INTEGRITY MANAGEMENT PROGRAMS FOR AGING INFRASTRUCTURES IN HYDROELECTRIC GENERATING STATIONS

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ABSTRACT
To ensure the hydroelectric power generation needs can be optimally met, total plant reliability is essential. In a recent 2011 Electric Utility Survey, one question asked to utility leaders was: “What environmentally-friendly technologies should the industry emphasize?” Following nuclear and natural gas, the highest-rated technology was hydroelectric power. Hence, it is of paramount importance to optimize an Asset Integrity Management Program, looking at both the short and long term, with a carefully applied approach using engineering experience and, nondestructive examination (NDE) knowledge and repair techniques, to ensure continuous reliable hydroelectric power generation.

Structural Integrity Associates, Inc. (SI) has long been involved in the inspection and evaluation of water conveyance systems to identify potential problems, and to enable forward planning for repairs and maintenance activities. These vital advanced inspection techniques enable information to be acquired on the condition of an asset, even when the location to be inspected is inaccessible and in most cases still in operation. A good example of this is Pacific Gas & Electric Company’s assessments of 24 of their hydroelectric assets. SI initially performed visual examination of the penstocks in order to determine the location of observed leaks and conditions that could lead to the loss of structural integrity, such as loss of support. This was followed by Ultrasonic Testing (UT) and quantitative thickness screening technologies. The UT data was used as input for the integrity assessment of the assets. A statistical approach was used to characterize the wall thickness of the penstock and identify the extent of the wall loss, if present. A demand-to-capacity ratio was determined as a benchmark for making decisions to a) do nothing, b) repair, c) replace or d) perform more sophisticated analysis to justify future operability of the assets. More sophisticated analysis includes defect analysis/assessment using Finite Element Analysis techniques. Also, as the need arose, SI provided advanced UT services (e.g., linear phased array), metallurgical analysis, and analytical engineering services. One of the lateral branches of the asset integrity management program is to inspect and provide engineering assessments on pressure boundary components within the powerhouse, including valves, manhole frames, etc.

INTRODUCTION
Faced with aging assets and limited resources, a more proactive approach is needed to ensure continued safe and reliable operation of conventional and pumped-storage hydroelectric powerhouses.

One recently implemented strategy to help achieve this has been the creation of an Asset Management group in many hydroelectric utilities. This group is responsible for increasing equipment reliability and availability by improving the underlying business processes used to (a) identify, plan, and execute projects in a prioritized manner; (b) define and implement best practices for maintenance across the system; and (c) ensure public and employee safety. The generic goals established for Asset Management are to:

• Manage the complete hydro asset inventory using current asset condition assessments
• Identify the highest priority projects based on facts which are used to establish an asset’s health, risk exposure, etc.
• Manage risk by planning work according to fact-based priorities
• Improve long term planning of project scopes, schedules and budgets.
• Continue to add to the body of knowledge regarding the condition of each asset and evolve the
level of detail used in their assessment.

To quote the Federal Energy Regulatory Commission (FERC) on the necessity for penstock inspection and assessment - “The FERC has become increasingly concerned about the number of penstock failures or other potentially dangerous incidents that have occurred in the operation of penstocks. The FERC has recognized the potential for loss of life and damage to the environment and has mandated inspection and testing of penstocks”.

Specific Governing Code Requirements for structural assessment of in-service Penstocks do not exist; however, useful guidance does exist and can be found in the following documents:

- ASCE Engineering Practice No. 79 – Steel Penstocks
- USBR Engineering Monograph No. 3 – Welded Steel Penstocks
- ASME Boiler & Pressure Vessel Code, Section VIII, Division 2

Degradation Mechanism Evaluation

Generic degradation mechanisms, for example, as noted in the EPRI's RI-ISI report [“Revised Risk-Informed In-service Inspection Evaluation Procedure,” EPRI TR-1 12657, Revision B-A, December 1999.] include:

- Corrosion
  - General Corrosion
  - Localized Corrosion
  - Pitting
  - Crevice corrosion
  - Under deposit corrosion
  - Microbiologically influenced corrosion
- Stress Corrosion Cracking
- Flow Sensitive Mechanisms
  - Erosion-cavitation
  - Flow accelerated corrosion
- Fatigue
  - Mechanical fatigue
  - Thermal stratification
  - Thermal transients
- Other effects
  - Overload
  - Embrittlement
  - Fabrication defects

For penstocks, the prevalent degradation mechanisms are general and localized corrosion.

General Corrosion

Bare carbon steel will corrode, primarily by general corrosion, at a rate determined by the water chemistry, the temperature, and the flow rate. The corrosion rate will be influenced the most dramatically by the dissolved oxygen content.

For coated penstocks, corrosion will be essentially nil as long as the coating is intact. However, all coatings will go into service with some number of holidays (voids in the coating), coatings have some level of permeability to water, and coating life is often less than the desired plant life, so that portions of
the penstock will become “uncovered” with time. General corrosion will occur at coating holidays from initial construction or where holidays form over time. The initiation of corrosion will have been delayed during the time that the coating has remained intact. It must be noted that the corrosion rate is not a discrete value, but is represented by a distribution, typically a normal or lognormal distribution.

Localized Corrosion

Carbon steels can also be susceptible to all forms of localized corrosion, including pitting, crevice corrosion, and microbiologically influenced corrosion (MIC). However, localized corrosion is usually far less significant than general corrosion and the distribution of rates of general corrosion. Further, the existence of the ID coating dramatically reduces the probability that a localized corrosion can initiate and begin to propagate. Finally, the flow conditions for the penstock, that is, continuous flow at relatively high rates nearly 100% of the time, further decrease the probability that localized corrosion cells can initiate. The probability of localized corrosion is considered low. Further, the general approach to characterizing general corrosion, specifically, the use of UT thickness scanning with a relatively small transducer, the reporting only the thinnest location in a grid, will detect localized corrosion.

OVERVIEW OF APPROACH FOR IN-SERVICE MONITORING AND INSPECTION OF STEEL PENSTOCKS

The structural assessment program of steel penstocks focuses primarily on the condition and integrity of the penstock shell using methods that do not require the penstock to be dewatered and allow the power plant to continue operating (i.e., using non-destructive examination techniques). This primarily includes obtaining a better understanding of the contribution of corrosion or wall loss — occurring both internally and when in contact with soil or backfill, externally — and the effects of transient pressures due to operations of turbine/generators and/or pressure regulating valves; especially when they too have aged and may produce pressure waves that are outside of the original design basis.

The initial structural assessment consists of three key parts: the process to (1) define where and how to collect the data, (2) the type of non-destructive examinations to be performed and amount of data needed to support decision-making, and (3) the analysis process. Each ‘step’ is described below:

Planning Process

The program consists of collecting wall thinning, or corrosion measurement, data where areas of concern are identified or suspected. This ‘targeted’ approach provides data on localized areas within a penstock segment, but it is difficult to extrapolate these results to other areas along the penstock. This process can be expanded to collect data at different representative points along the length of the penstock. These locations are determined by a combination of visual or suspected area of concern plus ease of access to collect the data. The program can be expanded to collect data by requiring that where partially buried segments exist, select locations be excavated to allow measurements to be taken.

Walkdown

The first phase of the work is to conduct walk-downs of the individual penstocks or siphon pipes to identify areas of concern and select locations to be examined. Depending upon the penstock’s length and the extent of data obtained, in general, a minimum of 4 to 7 locations on each penstock need to be identified for NDE data collection.

The notes and other data from the walk-downs are collected on planning templates that will later be
used to create the individual penstock investigation work plans which would finalize the locations to perform the NDE work. These locations are marked and documented using Global Positioning Systems. Other requirements and other logistical information needed to perform the work, such as the use of machine excavation, shoring, scaffolding and the lengths of surface preparation needed at each of the test sites, are noted as well.

Data Collection Process - NDE Method and Statistical Sampling Approach

The dominant degradation mechanism for the penstocks is corrosion, most commonly from the inside diameter (ID). If some amount of erosion has also been observed and buried portions of penstocks are also susceptible to outside diameter (OD) corrosion. Penstock inspections need to provide a sufficiently complete characterization of structural integrity that result in a high level of confidence. This requires that the thickness data sample size is sufficiently large and diverse to determine the thickness distribution, or the metal loss distribution, with a high level of confidence. This large and diverse sampling requires that a sufficient number of individual thickness measurements are collected so that a statistically significant sample of the entire structure is obtained. The diversity portion of the sampling will require that the thicknesses of various locations (e.g., cans made from different thickness plates) are sufficiently well characterized that stresses can be computed for all locations. It is important to focus on the remaining wall thickness as opposed to only looking at the wall loss to date. While the corrosion rate is useful information for determining future wall loss, after years of corrosion the remaining wall thickness may still be greater than the original design or nominal thickness. Therefore, to calculate accurate stresses in the penstock it is ideal to use the remaining wall thickness instead of subtracting thickness from what may have been a greater wall thickness to begin with. The other aspect of the diversity of sampling is that a number of locations along the length need to be characterized to assure that the metal loss as a function of length, elevation, etc. is well understood, and so that areas that might have slightly different operative mechanisms have been properly characterized. The latter locations include the top portions of the penstock and siphon (e.g., where water line effects may exist), the bottom (where more erosion may occur), both vs. the sides (where general corrosion would be expected to be the dominant or only operative mechanism).

For each unique component, a minimum of four locations needs to be characterized. The number of individual thickness measurements at a location defined above will generally be several dozen to several hundred measurements per location. For example, a sample location that is 12”x12” should have a minimum of 100 individual thickness measurements reported. The number of individual measurements that are made may significantly exceed the number that are reported (refer to Figure 1 for a typical riveted buried penstock joint that was inspected using NDE technology). The total number of individual inspections for a penstock should never be less than 1000.

POST-PROCESSING OF FIELD DATA

A histogram of penstock wall loss (t_nominal design minus t_inspected) UT measurements with a normal or log-normal curve fit distribution is presented in Figure 2. Wall loss measurements enable the comparison of UT measurements taken on shells of different thickness.
STRUCTURAL ANALYSIS PROCESS

PG&EE developed an evaluation approach based on a ratio of the “demand” to the “Capacity” (D/C). The demand stress represents the current hoop stress based on applied loading conditions. The capacity stress represents the allowable stress based on the Guidelines for Evaluating Aging Penstocks – Task Committee on Guidelines for Aging Penstocks of the Energy Division of the American Society of Civil Engineer, 1995 Edition. A D/C equal to 1.0 represents a condition where the stress associated with the applied loading condition equals the allowable stress. A D/C greater than 1.0 represents a condition where the applied stress is greater than the allowable, while a D/C less than 1.0 represent a condition where the applied stress is lower than allowable. For each penstock, Microsoft ExcelTM was used to create an asset specific spreadsheet used to calculate both the allowable hoop stress from internal pressure (pressure stress) and the actual pressure stress at various locations along the penstock. Currently, the spreadsheets are set up to calculate these stresses where there is a change in penstock diameter, thickness, or longitudinal joint efficiency.

Inputs to the spreadsheet include: the static head, water hammer pressure (as a % of static), pipe diameter, original plate thickness, estimates of wall thinning or loss of material due to corrosion, material strength (e.g. yield, and ultimate stress), and joint efficiency. The output is a plot of the ratio of demand (actual stress) to the allowed stress. The allowable stress intensity, or capacity, is based on the smaller of
1/3 of the ultimate tensile strength or 2/3 the yield strength associated with the normal operating condition as defined in Guidelines for Evaluating Aging Penstocks. The D/C spreadsheet also has a trend function that extrapolates the current estimated rate of corrosion or wall loss out in time, which aids in establishing the timing to implement either a re-inspection or a corrective action. When the D/C ratio is greater than 1.0, additional evaluation or corrective action is required. Depending on the results, additional data collection may be warranted to augment current data to reduce the uncertainty in a specific input (e.g., rivet joint efficiency, or the maximum transient pressure). It is important to note that this method of analysis currently does not address evaluation of flaws such as cracks or weld flaws, and it does not evaluate additional stresses in locations such as supports, bends, bifurcations, and appurtenances.

Figure 3 is the graphical D/C output associated with this example for both the condition as originally designed, and with estimates of corrosion and wall loss. It shows that the D/C is less than 1.0 from the reservoir or ‘headworks’ to about 4,000 feet along the penstock and the D/C changes to be above 1.0 from about 4,500 feet to the powerhouse. Where the D/C is greater than 1.00, it means the applied loading condition no longer meets the acceptance criteria, and therefore further evaluation or action is required. The condition becomes greater when the effects of corrosion are applied. Figure 4 shows these results by comparing the present material thickness with that required to meet design requirements.
ULTRASONIC TESTING FOR INTERNAL CORROSION

The ultrasonic phased array corrosion wheel probe is ideally suited for hand scanning of penstocks for internal corrosion and remaining wall thickness. The system is made to inspect large areas quickly, efficiently, and accurately with high resolution encoded data. The corrosion wheel probe’s conformable water filled wheel (tire) allows excellent coupling, even capable of inspecting on rough, corroded surfaces. The 50 mm (approximately 2 inches) wide probe houses a 5MHz, 64 element, linear phased array transducer. The 0.8 mm (0.031 inches) phased array probe resolution coupled with the high resolution position encoder can easily allow for over 90,000 inspection points to be taken in a 1.0 foot square area. Each two inch wide encoded scan can be collected circumferentially or longitudinally along the penstock at scanning speeds up to 100 mm per second (4 inches/second).

For both scanning systems, immediate analysis of the encoded “strips” of data via A-Scan, B-Scan, and C-Scan views is possible on-board the OmniScan MX ultrasonic inspection unit, thereby allowing the inspector the opportunity to identify areas of concern while still on the penstock. The individual (approximate 2.0 inches wide) scans can also be exported to off-line UltraVision analysis software and “merged” to show a complete C-Scan presentation, which uses a color-coded scheme relative to material thickness. Raw data values relative to the lowest thickness reading at each sample point can also be
exported using industry standard formats (e.g., CSV, Excel™, etc.) to support further statistical analysis of the ultrasonic data.

Figure 7: Ultravision Analysis Software Display

CONCLUSION
To ensure continued safe and reliable operations when faced with aging assets, limited resources, and retiring talent; it is imperative to invest in the implementation of a robust Asset Management Program for hydroelectric penstocks. Due to the number of penstock assets and the complexity of some of the evaluation processes, an iterative approach has been discussed to ensure forward progress towards understanding the condition of each asset while needing to make decisions on their continued operation. Due to the complexity of the structural assessment process, the penstock program has focused on the basic method to characterize the penstock by evaluating the hoop stress and will continue to evolve this process to address other factors such as: (a) the effects of differences in material properties and fabrication processes, (b) contribution of secondary stresses associated with saddle supports, differential settlement, or appurtenances, (c) address other load cases, such as creation of vacuum pressures which can cause buckling or collapse type failures, and (d) ensure that adequacy, reliability, and redundancy is ‘built’ into each penstock’s protection schemes.

In addition, this program will need to be expanded to quantify the risk to above-grade penstocks associated with both falling tree hazard and how to prevent or minimize the consequences associated with acts of terrorism or vandalism. In addition, for both buried and above-grade penstocks, develop a strategy to address the potential that differential settlement can be contributing to secondary stresses or how to identify where such conditions may likely be occurring.