Condition Assessment Manual

Appendix 1.02 – Guide for Pressurized Water Conveyance System Condition Assessment

HAP
HYDROPOWER
ADVANCEMENT PROJECT

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1.0 General

Pressurized water conveyances such as penstocks and tunnels are an important component in the power generation process at a hydropower facility. Penstocks and tunnels are pressurized conduits that transport water to the turbine with maximum hydraulic performance. Since penstocks and tunnels are subject to internal pressures and rapid flow velocities, they are likely to experience several maintenance and reliability issues. These issues can include:

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

Emergency repairs, unscheduled maintenance, or replacement of water conveyance system components can be very costly. Therefore, routine maintenance and condition assessments are important in extending the life expectancy of conveyance components, limiting unscheduled shutdowns, and improving hydraulic performance by minimizing head losses. By performing a condition assessment, plants can estimate the remaining component life expectancy, indentify potential failure risks, and evaluate the benefits of component upgrades.

For a water conveyance system, the three following steps are necessary to establish its condition indicator:

1) What parts/items are to be included in the condition assessment and what is their level of importance (parts and their weighting factors)?

2) What metrics/parameters are to be investigated for the quantitative condition assessment and what is their level of importance (condition parameters and their weighting factors)?

3) How to assign numerical scores to the parts (rating criteria)?

This Appendix provides guides to help answer the questions above, which can be applied to penstocks, tunnels, and surge tanks. The condition assessment is to be performed on the pressurized water conveyance system for an individual unit. This can include a wide variation in arrangement schemes. Figures 1a, 1b, and 1c represent three separate schemes often found in hydropower facilities. Since plants can have a large variation in the arrangement of water intakes and conveyances, the guides provided in this Appendix cannot quantify all factors which can affect individual conveyance conditions. Mitigating factors not included in this Guide may

trigger testing and further evaluation to determine the final score of the water conveyance condition and aid in the decision of component replacement or rehabilitation.

This Appendix is not intended to define pressurized water conveyance maintenance practices or describe in detail inspections, tests, or measurements. Utility-specific maintenance policies and procedures must be consulted for such information.

2.0 Constituent Parts Analysis

For pressurized water conveyance systems, the constituent parts need to be mapped and determined for a specified unit, as some parts are commonly used by two or more units. Tables 1a, 1b, and 1c, respectively, coincide with the three different system design schemes shown in Figure 1a, 1b, and 1c for Unit 1.

If any part (e.g., surge tank) does not exist in a particular pressurized conveyance system, this part will be excluded from scoring mechanism by inputting “NA” into the Table. The effect of one component exclusion is usually insignificant to the entire system assessment and does not justify an adjustment of the weighting factors for the other components.

Actually, Table 1c can be applied for all three conveyance system schemes by inputting “NA” for the parts that do not exist in schemes 1a and 1b.

Figure 1a: Scheme A – Single Unit Penstock

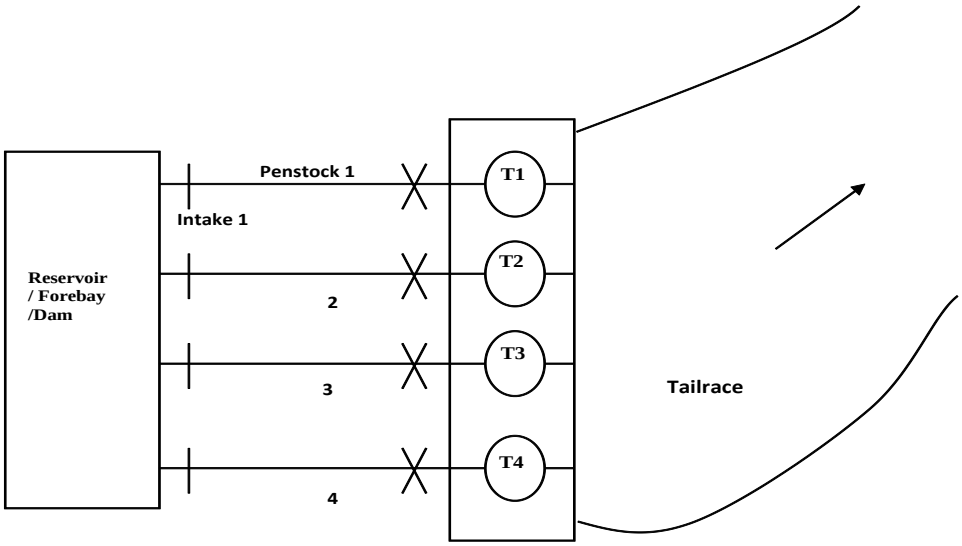

Table 1a: Scheme A Pressurized Water Conveyance Condition Assessment & Scoring - XXX Hydropower Plant (Unit 1)

Parts/Items for Unit 1	Taxonomy ID	Physical Condition Score	Age Score	Installed Technology Score	Operating Restrictions Score	Maintenance Requirement Score	Data Quality Score	Weighting Factors for Parts
Penstock 1	3.4.1							3.0
Linings and Coatings	3.4.3							1.0
Foundation and Supports	3.4.4							1.0
Air Vent/Pressure Relief Valve	3.4.5							1.0
Joints and Couplings	3.4.6							1.0
Weighting Factors for Condition Parameters		2.0	1.0	1.0	1.0	1.5	Data Quality -->	*0.00*
							Condition Indicator -->	*0.00*

Figure 1b: Scheme B – Group Shared Penstock

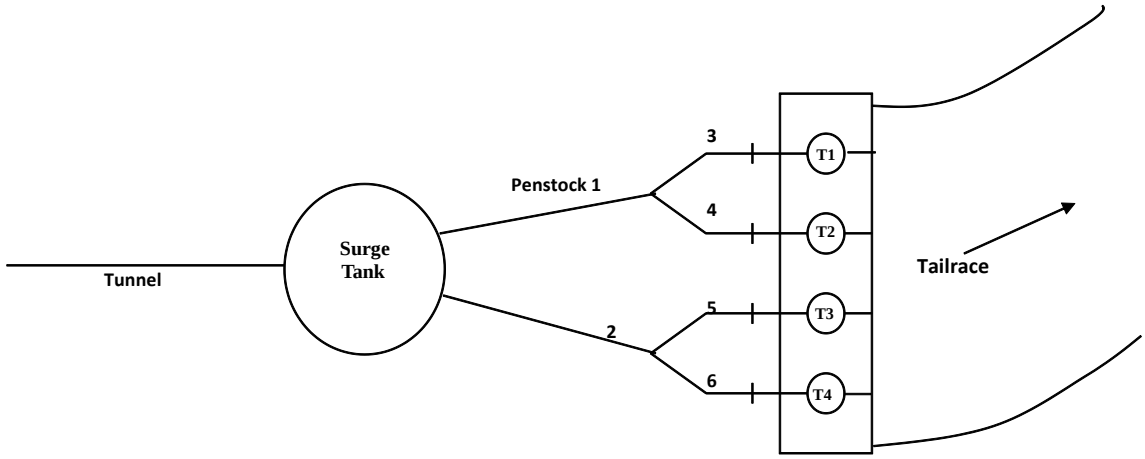

Table 1b: Scheme B Pressurized Water Conveyance Condition Assessment & Scoring - XXX Hydropower Plant (Unit 1)

Parts/Items for Unit 1	Taxonomy ID	Physical Condition Score	Age Score	Installed Technology Score	Operating Restrictions Score	Maintenance Requirement Score	Data Quality Score	Weighting Factors for Parts
Tunnel	3.3							2.0
Surge Tank	3.6							1.5
Penstock 1	3.4.1							3.0
Penstock 3	3.4.1							2.0
Bifurcation 1	3.4.2							1.0
Linings and Coatings	3.4.3							1.0
Foundation and Supports	3.4.4							1.0
Air Vent/Pressure Relief Valve	3.4.5							1.0
Joints and Couplings	3.4.6							1.0
Weighting Factors for Condition Parameters		2.0	1.0	1.0	1.0	1.5	Data Quality -->	*0.00*
							Condition Indicator -->	*0.00*

Figure 1c: Scheme C – Plant Shared Penstock

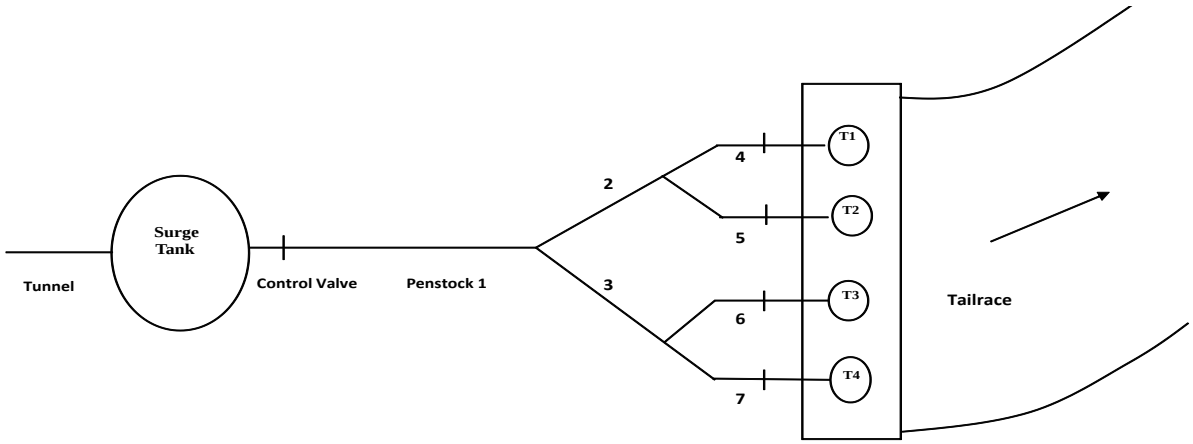

Table 1c: Scheme C Pressurized Water Conveyance Condition Assessment & Scoring - XXX Hydropower Plant (Unit 1)

Parts/Items for Unit 1	Taxonomy ID	Physical Condition Score	Age Score	Installed Technology Score	Operating Restrictions Score	Maintenance Requirement Score	Data Quality Score	Weighting Factors for Parts
Tunnel	3.3							2.0
Surge Tank	3.6							1.5
Penstock 1	3.4.1							3.0
Penstock 2	3.4.1							2.0
Penstock 4	3.4.1							2.0
Bifurcation 1	3.4.2							1.0
Bifurcation 2	3.4.2							1.0
Linings and Coatings	3.4.3							1.0
Foundation and Supports	3.4.4							1.0
Air Vent/Pressure Relief Valve	3.4.5							1.0
Joints and Couplings	3.4.6							1.0
Weighting Factors for Condition Parameters		2.0	1.0	1.0	1.0	1.5	Data Quality -->	*0.00*
							Condition Indicator -->	*0.00*

3.0 Metrics for Condition Assessment

As listed in Tables 1a, 1b and 1c, the following five condition parameters are considered for the condition assessment of pressurized water conveyances:

- The Physical Condition
- The Age
- The Installed Technology Level
- The Operating Restrictions
- The Maintenance Requirement

These five condition parameters are scored based on previous testing and measurements, historical Operation and Maintenance (O&M) records, original design drawings, previous rehabilitation feasibility study reports if available, interviews with plant personnel, and inspections for wherever accessible.

It can be noted that there is a certain level of relevance between the age and physical condition, maintenance needs, or some operating restrictions. However, as a benchmark condition assessment (without specific testing and measurements conducted on site) these five parameters are regarded as providing the basis for assessing the condition of pressurized water conveyance systems and components (i.e., penstocks).

In addition, the Data Quality Indicator, as an independent metrics, is to reflect the quality of the available information and the confidence of the information used for the condition assessment. In some cases, data may be missing, out-of-date, or of questionable integrity. Any of these situations could affect the results of the condition assessment. The scores of data quality are determined by the on-site evaluators for each assessed component to indicate the data availability, integrity, and accuracy; and the confidence of the given condition ratings (MWH 2010).

4.0 Weighting Factors

There are two categories of weighting factors in Table 1a, Table 1b, and Table 1c. It is recognized that some condition parameters affect the condition to a greater degree than other parameters. Also, some parts are more or less important than other parts to the entire conveyance system. These weighting factors should be pre-determined by consensus among experienced hydropower engineers and plant O&M experts. Once they are determined, they

should be largely fixed from plant to plant for similar conveyance system arrangements. Depending on the refining process during the demonstration and baseline assessments, the weighting factors for the parts/items of water conveyance system may have to be adjusted for some plants. In this case, the adjustment of weighting factors must be conducted by HAP core process development team. The range of absolute values of weighting factors will not affect the Condition Indicator of a conveyance system, which is the weighted summation of all scores assigned to the components and five condition parameters.

5.0 Rating Criteria

Physical Condition - Rating Criteria for Pressurized Water Conveyances

Physical Condition of pressurized water conveyance components refers to those features that are observable or detected through measurement and testing. It includes corrosion or cavitation of shell or tunnel liners, presence of organic growth on interior surfaces, shell thinning, localized buckling of penstock shell, leakage, slope stability, tunnel erosion, hydraulic flow conditions inside the water conveyance system, etc. The surface of the conveyance is important since increased surface roughness can affect efficiency by increasing head losses. Excessive leakage can lead to uncontrolled water losses which can also affect efficiency. In addition to efficiency related issues, evidence of severe corrosion, shell thinning, or localized buckling may indicate a safety issue or potential component failure. Thus, they should be carefully evaluated. The Best Practices for Penstocks, Tunnels and Surge Tanks can assist in evaluating the physical condition. For HAP site assessment, it is important to interview and discuss with plant personnel to score the physical condition of the water conveyance. The results of all related information are analyzed and applied to Chart 1 to assign the condition scores.

Chart 1 Pressurized Water Conveyance Physical Condition Rating Criteria		
Physical Condition Description		**Physical Condition Score**
Excellent	Limited corrosion or cavitation on the liners of water passage; limited organic growth on interior surfaces; no localized buckling of penstock shell; coating is in good condition; minimum leakage at joints/couplings; the air valve or pressure relief valve is regularly tested and functions well; the foundation and slope of penstock is stable and in good condition.	**8 – 10**
Good	Moderate corrosion or cavitation on the liners of water passage; moderate organic growth on interior surfaces; slight localized buckling of penstock shell; coating is in good condition; slightly increased leakage at joints/couplings; the air valve or pressure relief valve is tested and functions; the foundation and slope of penstock is stable and in adequate condition (i.e., minimal cracking or signs of erosion).	**5 – 7**
Fair	Large area of corrosion or cavitation on the liners of water passage; moderate organic growth on interior surfaces; slight localized buckling of penstock shell; coating is less than adequate; seals and seats have some damage with minor leakage at joints/couplings; the air valve or pressure relief valve is regularly exercised; the foundation and slope of penstock is stable and in fair condition (i.e., moderate cracking or erosion).	**3 – 4**
Poor	Severe corrosion or cavitation on the liners of water passage; severe organic growth on interior surfaces found; localized buckling of penstock shell; coating is inadequate; seals and seats have severe damage with minor leakage at joints/couplings; the air valve or pressure relief valve is not regularly exercised; the foundation and slope of penstock is unstable and in poor condition (i.e., severe cracking or erosion).	**0 – 2**

Age - Rating Criteria for Pressurized Water Conveyances

Age is an important factor when considering component or system upgrade as it can be an indication of performance degradation. As water conveyances age, they become more susceptible to wear due to vibrations, rapid flow velocities, and varying internal pressures. Not only does increased wear result in operational problems and loss of efficiency, it can also increase the risk of sudden failure.

Age scoring is relatively more objective than other condition parameters. The detailed scoring criteria developed in Chart 2 allow the age score to be automatically generated in the HAP Database by the actual years of the installed part. Liners typically have a maximum life span of 25 to 30 years depending on the type of liner material and application, whereas, water conveyance structural parts (i.e., penstock shell) can last up to 80 years with routine and proper maintenance. Older liners generally have increased surface roughness which can lead to

frictional head losses. By replacing liners that are nearing the end of their life span, plants have the opportunity to install a more hydraulically efficient liner. The age scoring criteria for various components are shown in Chart 2.

Chart 2 Age Rating Criteria for Pressurized Water Conveyance Parts		
Age of Penstock, Bifurcation, Surge Tank, Tunnel, Foundation and Supports, and Joints/Couplings	**Age Score**	**Age of Coatings/Linings and Air Vents/Pressure Relief Valves**
< 30 Years	**8 – 10**	< 10 Years
30-60 Years	**5 – 7**	10 to 20 Years
60-80 Years	**3 – 4**	20 to 30 Years
> 80 years	**0 – 2**	> 30 years

Installed Technology Level – Rating Criteria for Pressurized Water Conveyances

The Installed Technology Level indicates advancement in pressurized water conveyance design, installation/construction techniques, liner/coating materials and application process, and other component materials which may affect unit performance. Outdated technology may cause difficulties for supplying replacement parts or performing routine maintenance which can result in prolonged outages.

Scoring the Installed Technology Level requires historic knowledge of water conveyance technology advancement and familiarity with industry standards and materials. For example, penstock lining technology has advanced significantly since the 1980's with the use of silicone and epoxy liners. Therefore, penstocks lined prior to the 1980's or those lined with coal tar enamels would receive a lower score than those lined in the 1990's or later. The overall arrangement and design of the pressurized water conveyance system is another factor to consider for scoring the Installed Technology Level. With advances in computer modeling, designers are able to provide a more hydraulically efficient arrangement while limiting erroneous

design inputs. Other factors can include advances in tunneling technology, penstock joints (riveted joints versus bolting or welding), and improved penstock shell materials.

The competence, professionalism, and reputation of the original suppliers could also impact the Installed Technology Levels. As compared to large and well-known manufacturers, the components supplied or installed by small, unknown companies would get lower scores. The installed technology scoring criteria for various components are shown in Chart 3.

Chart 3 Pressurized Water Conveyance Technology Rating Criteria	
Technology Levels of Design and Construction	**Score for Installed Technology Level**
The technology has not been changed significantly since the component was installed; and the installed technology was supplied by brand name companies with great reputation	**8 – 10**
The technology has been more or less advanced but no problem to supply the matching parts in next 5-10 years, or the technology change has little effect on the efficiency and reliability of power generation (but may reduce the cost of replacement). The installed technology was supplied by medium companies with good reputation.	**4 – 7**
The installed technology has been phased out, it is a problem to supply parts in reasonable order time, or the technology change has significantly improved the efficiency and reliability of power generation. The installed technology was supplied by small companies with bad reputation.	**0 – 3**

<u>Operating Restrictions - Rating Criteria for Pressurized Water Conveyances</u>

The Operating Restrictions refers to the current limitations on the operating ranges including internal pressures, power capacity, and flow. Either under-sized or under-utilized capacity may reduce the overall operational efficiencies and accelerate the deterioration of the water conveyance physical condition. Operational limitations play a role in determining the serviceability of the unit: the greater the limitations, the greater the generation loss.

Operating restrictions can be caused by to two sources:

1) The conveyance system itself. To limit deterioration or to ensure structural safety, the operating ranges of maximum and minimum pressures and flows are constrained due to the limitations of the original design and/or the current deteriorated physical condition.

2) Environmental restrictions due to habitat maintenance, water quality issues (i.e., Dissolved Oxygen), or fish passage. These restrictions can affect minimum required flows and thus change the current available flow conditions for the existing water conveyance system. Other environmental restrictions can stem from changes in flow conditions due to climate change. However, any constraints from other components within the facility, which may affect the unit and plant generations, will not be included in the constraints of pressurized water conveyances. For example, if the water level in the headwater reservoir is limited due to dam safety concerns, then the dam (not the water conveyance system) will receive a lower score for operating restrictions.

Chart 4 describes the ratings of operating restrictions.

Chart 4 Pressurized Water Conveyance Operating Restrictions Rating Criteria	
Operating Restrictions or Off-Design Conditions	**Score for Operating Restrictions**
The design standard has no changes, and the original design has no constraints on the required operation. Tested as Required; no known design and operational inefficiencies.	**8 – 10**
Minimal restraints: Operations to avoid minor rough zones; operation range can be expanded with revised equipment selection and design. No known design and operational inefficiencies.	**5 – 7**
Moderate restraints: Operations to avoid large rough zones with high vibration. The operation range and performance can be significantly improved with revised system design.	**3 – 4**
Severe limitations: The equipment does not meet the operational criteria or not tested as required or has a known design and operational deficiency.	**0 – 2**

Maintenance Requirement – Rating Criteria for Pressurized Water Conveyances

The amount of corrective maintenance that either has been or must be performed is an indication of the water conveyance condition. If the conveyance system has required limited or no maintenance, then that is an indication that the system is in good condition. If a component

has required extreme corrective maintenance resulting in unscheduled or forced outages, then the component is considered to be in poor condition.

Other factors to consider for maintenance scoring include:

- Maintenance needs are increasing with time or problems are re-occurring
- Experiencing frequent rough-zone operations
- Previous failures related to pressurized water conveyances
- Failures or problems with pressurized water conveyances of similar design and material

The results of the maintenance history (including routine maintenance and corrective maintenance) are analyzed and applied to Chart 5.

Chart 5 Pressurized Water Conveyance Maintenance Requirement Rating Criteria

Amounts of Corrective Maintenance	Maintenance Requirement Score
Minimum level (normal condition): A small amount of routine preventive maintenance is required. No corrective maintenance.	9 – 10
Low level: Small amounts of corrective maintenance. Repairs that could be completed during a unit preventive maintenance outage that is scheduled on a periodic basis.	7 – 8
Moderate level: Some corrective maintenance that causes extensions of unit preventative maintenance outages.	5 – 6
Significant/Extensive level: Significant additional and corrective maintenance is required; forced outage occurs and outages are extended due to maintenance problems (e.g., corrosion caused leaks).	3 – 4
Severe level: Severe corrective maintenance that requires scheduled or forced outages. Repeated forced outages, frequent repairs, abnormal wear to components, and/or labor-intensive maintenance is required.	0 – 2

Data Quality – Rating Criteria for Pressurized Water Conveyance Components

The Data Quality score reflects the quality of the inspection, test, and measurement results used to evaluate the pressurized water conveyance system. The more current and complete the

inspection, tests, and measurement results are, the higher the Data Quality scores. The frequency of normal testing is as recommended by the HAP assessment team in conjunction with industry standards.

Reasonable efforts should be made to perform visual inspections and data collection (measurements, tests, operation logs, maintenance records, design drawings, previous assessment reports, etc.). However, when data is unavailable to score a condition parameter properly, it may be assumed that the condition is "Good" or numerically equal to some mid-range number 3-7. Meanwhile, the Data Quality score is graded low to recognize the poor or missing data.

Qualified personnel should make a subjective determination for the Data Quality scores, considering as many factors as possible. The suggested criteria for scoring the Data Quality are developed in Chart 6.

Chart 6 Pressurized Water Conveyance Data Quality Rating Criteria	
Data Availability, Integrity and Accuracy	**Data Quality Score**
High – The maintenance policies and procedures were followed by the plant and the routine inspections, tests and measurement were performed within normal frequency in the plant. The required data and information are available to the assessment team through all means of site visits, possible visual inspections and interviews with experienced plant staff.	**8 – 10**
Medium – One or more of routine inspections, tests and measurement were completed 6-24 months past the normal frequency, or small portion of required data, information and documents are not available to the assessment team.	**5 – 7**
Low – One or more of routine inspections, tests and measurement were completed 24-36 months past the normal frequency, or some of results are not available.	**3 – 4**
Very Low – One or more of required inspections, tests and measurement were completed >36 months past the normal frequency, or significant portion of results are not available.	**0 – 2**

6.0 Condition and Data Quality Indicator

In Table 1a, 1b or 1c, the final condition score of the pressurized water conveyance, i.e., the Condition Indicator, *CI*, can be calculated as follows:

$$CI = \frac{\sum_{K=1,M}^{J=1,5} S_C(K,J) \times F(K) \times F(J)}{\sum_{K=1,M}^{J=1,5} F(K) \times F(J)} \qquad (1)$$

The Data Quality Indicator, *DI*, will be the weighted summation of all Data Quality scores received for its associated parts:

$$DI = \frac{\sum_{K=1,M} S_D(K) \times F(K)}{\sum_{K=1,M} F(K)} \qquad (2)$$

Here M = the total number of parts associated with a pressurized water conveyance; K = the identification No. of parts (from 1 to M); J = the identification No. of condition parameters (from 1 to 5, respectively for physical condition, age,…); $S_C(K, J)$ = the condition score of a part for one of 5 condition parameters; $S_D(K)$ = the data quality score for a part; $F(J)$ = the weighting factor for a condition parameter; $F(K)$ = the weighting factor for a part.

The calculated Condition Indicator from equation (1) may be adjusted by the results of internal inspections and specific testing results that would be performed, since the specific testing, such as penstock shell thickness measurements, would more directly reveal the condition of the pressurized water conveyance.

7.0 References

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