Best Practice Catalog

Penstocks and Tunnels

Revision 2.0, 8/02/2012

Prepared by

MESA ASSOCIATES, INC.
Chattanooga, TN 37402

and

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Contents

1.0 Scope and Purpose

This best practice for penstocks, tunnels, and surge tanks addresses how innovations in technology, proper condition assessments, and improvements in operation and maintenance practices can contribute to maximizing overall plant performance and reliability. The primary purpose of a penstock or tunnel is to transport water from the intake and deliver it to the hydraulic turbine in the powerhouse. Once the water has been delivered to the turbine, it is then released downstream into the discharge channel.

1.1 Hydropower Taxonomy Position

Hydropower Facility → Water Conveyances → Penstocks, Tunnels, & Surge Tanks

1.1.1 Components

Penstocks: Penstocks are pressurized conduits that transport water from the headpond free water surface to a turbine. Penstocks can be either exposed or built integral with the dam structure as shown in Figure 1 and 2. Characteristics of functional penstocks are structural stability, minimal water leakage, and maximum hydraulic performance. Specific features of a penstock system include:

- Main Shell Material: Typically penstock shells are constructed of large round steel cross-sections. Fabricated welded steel is generally considered to be the better option when dealing with larger heads and diameters; however, pre-stressed or reinforced concrete, glass-reinforced plastic (GRP), and PVC plastic pipes are also utilized. Also, there are still many older wood stave penstocks in active service.

- Shell Linings and Coatings: The protective membrane applied to the interior (linings) and exposed exterior surfaces (coatings) which provide corrosion protection and water tightness.

- Connection Hardware: Includes rivets, welds, bolts, etc.

- Unrestrained Joints: Includes expansion joints or sleeve-type couplings spaced along the penstock span to allow for longitudinal expansion of the pipe due to changes in temperature.

- Air Valves: The primary function of air valves is to vent air to and from the penstock during both operating conditions and watering/dewatering of the penstock.

- Control Valves: Includes bypass, filling, shutoff valves, and gate valves used during watering and dewatering, redirecting flows, emergency shutoff, etc [2].

- Manholes and Other Penetrations: Includes items directly attached to the penstock and exposed to the internal pressure such as manholes, air vents and, filling line connections.

- Above Ground Supports: Includes saddles, ring girders, and anchor/thrust blocks which are susceptible to settlement or movement. The shell material and exterior coating are also more likely to experience premature failure at support locations due to high stresses and surface irregularities and should be periodically inspected.
- Surrounding soil backfill or concrete encasement for below ground structures
- Appurtenances: Includes transitions, bends, tees, elbows, and reducers. Appurtenances are especially susceptible to excessive vibrations, aging, and lining loss.
- Dewatering Drains: Drains located typically at low points along the penstock span used during dewatering. Since drains are prone to blockage or leakage, regular inspection and cleaning of drains should be implemented [2].
- Instrumentation: Any instrumentation associated with water conveyances. This can include pressure relief systems, emergency gate control system, and valve operators.

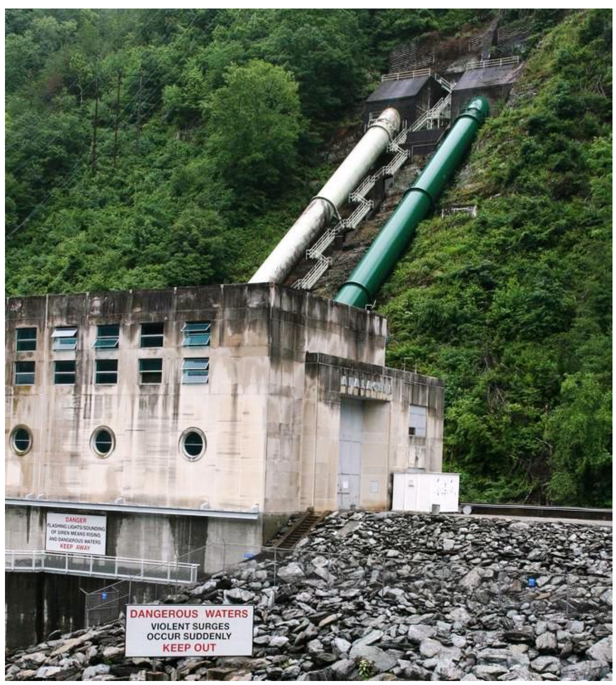

Figure 1: Exposed Penstocks at the Appalachia Hydroelectric Plant, Polk County, Tennessee

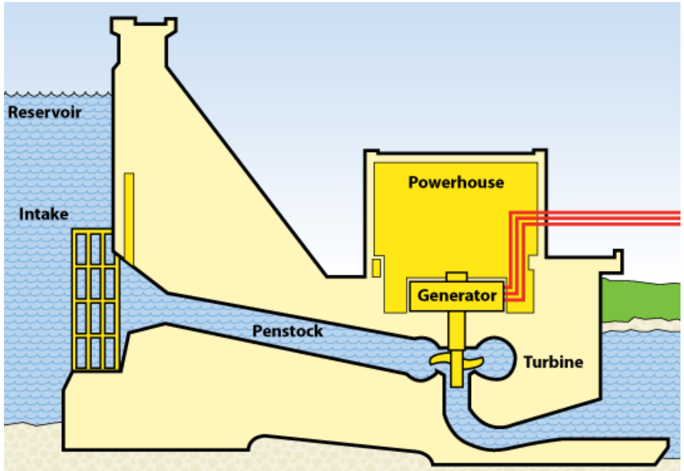

Figure 2: Penstock Integral with Dam Structure

- Tunnels: Tunnels are underground passageways commonly in rock used to carry water for power between two points. A typical arrangement is to convey water for power in a tunnel at low head, followed by a transition to a steep penstock to the powerhouse, with surge and vacuum pressures mitigated by a surge tank at the transition. A tunnel can be pressurized or unpressurized. Unpressurized tunnel flow is similar to open channel flow. This document addresses tunnels with pressurized flow. Depending on the condition of the surrounding rock or available tunneling technology, tunnels can be lined with concrete, shotcrete, or unlined. Different linings and rock conditions will determine the amount of water leakage and head loss through tunnels.

- Surge Tanks: The surge tank is an integral part of the penstock system whose purpose is to help provide plant stability and minimize water hammer by limiting the rise and fall of pressure within the penstock. Surge tanks also help to regulate flow, improve turbine speed regulation, and prevent penstock vacuum pressures during load acceptance. There are two categories of surge tanks: conventional atmospheric surge tank and closed air cushion surge chamber. Most North American surge tanks are of the atmospheric type and above ground. The atmospheric surge tank can have various shapes (horizontal area as a function of elevation) and overflow arrangements and are typically either a simple, restricted orifice, or differential type. Simple type tanks are tanks directly connected to the water conveyance pipeline or penstock. Restricted orifice tanks are similar to simple tanks but throttle flow in and out of the tank through an orifice. The differential type tank has a vertical riser similar to a chimney constructed inside the tank and connected directly to the penstock [9]. Any space that may be temporarily occupied by water during transient operation should be regarded as a surge tank (e.g. aeration pipe, gate shaft, access shaft). The air cushion chamber can reduce the total volume of the tank and can be designed for less favorable topographic conditions; however, maintenance may be needed for compressed air compensation. Surge tank excavated underground are typically lined with steel plate, wood, or reinforced concrete. They experience issues similar to that of penstocks such as deterioration or corrosion of tank material, breakdown in coatings and linings, and damage or deterioration to tank mechanical appurtenances. Figure 3 shows an example of a surge tank erected on the ground surface.

- Pressure Relief Valves: A mechanical valve within a pressurized conduit used to provide plant stability by mitigating pipe transient pressures within the penstock. Pressure valves are sometimes used in place of surge tanks. These valves can be used during both normal and extreme operating conditions. The valves are generally calibrated to open when the pressure acting on the valve reaches a preset value.

In some hydropower stations, the tailrace also consists of pressurized tunnels with or without surge tanks.

Figure 3: Steel Surge Tank at Isawa II Power Station in Japan

1.2 Summary of Best Practices

1.2.1 Performance/Efficiency & Capability - Oriented Best Practices

- Routine monitoring and recording of head loss through penstocks and tunnels.
- Trend head loss through penstocks and tunnels, comparing Current Performance Level (CPL) to Potential Performance Level (PPL) to trigger feasibility studies of major upgrades.
- Maintain documentation of Installed Performance Level (IPL) and update when modification to components is made (e.g. replacement of lining or coating, addition of slot fillers).
- Include industry acknowledged “up-to-date” choices for penstock and tunnel component materials and maintenance practices to plant engineering standards.

1.2.2 Reliability/Operations & Maintenance - Oriented Best Practices

- Develop a routine inspection and maintenance plan.

- If the exterior surface of a steel penstock is not already coated, provide exterior coating to protect penstock shell and extend life.
- Routinely inspect exterior supports or anchor blocks for signs of settlement or erosion. Misalignment of the penstock could also indicate slope stability and/or foundation issues or settlement.
- Regularly inspect joints for leakage, corroded or missing rivets or bolts, cracked welds and for concrete penstocks deterioration of waterstops or gaskets.
- Periodic internal inspections to detect deterioration.
- If build-up within the penstock presents unacceptable head losses, recommend high-pressure cleaning. If organic build-up is a persistent problem, recommend replacing liner with a fouling release type product.
- Repair/replace interior liners as required to prevent shell corrosion and extend the penstock shell life.
- Routinely inspect tunnels for signs of erosion or leakage.
- Water hammer or transient flow is an unavoidable and critical issue in any pressurized water conveyance system. Water hammer can result from any load variations, load rejections, operating mode changes, unit startup and shutdown, and operational errors. Water hammer and transient flow can cause major problems ranging from noise and vibrations to pipe collapse and total system failure. Therefore, water hammer protection devices such as surge tanks, air chambers, air valves, and pressure relief valves should be routinely inspected to ensure they are functioning properly. In addition, flow and load control devices such as the governor, turbine wicket gates, and penstock control valves should be routinely checked to prevent water hammer incidences. If found to be suspicious, measurements and further investigation should be immediately performed.
- Cursory inspections should be performed at monthly as a minimum.
- Periodic comprehensive inspections and evaluations should be performed every 5 to 10 years to determine the penstock's current condition.

1.3 Best Practice Cross-references

- Civil – Trash Racks and Intakes Best Practice
- Civil – Leakage and Releases Best Practice
- Civil – Flumes and Open Channels Best Practice
- Civil – Draft Tube Gates Best Practice

2.0 Technology Design Summary

2.1 Material and Design Technology Evolution

Coatings and linings for penstocks provide protection for the shell material and are critical to the performance and longevity of the penstock [7]. Coating and lining technology has rapidly evolved in recent years. Penstocks in many hydroelectric facilities have not been re-lined in several years or have only applied local repairs to the original linings. For this reason, it is crucial that plants perform routine evaluations as to the condition of both linings and coatings so as to avoid costly repairs or loss of revenue due to unscheduled shutdowns.

Historically, thin film (10 to 20 mills Dry Film Thickness (mDFT)) pipe liners were used to prevent steel corrosion. From the 1800's to 1940 a molten coal tar was used with a 15 to 20 year expected life span. However, these liners became brittle with time which led to cracking. Coal tar enamels became readily used after 1940 with an expected life span of 20 to 30 years. These liners were discontinued after the 1960's due to health and environmental concerns over high Volatile Organic Compound (VOC) levels. Between 1960 and 1980, coal tar epoxies were used; however, due to thinner applications, these liners had only a 15 year life span. It was not till the 1980's that high performance epoxies were commonly used (25 to 30 year life expectancy) [6]. Innovations in liners are rapidly evolving and more recently, since the early 1990's, thick film liners (up to 120 mDFT) have been used for both corrosion protection and to prevent leakage from areas such as pin holes and rivet seams. Most recent innovations in silicone and epoxy liners can reduce build-up due to organic growth (reduce frictional resistance) and increase the water flow turbine capacity. Also, newer liners have longer life expectancies and limit costly maintenance or repair expenses.

Tunneling technology has also evolved over the last decades. In the 1950's most pressurized tunnels and shafts were steel lined. Today, there are specialized techniques and design concepts for unlined, high-pressure tunnels, shafts, and air cushion surge chambers which have been developed and well-practiced in Europe and China. The cost of lining a meter of tunnel is often two to three times the cost of excavating the tunnel; therefore, new tunneling technology significantly saves in cost and construction time. This allows for the design of a larger cross-sectional area of tunnel with lower flow velocity. Larger tunnels are more tolerant of falling rocks and minor blockage along the tunnel floor given there is a rock trap at the end of the headrace tunnel. This trade-off in tunnel design and construction may not increase the head loss or leakage; however, the condition of the tunnel should be routinely inspected to detect serious collapses or local tunnel blockages.

2.2 State of the Art Technology

Penstocks are pressurized conduits designed to transport water from the headpond to the turbine with maximum hydraulic performance. By using state of the art technology for new liners such as silicone-based fouling release systems, the surface roughness of the penstock interior can be reduced (i.e. minimize frictional resistance) and organic buildup can be limited thus reducing head loss through the system. Advancement in computer modeling technology has also yielded more accurate penstock designs for hydrodynamic loading limiting head loss, reducing water hammer effects, and extending life expectancy of both liners and shell material. In addition computer modeling allows for more accurate design for updated seismic criteria per modern building codes.

It is important to periodically collect and trend performance data on penstocks, tunnels, surge tank and associated components. Instrumentation technology is rapidly evolving and improving in accuracy and reliability. By using state-of-the-art technology, hydroelectric facilities can monitor pressure levels, movement, flow, temperature, stress, and strain. These measurements can alert plant personnel to any changes in performance levels or required maintenance. Also reliable performance data can be used to determine upgrade or modernization opportunities for water conveyance systems such as penstocks and tunnels.

State of the art tunneling technology allows for a larger excavation volume which reduces the flow velocity and thus reduces hydraulic head losses. The innovative containment principles and permeability control measures (e.g. grouting) used in tunnel design and construction can minimize water leakage through the rock mass.

3.0 Operation and Maintenance Practices

3.1 Condition Assessment

Since penstocks, tunnels, and surge tanks are exposed to occasional severe service conditions and are expected to perform reliably for extended periods of 50 years or more, they are prone to the following maintenance issues:

- Deterioration of linings and coatings
- Corrosion/thinning of steel penstock shell and other steel components
- Leaking at joints/couplings
- Erosion or cavitation
- Organic growth on interior surfaces
- Localized buckling
- General buckling caused by air vent blockage or pressure relief valve malfunction
- Foundation settlement
- Slope instabilities
- Sedimentation

Condition assessments of penstocks, tunnels, and surge tanks are conducted primarily by visual examination and physical measurements. The purpose of these inspections is to determine structural integrity, life expectancy, and necessary improvements of the conveyance components. Most parts of these components will be difficult to inspect. Typically, the interior inspections will require dewatering and will present a hazardous working environment, with poor ventilation, slippery surfaces, and steep inclines. Inspection of some components may require the use of divers or remote-controlled video equipment (e.g., remote-operated vehicles, or ROVs). If a penstock is buried or integral with the dam structure, an exterior inspection is not possible. Where exposed, the penstock exterior should be inspected during full operating pressure to detect any leakage [11]. Visual inspection typically includes assessments of corrosion, coatings, rivets/joints, general alignment, foundation conditions, and stability of supporting and adjacent earth slopes. Non-destructive examination (NDE) testing, which should be performed on penstocks where accessible, includes shell thickness measurements and dimensional measurements for alignment, ovalling, and bulging. Additionally, concrete structures must be inspected for excessive cracking and pitting. Baseline crack maps should be prepared so that trending can detect new or worsened conditions can be observed and documented [1].

It is important to schedule routine and thorough inspections of all penstock, tunnel, and surge tank components. This will help identify any defects or other maintenance issues. Through proper inspection, any unscheduled shutdowns for maintenance or repair can be minimized.

When developing an inspection program, an important step in the planning phase is to acquire critical design and operating histories. This can include, but is not limited to, the initial design criteria, geotechnical/foundation information, as-built drawings, construction information, operation history, and records of previous maintenance issues [6].

Once a comprehensive history of the penstock, tunnel, and surge tank performance has been acquired, personnel can develop an inspection plan. A schedule should be implemented to periodically monitor maintenance issues. Cursory inspections should occur at a minimum of once a month or more often depending on plant specific issues. Cursory inspections shall include visual observations for signs of obvious distress such as leakage, displacements or distortions, sudden changes in instrument readings, or unexpected operational performance [11]. Every 5 to 10 years the plant shall perform a more comprehensive inspection of the pressurized conduit. This inspection shall include visual inspection and subsequent non-destructive examinations and destructive testing as required. Comprehensive inspections may occur on a more frequent basis as determined by previously identified abnormalities or special events such as flood or earthquakes [11].

Several factors can affect how often inspections of penstocks and tunnels should occur, including age, accessibility, public safety or environmental concerns, construction, and previous maintenance problems [2]. An efficient and comprehensive inspection plan, specific for each facility, should be developed after carefully considering all contributing factors. As previously noted, inspections of penstock and tunnel components generally require dewatering of the system. Therefore, inspections would ideally occur during scheduled unit outages to minimize system down time. See Tables 2-1 and 2-2 in *Steel Penstock – Coating and Lining Rehabilitation: A Hydropower Technology Round-Up Report* [6] for additional guidance in developing an inspection program.

3.2 Operations

Periodic flow measurements should be obtained to determine that the water conveyance system is functioning optimally. It is also important to routinely monitor changes in pressure within the water conveyance system.

Performing a hydraulic transient analysis consists of computer simulation of the water conveyance system and turbine-generator units to calculate pressure at all critical locations in the system [2]. The actual maximum operating pressures within the system can then be periodically confirmed to match the design calculations through load rejection testing. Testing should be performed for a full range of operating conditions. The scope of measurement during the transient testing should include continuous records for the following:

- Pressures at the chosen points along the tunnel, penstock, immediately upstream and downstream of the turbine, and along the outlet tailrace tunnel;
- Pressures within the turbines: spiral case, head cover, under runner, and in the draft tube;
- Wicket gate openings;

- Angles of runner blades for the Kaplan turbines;
- Strokes of penstock control valves;
- Speed of turbine units;
- Displacement and vibration of bearings.

The recorded data is very important for transient investigation and analysis. In addition, the following parameters are to be recorded intermittently during steady-state operations before and after transient conditions. Note that these values should agree with the corresponding values recorded continuously.

- Water levels in head reservoir and tailrace;
- Wicket gate openings and angle of runner blades for Kaplan turbines;
- Pressures in penstock, upstream and downstream of the powerhouse, and the tailrace tunnel;
- Pressures within the turbines: spiral case, head cover, under runner, and in the draft tube;
- Electric current and voltage in the generator;
- Rotational speed of turbine units.

When observed and computer simulated values fit well with each other, the program of measurements and investigations could be shortened or revised. By determining the maximum and minimum operating pressures, a comparison to the original system design can be made which can help to identify significant operational changes and potential upgrade needs.

In addition, it is important to ensure that the penstock emergency gates are functioning properly, i.e. gates open and close freely with no binding or leakage. Emergency gate tests at balanced head should be performed on an annual basis and every 5 to 10 years for unbalanced head. Opening/closing times and operating pressure should be recorded for future testing comparison [2].

During plant operations, it is important to routinely inspect the exterior surfaces of penstocks for signs of leakage while penstock is under hydrostatic pressure. If any leaks are discovered, the source should be promptly identified and repair performed. Leakage not only accelerates deterioration over time, it may be indicative of more severe issues such slope instability, foundation movement, penstock misalignment, severe corrosion, or joint failure.

3.3 Maintenance

Penstocks and tunnels carry water from the intake to the generator and introduce head loss to the system through hydraulic friction and geometric changes in the water passageway such as bends, contractions, and expansions. Reduction of these losses through upgrades or replacement can improve plant efficiency and generation. However, because of the relatively small available efficiency improvements, these actions are unlikely to be justifiable on the grounds of reducing head losses alone [10]. Therefore, upgrading or replacing penstock and tunnel structures will typically be economically viable only if the plant is already scheduled for a shutdown to address other related improvements or maintenance concerns.

Although upgrades to penstocks and tunnels will have a minor effect on generation efficiency, scheduled maintenance and life-extending repairs of these structures are very important. Since any unscheduled repair generally requires dewatering of the system with subsequent loss of power production, any plant shutdowns to repair penstock and tunnel structures will have a significant effect on plant availability and generation.

Evaluating head loss in penstocks and tunnels can point to ways of increased plant efficiency. Head loss can be caused by joints and bends, changes in diameter, and roughness and irregularities of conveyance structures. The geometry of a penstock or tunnel structure is not easily modified. Therefore, decreasing head losses by removing or reducing the number of existing joints and bends is not usually an economically viable undertaking. However, if replacement of a penstock or tunnel structure is required for other maintenance reasons, a detailed evaluation of the sizing and rerouting the waterway to increase efficiency would be warranted. In this case, the penstock or tunnel material and diameter should also be a design consideration. *Friction Factors for Large Conduits Flowing Full* [3] gives Darcy friction factors for different conduit materials and construction types as a function of Reynolds number (Re). These friction coefficients are directly proportional to the total frictional head loss. Therefore, if replacement is required, selection of lower friction material and construction types would be integral in reducing head loss through the penstock or tunnel structure. Head losses are also proportional to the square of the velocity, so the appropriate diameter should be verified. This is particularly important at older facilities where the hydraulic capacity requirements of the penstock or tunnel structure may have changed over time.

The internal surface roughness of penstocks contributes to head loss and can often be reduced to yield an increase in efficiency. "In one plant studied where the penstock is 130 feet long a net gain of head of 0.65 feet could be realized by replacing the riveted penstocks with welded steel, spun-tar lined penstocks. The generation gain would be more than one million kWh per year [10]." Surface roughness reductions can also be achieved by coating the inside of the penstock. Many different coating materials are available and the use of a specific material type will be dependent on project-specific needs. Some coatings not only improve surface roughness but can also prevent organic buildup. These coatings, such as silicone-based fouling release systems, should be considered where bio-fouling is a design consideration. Surface roughness may also be reduced by scrubbing and cleaning the interior of the penstock, removing buildup of foreign material such as invasive zebra mussels as shown in Figure 4. In one study, the surface roughness of two identical steel conduits was examined. One conduit surface was considered "quite smooth" while the other had accumulated significant organic buildup. The average Darcy friction factors under normal operating conditions were calculated at 0.13 for the smooth pipe and 0.20 for the pipe with buildup [3]. By restoring similarly affected penstocks to their original surface conditions, plant operators could expect comparable results, possibly reducing friction head losses by up to 35%, as in the case study.

Figure 4: Invasive Zebra Mussels on Steel Surface

Head loss in tunnels can be caused by similar hydraulic phenomena that affect head loss in penstocks such as sharp bends in routing, variations in diameter, and surface roughness of the tunnel wall. Tunnels can be both lined and unlined, and the roughness of the wall "relative to its cross-sectional dimensions is fundamental to the efficiency with which it will convey water [12]." Typical causes of head loss in tunnels that have the potential for efficiency upgrades include rock fallout in unlined tunnels, significant and abrupt changes in rock tunnel diameter, and organic buildup. "Slime growth in tunnels can be a serious problem…one plant is on record as losing 3% of maximum power due to this [10]." It should be noted that by relieving one problem, others may emerge. Removing organic buildup can expose rough linings or rock walls that have comparable head loss characteristics. Perhaps the best technique for improving efficiencies in tunnels is to decrease surface roughness by either filling in large cavities in the rock wall with grout or installing some type of lining. "A major modification for substantial reduction in head loss is the installation of concrete lining (or to a lesser extent a paved invert) in a formerly unlined tunnel [10]." Lining or grouting the tunnel wall can result in an increase in efficiency by reducing leakage into the surrounding rock which can reduce the available generation flow.

Penstock shell thickness measurements need to be taken and monitored periodically to identify losses in thickness, which must then be compared with minimum acceptable thickness values. If shell thinning exceeds acceptable values for structural integrity, corrective actions must be taken [11]. Deteriorated penstocks may be rehabilitated by patching localized areas, lining with a material such as fiberglass to reinforce the structure of the penstock, or replacing the existing penstock [8].

Figure 5: Exposed Portion of Penstock at Center Hill Hydro Plant in DeKalb Co., Tennessee

Another concern for penstock structural integrity is ovalization or out-of-roundness due to improper installation, design, or excessive external pressure during operation. If this occurs, the penstock diameter should be measured at various locations along its length and recorded to help monitor any geometric changes. Other possible structural problems that must be carefully monitored include penstock alignment, pinhole leaks, and localized shell buckling. Additionally, it is important to carefully inspect the shell liner for protrusions, caused by organic growth, marine organisms (e.g., mussels), and degradation of the linings or coatings – all of which can impede water flow [2].

Ultrasonic devices can be utilized for determining shell thickness. There have also been advances in remote-controlled video equipment (e.g., ROVs) for use in inspections of penstocks and intakes where access is limited that allow for safe and efficient inspections. Portions of penstocks that cannot be dewatered or readily dewatered should be periodically inspected by a diver or an ROV. For more information on non-destructive testing methods see *Steel Penstocks* [11].

After the inspection, an evaluation should be done to determine if corrective actions need to be taken and what is the best way to implement them. The evaluation of penstock and tunnel components should be performed by a qualified individual or team to determine the system's reliability to perform per the original design criteria and to make recommendations for future inspection frequency and areas of focus.

The key to improving system performance through penstock and tunnel component rehabilitation can be summarized as follows: 1) Development of an inspection/maintenance program based on individual system needs; 2) Effective implementation of the inspection program; 3) Proper evaluation of inspection results; 4) Recommendations for rehabilitation and repairs with focus on efficiency improvements and service life extension; and 5) Execution of upgrades and repairs with limited system shutdown time. Establishing a proper maintenance program can reduce the occurrence of unscheduled shutdowns and efficiency losses in penstock and tunnel components.

4.0 Metrics, Monitoring and Analysis

4.1 Measures of Performance, Condition, and Reliability

The fundamental equations for evaluating efficiency through penstocks and tunnels is the Darcy-Weisbach equation for head loss due to friction and the equation for head loss due to minor losses from geometric irregularities such as gate slots and bends. Avoidable head losses can be directly related to overall power/energy loss and subsequent loss of revenue for the plant. These equations are defined as follows:

Avoidable head loss due to friction, Δh_f (ft), from the Darcy-Weisbach equation:

$$\Delta h_f = \Delta f \frac{L}{D}\frac{V^2}{2g}$$

Where:
- · Δf is the difference in Darcy friction factors computed for the existing roughness conditions and roughness conditions after potential upgrade
- · **L** is the length of the conveyance component (ft)
- · **V** is the average flow velocity or flow rate per cross-sectional area (ft/s)
- · **D** is the hydraulic diameter (ft)
- · **g** is the acceleration due to gravity (ft/s^2)

Avoidable head loss due to minor losses (e.g., gate slots), Δh_m (ft):

$$\Delta h_m = \Delta K \frac{V^2}{2g}$$

Where:
- · ΔK is the difference in minor head loss coefficients computed for existing wall irregularities from gate slots and for conditions with irregularities removed by use of slot fillers after potential upgrades.
- · **V** is the average flow velocity or flow rate per cross-sectional area (ft/s)
- · **g** is the acceleration due to gravity (ft/s^2)

Other key values required to complete the computations for avoidable head losses include the dimensionless Reynolds number, Re, Darcy friction factor, *f*, kinematic viscosity, ν (ft^2/s), and equivalent roughness ε (ft). If the Reynolds number and relative roughness of the penstock shell or tunnel interior are known, the Darcy friction factor can be determined using either the Moody diagram or the associated Colebrook-White equation. If exact relative roughness measurements are unavailable, an approximate Darcy friction factor can be determined by comparing the existing conditions with charts found in publications such as *Friction Factors for Large Conduits Flowing Full* [3], which provide data of measured Darcy friction factors for various construction materials.

Avoidable power loss, ΔP (MW), associated with Δh_f or Δh_m:

$$\Delta P = 0.85\ Q\ \gamma\ \Delta h\ /\ 737{,}562$$

Where:
- · **0.85** is a factor to account for the water to wire efficiency of the turbines
- · **Q** is the average volumetric flow rate through the plant (ft^3/sec)

· **γ** is the specific weight of water (62.4 lb/ft^3)
· **Δh** is the avoidable head loss
· **737,562** is the conversion from pound-feet per second to megawatts

Avoidable energy loss, ΔE (MWh), associated with Δh_f or Δh_m:

$$\Delta E = \Delta PT$$

Where: · **ΔP** is the avoidable power loss (MWh)
· **T** is the measurement interval (hrs.)

Avoidable revenue loss, ΔR ($), associated with Δh_f or Δh_m:

$$\Delta R = M_E \, \Delta E$$

Where: · **M_E** is the market value of energy ($/MWh)
· **ΔE** is the avoidable energy loss

4.2 Data Analysis

Determination of the Potential Performance Level (PPL) will require reference to the flow characteristics of the modified geometry and/or surface roughness of the penstock or tunnel components. The PPL will vary for each plant. However, the maximum PPL will be based on the flow characteristics of the most efficient available upgrade.

The Current Performance Level (CPL) is described by an accurate set of water conveyance component performance characteristics determined by flow and head measurements and/or hydraulic modeling of the system.

The Installed Performance Level (IPL) is described by the water conveyance component performance characteristics at the time of commissioning or at the point when an upgrade or addition is made. These may be determined from reports and records of efficiency and/or model testing at the time of commissioning or upgrade.

The CPL should be compared with the IPL to determine decreases in water conveyance system efficiency over time. Additionally, the PPL should be identified when considering plant upgrades. For quantification of the PPL with respect to the CPL, see *Quantification for Avoidable Losses and/or Potential Improvements – Integration: Example Calculation*.

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 data should be made available to all involved personnel (particularly unit operators), their importance emphasized, and their ability to be understood confirmed. All necessary upgrades or maintenance (penstock re-lining, penstock cleaning, etc) and methods to routinely monitor unit performance should be implemented.

Integration: Example Calculation

A theoretical hydroelectric plant has three girth-welded steel penstocks integral with the dam structure. The interior of the penstocks has significantly corroded over time. The hydraulic properties of each penstock are as follows:

- Length = 600 ft
- Diameter = 14 ft
- Average flow = 2200 cfs
- Average velocity = 14 ft/s

If the penstocks are treated with a silicone-based coating system, the decrease in head loss can be calculated as follows:

Surface roughness of existing penstocks (corroded steel w/ welded girth joints) = 0.005 ft

Relative roughness of existing penstocks = (0.005 ft) / (14 ft) = 3.6×10^{-4}

Surface roughness of silicone coating = 0.000005 ft

Relative roughness of silicone coating = (0.000005 ft) / (14 ft) = 3.6×10^{-7}

$$Re = (14\ ft/s)(14\ ft) / (1.0 \times 10^{-5}\ ft^2/s) = 1.9 \times 10^7$$

From the Moody diagram:

$$f_{existing} = 0.016$$

$$f_{silicone} = 0.008 \quad \rightarrow \quad \Delta f = 0.016 - 0.008 = 0.008$$

The decrease in head loss per penstock:

$$\Delta h_f = (0.008)\ [(600\ ft) / (14\ ft)]\ [(14\ ft/s)^2 / 2(32.2 ft/s^2)] = 1.04\ ft$$

The decrease in head loss in all three penstocks:

$$\Delta h_f = 3\ (1.04\ ft) = 3.13\ ft$$

The increase in power production can be calculated as:

$$\Delta P = 0.85(2200\ cfs)(62.4\ pcf)(3.13\ ft) / 737{,}562 = 0.495\ MW$$

At an estimated market value of energy of $65/MWh, and assuming the plant produces power 75% of the time, the market value of increased power production can be calculated as:

0.75 (0.495 MW)($65/MWh)(8,760 hours/year) = $211,500/year

This analysis indicates an available energy and revenue increase over the performance assessment interval.

5.0 Information Sources:

Baseline Knowledge:

1. Bureau of Reclamation, Veesaert, Chris J., *Inspection of Spillways, Outlet Works and Mechanical Equipment, National Dam Safety Program Technical Seminar Session XVI*, February 2007.

2. Bureau of Reclamation, McStraw, Bill, *Inspection of Steel Penstocks and Pressure Conduits, Facilities Instructions, Standards, and Techniques, Volumes 2-8*, September 1996.

3. Bureau of Reclamation, *Friction Factors for Large Conduits Flowing Full, A Water Resources Technical Publication, Engineering Monograph No. 7*, Reprinted 1992.

4. Pejovic, Boldy and Obradovic, *Guidelines to Hydraulic Transient Analysis.* Gower Publishing Company, Brookfield, Vermont. 1987.

5. *Hydro Life Extension Modernization Guide, Volume 3: Electromechanical Equipment,* EPRI, Palo Alto, CA: 2001. TR-112350-V3.

State of the Art:

6. Electric Power Research Institute (EPRI), *Steel Penstock – Coating and Lining Rehabilitation: A Hydropower Technology Round-Up Report, Volume 3*, TR-113584-V3, 2000.

7. American Society of Civil Engineers (ASCE), *Civil Works for Hydroelectric Facilities – Guidelines for Life Extension and Upgrade*, ASCE Hydropower Task Committee, 2007.

8. Kahl, Thomas L., *Restoring Aging Penstocks, Hydro Review*, December 1992.

9. Otter, Paul, *Design and Performance of a Differential Surge Tank, Hydro Review,* October 1988.

Standards:

10. EPRI, *Increased Efficiency of Hydroelectric Power*, EM-2407, Research Project 1745-1, Final Report, June 1982.

11. ASCE, Steel Penstocks, *ASCE Manuals and Reports on Engineering Practice No. 79*, 1993.

12. United States Army Corps of Engineers (USACE), *Engineering and Design – Tunnels and Shafts in Rock*, EM 1110-2-2901, May 1997.

13. USACE, *Engineering and Design – Hydraulic Design of Reservoir Outlet Works*, EM 1110-2-1602, October 1980

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.