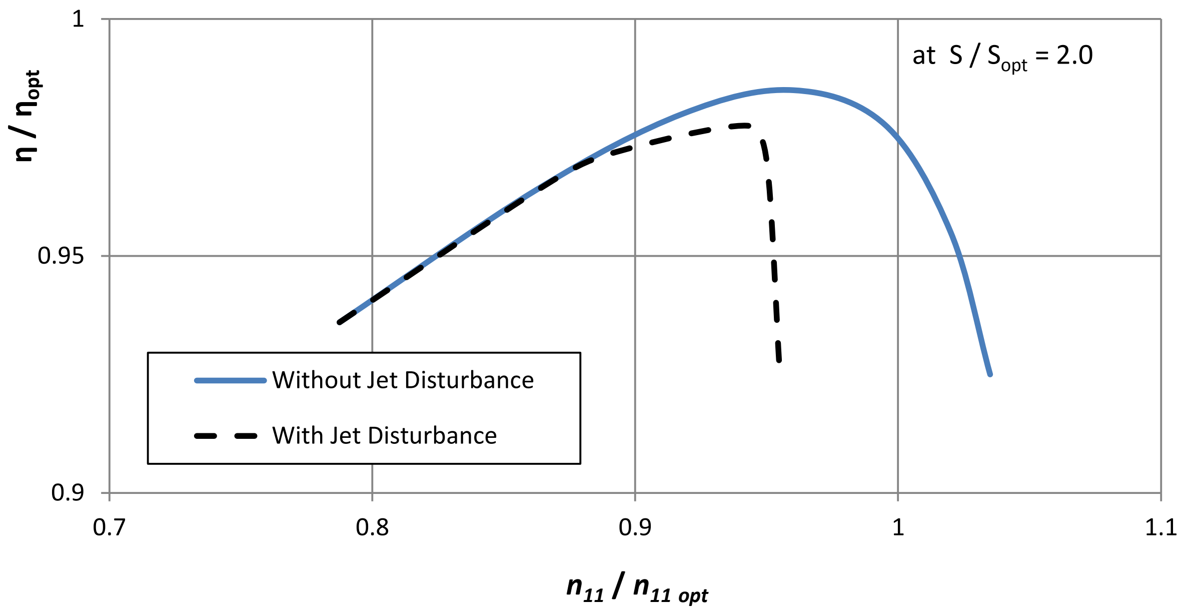

Figure 7: Typical Deterioration Due to Jet Disturbance [8]

3.1.3Nozzle

Deterioration assessment of the nozzle is paramount. Needle erosion, as seen in the examples of Figures 8 and 9, can cause both direct and indirect losses. Direct losses are the well known losses of friction and turbulence (inner friction), where indirect losses are caused by bad jet quality, shown in Figure 10 [5].

The purpose of needle and nozzle is to concentrate the jet in a cylindrical and uniform shape in order to maximize the energy transformation in the runner. Wear on the needle and nozzle causes a jet deformation which results in decay of efficiency and an appearance of cavitation.

Figure 8: Eroded Needle

Figure 9: Eroded Needle

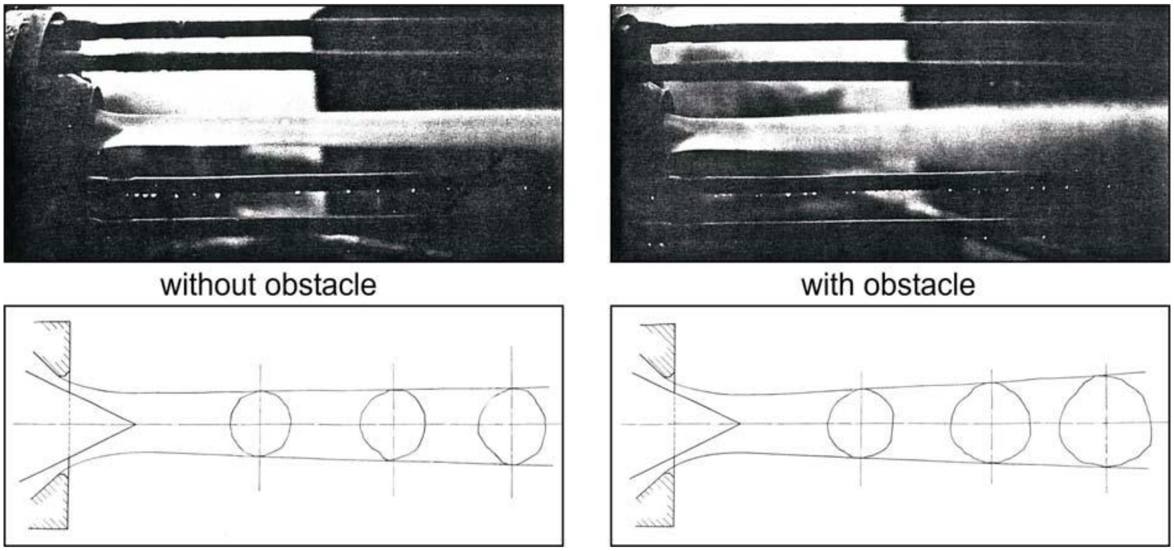

Figure 10: Photos and sketches of jet quality

Jet visualization is an assessment tool to determine jet deformation. Jet dispersion and jet deviation can be quantitatively determined from visualization in most cases. Clear correlation between turbine efficiency and jet quality has been observed. The installation of equipment for prototype visualization is delicate since the best positioning of camera and lighting instrumentation cannot be found on the basis of trial and error but must be based on experience due to the inaccessibility of the equipment.

Furthermore, the mechanical forces of possible water impingement, on the camera and lighting instrumentation, require a rigid installation (Figure 11). Housings for camera and lights should be waterproof and measures must be taken to avoid condensation building up on the lenses. In order to achieve acceptable image quality under the adverse circumstances present in the housing of an operating Pelton turbine, special equipment is necessary. The camera housing and the stroboscopic lights were mounted within protecting housings in the shelter of the injector and cut-in deflector and could be adjusted at different distances from the nozzle exit with a stepping motor [6].

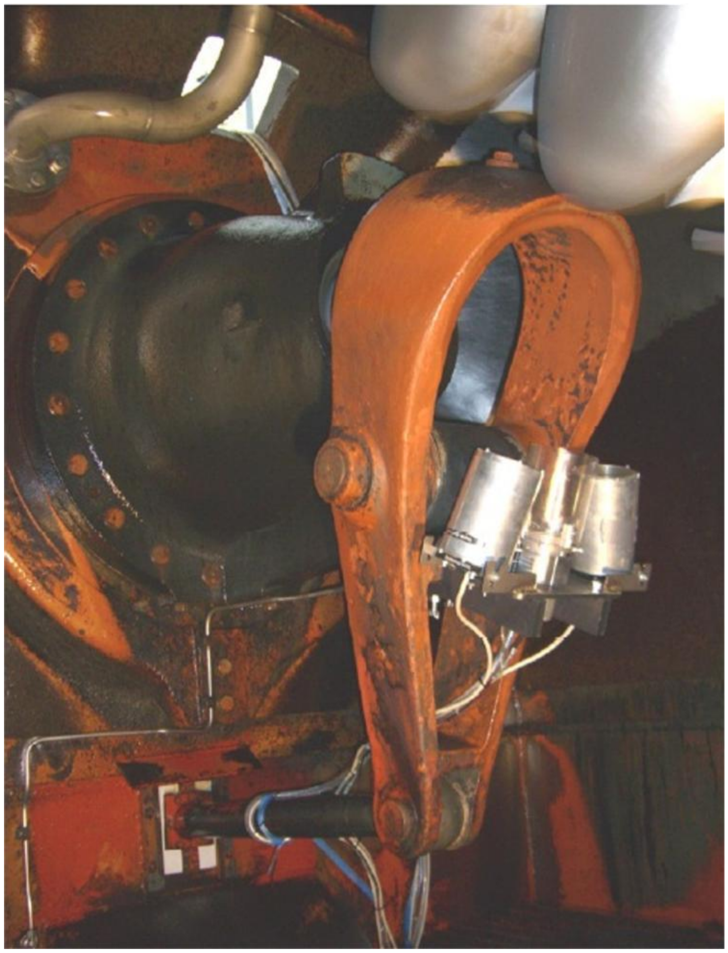

Figure 11: Internal view of bracket with camera supports for visualization

3.1.4 Distributor/Manifold

Depending on the age of the turbine unit and original hydraulic design, the distributor size may contribute to losses and turbulence. A good rule of thumb is to size the unit so that at full load, the spiral velocity head is 10 % or less of the total unit's velocity head. Older spiral distributors were often constructed in large curved cast sections as compared with newer units that are usually constructed of shorter mitred ring sections [7].

The ring sections must be assessed routinely for friction increasing internal surface deterioration. This can take the form of a visual inspection carefully performed during an outage situation when the unit is in a dry state. For examples of distributor arrangements see Figures 12 and 13.

Figure 12: Twin Nozzle distributor arrangement

Figure 13: Multi-Nozzle distributor arrangement

3.2 Operations

Turbine performance is often represented by a graph of turbine efficiency curves versus flow or output as shown in Figure 14. Also shown are typical turbine performance curves illustrating the relationship between modern performance, the original design, and a deteriorated turbine runner (noted as "present performance") [3].

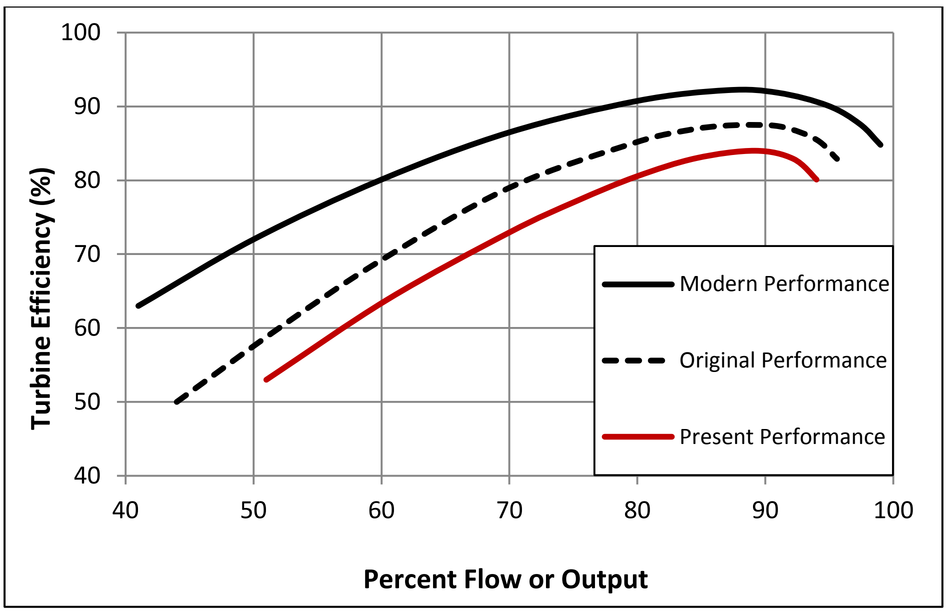

Figure 14: Typical Performance Chart for Pelton Unit [3]

Performance data must be accurately collected. The performance of the turbine can degrade over time due to cavitation and/or erosion damage and resulting weld repairs. Periodic performance checks, through absolute or relative (e.g. index) testing, are necessary for maintaining accuracy, and must be made at a number of operating heads in order to be comprehensive [3].

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. Plants should "as best practice" perform periodic performance testing (such as index testing according to PTC 18 [16]) 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

3.3.1 Weld Repair

It is commonly accepted that turbines normally suffer from a progressive deterioration in performance over time (in default of restorative action) [4]. The usual causes include cavitation damage, abrasive erosion wear, galvanic corrosion and impact damage from debris passing through the unit.

Performance-related maintenance techniques involve mainly weld repairs of the turbine components such as the runner, housing, and distributor tubes. The best practice is to use a 309L stainless steel welding electrode to return original geometry to runner buckets

3.3.2 Grinding Template

Errors in welding repairs to original bucket profile occur as the unit ages. Original bucket contour templates should be available at the plant. Trained maintenance personnel should use these templates to grind and polish the buckets thereby returning them back to OEM specifications.

3.3.3 Surface Coating

After assessment of the water supply quality and historical wear data, it can be evaluated whether a coating over the natural polished finish of the ASTM A743 [15] stainless steel (preferred modern erosion and corrosion resistant material) bucket is required. The results from North American technical papers are inconclusive regarding the benefits for any hard coating.

3.3.4 Turbine Shaft

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, or replace of wearing sleeve, and re-truing coupling faces during a major unit overhaul.

3.3.5 Guide Bearings

Turbine guide bearings are usually oil lubricated hydrodynamic 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.

Extreme shaft vibration can cause contact of the turbine runner's seal rings resulting in wear and the possible failure of the seal rings and subsequent major extended unit outage. Major maintenance requires the refurbishment of the bearings, such as re-babbitting of an oil bearing.

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.

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)

The general expression for this efficiency (η): $\eta = \dfrac{P}{\rho g Q H}$ [10]

Turbine performance parameters for Pelton 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 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 Pelton turbine can be monitored by the Condition Indicator (CI) as defined according to *HAP Condition Assessment Manual* [11].

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 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 reliability of electric generating equipment. It can be used to support equipment reliability and availability analyses 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, the analysis to determine unit efficiency and available power output relative to turbine discharge, head, and determine operating limits based on vibration and acoustic emission measurements (CPL). The results will be compared to previous or original unit test data (IPL), and determine efficiency, capacity, annual energy, and revenue loss. The results will also be compared 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.

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 Pelton turbine is quantified through the CI as derived according to *HAP Condition Assessment Manual* [11]. 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* [11].

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, their importance to be emphasized, and their ability to be understood and confirmed.

Justified projects (hydraulic profiling, 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.

The improvement of any hydraulic machinery performance can basically come from three types of intervention:

- Replacement of obsolete runner (the profiled machinery parts) with new ones
- Replacement/Improvement of nozzles with new nozzle components
- Repair for surface restoration and for improvement of wear resistance.

It is clear that these interventions are not alternative but complementary, depending on the actual problems of hydraulic design obsolescence of turbine parts and corrosion, erosion, or cavitation of turbine parts.[10]

<u>Runner Replacement</u>

The modeling of the modern Pelton turbine runner geometry can be carried out with Computational Fluid Dynamics (CFD) analysis of the jet/bucket interaction. For Pelton runners, both the flow field itself and the influence of water on the structural properties are more difficult to determine than for Francis or Kaplan turbines because Pelton buckets are moving through the jets, filling and emptying continuously. The bucket unsteady loading analysis requires knowing the unsteady pressure loading in the rotating buckets [9].

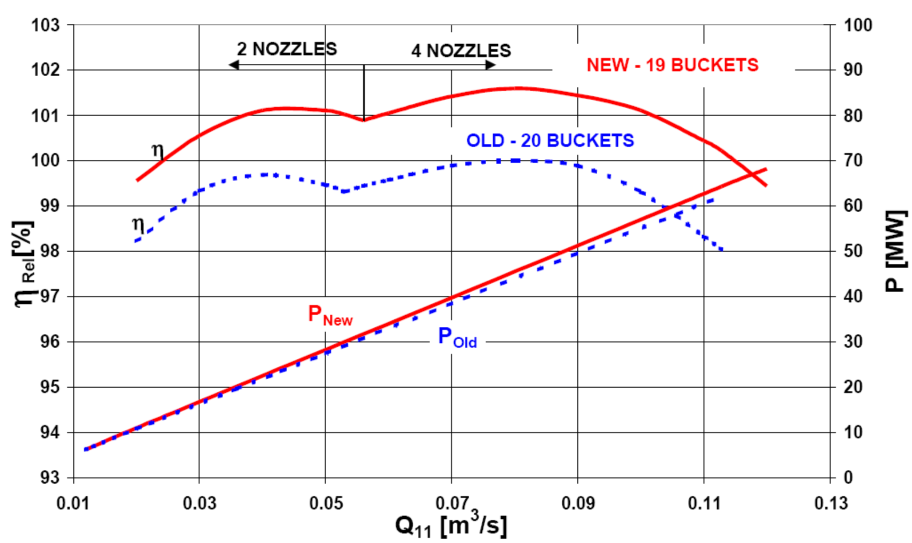

Figure 15: Typical results for new runner upgrade [13]

<u>Needle Seat Enlargement</u>

A detailed study showed that the turbine jets could be easily enlarged up to 6 % in diameter with minor negative effects on efficiency but with a substantial increase in output. This study details a six-jet Pelton unit with rated head of 675.7 m and an output of 75.2 MW at a rated jet of 152 mm diameter with a discharge of 12.6 m^3/s. The new rated power capacity is 87.6 MW with an enlarged jet of 160 mm diameter. Most manufacturers size the needle seat to accommodate some nozzle machining for maintenance. Normally this will not significantly affect the contact sealing or interface relationship at small needle opening [7]. Figure 16 shows the typical components that make up a nozzle assembly including the needle seat.

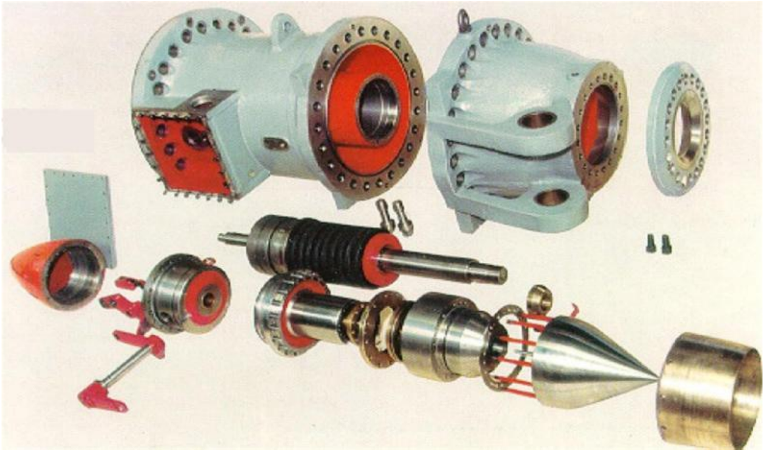

Figure 16: Typical modern nozzle assembly

5.0 Information Sources

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16. ASME PTC 18, *Hydraulic Turbines and Pump-Turbines, Performance Test codes* - 2011

17. IEC 60041 *Field Acceptance Tests to Determine the Hydraulic Performance of Hydraulic Turbines, Storage Pumps and Pump-Turbines*, 1991

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

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

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