Condition Assessment Manual

Appendix 1.07 – Guide for Francis Turbine, Kaplan/Propeller Turbine and Pelton Turbine Condition Assessment

HAP
HYDROPOWER
ADVANCEMENT PROJECT

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Contents

1.0 General 4
2.0 Constituent Parts Analysis 5
3.0 Metrics for Turbine Condition Assessment 5
4.0 Weighting Factors 6
5.0 Rating Criteria 8
6.0 Turbine Condition and Data Quality Indicators 14
7.0 References 16

1.0 General

The hydraulic turbine is the most critical component in the powertrain of a hydropower plant. Unlike the generators and transformers, catastrophic failure is rare to happen on turbines, but a turbine does have an economic lifespan. Contributed by (a) the surface damages from cavitation, erosion and corrosion; (b) the cracks from fatigue and “rough zone” operations; and (c) the off-design contours accumulated from welding repairs, the turbine efficiency and capacity decline with time while the annual cost of repairs and maintenance increases with time. Thus, rehabilitation and replacement of an aging turbine may become more economical and less risky than maintaining the original turbine, especially considering the potential efficiency improvement from the state-of-art turbine design and from the turbine material and fabrication technology advancement achieved during last decades. Yet, turbine condition assessment is essential to estimate the economic lifespan and potential risk of failure, and to evaluate the benefits and cost of turbine upgrading.

For any type of turbine, the following three step analyses are necessary to arrive at a turbine condition indicator:

1) What parts should be included for a turbine condition assessment and which parts are more important than others (parts and their weighting factors)?

2) What metrics/parameters should be investigated for quantitative condition assessment and which ones are more important than others (condition parameters and their weighting factors)?

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

This Appendix provides guides to answer the above questions, which can be applied to Francis, Propeller/Kaplan and Pelton turbines. The condition assessment is performed on individual turbines in a plant, because even the originally identical turbines may have experienced different Operation & Maintenance (O&M) stories and would arrive at different values of condition indicators. Due to the uniqueness of each individual turbine, the guides provided in this Appendix cannot quantify all factors that affect individual turbine condition. Mitigating factors not included in this Guide may trigger testing and further evaluation to determine the final score of the turbine condition and to make the decision of turbine replacement or rehabilitation.

This Appendix is not intended to define turbine 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 three major types of turbines (i.e., Francis, Propeller/Kaplan and Pelton), their constituent parts are analyzed and listed in Tables 1a, 1b and 1c, respectively (references to HAP Taxonomy). Among all the turbine parts, the runner is the most critical part for a turbine. If any part (e.g., draft tube) does not exist in a particular turbine unit, this part will be excluded from scoring mechanism by inputting “NA” into the Table. The effect of one part exclusion is usually insignificant to the entire turbine assessment, which usually does not justify any adjustment of the weighting factors for other parts of the turbine.

3.0 Metrics for Turbine Condition Assessment

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

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

These five condition parameters are scored based on the previous testing and measurements, historical O&M records, original design drawings, previous rehabilitation feasibility study reports if conducted, interviews with plant staff and some limited inspections. It is noticed that there are certain level of relevance between the age and physical condition, maintenance needs, or some operating restrictions. However, as a benchmarking condition assessment without specific testing and measurements conducted on site, these five parameters are regarded as providing the basis for assessing the condition of turbine parts and entire turbine.

In addition, the Data Quality Indicator, as an independent metrics, is to reflect the quality of available information and the confidence on the information used for the condition assessment. In some cases, data may be missing, out-of-date, or of questionable integrity, and any of these situations could affect the results of condition assessment. The scores of data quality are determined by the on-site evaluators for each assessed part/item to indicate the data availability, integrity and accuracy and the confidence on 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 turbine condition to a greater or lesser degree than other parameters; also some parts are more or less important than other parts to an entire turbine. These weighting factors should be pre-determined by consensus among experienced hydropower mechanical engineers and plant O&M experts. Once they are determined for each type of turbines, they should be largely fixed from plant to plant for the same type of turbines, except for special designs found in a turbine where the weighting factors have to be adjusted. 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 won't affect the Condition Indicator of a turbine, which is the weighted summation of all scores that assigned to the turbine parts and five condition parameters.

Table 1a: Typical Francis Turbine Condition Assessment & Scoring - XXX Hydropower Plant (Unit #)

Francis Turbine Unit ____	Taxonomy ID	Physical Condition Score	Age Score	Installed Technology Score	Operating Restrictions Score	Maintenance Requirement Score	Data Quality Score	Weighting Factors for Parts
Spiral/Scroll Case	4.1.1.1							1.5
Stay Ring/Vanes	4.1.1.2							1.5
Wicket Gates Mechanism/Servomotors	4.1.1.3							3.0
Runner	4.1.1.4							5.0
Draft Tube	4.1.1.5							2.0
Main Shaft	4.1.1.6							1.0
Guide Bearings	4.1.1.7							1.5
Mechanical Seal/Packing	4.1.1.8							1.0
Head Cover	4.1.1.9							1.5
Vacuum Breaker/PRV	4.1.1.10							1.5
Aeration Devices	4.1.1.11							2.0
Bottom Ring	4.1.1.12							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*

Table 1b: Typical Propeller/Kaplan Turbine Condition Assessment & Scoring - XXX Hydropower Plant (Unit #)

Kaplan or Propeller Turbine Unit_____	Taxonomy ID	Physical Condition Score	Age Score	Installed Technology Score	Operating Restrictions Score	Maintenance Requirement Score	Data Quality Score	Weighting Factors for Parts
Spiral Case	4.1.1.1							1.5
Stay Ring/Vanes	4.1.1.2							1.5
Wicket Gates Mechanism/Servomotors	4.1.1.3							3.0
Runner	4.1.1.4							5.0
Draft Tube	4.1.1.5							2.0
Main Shaft	4.1.1.6							1.0
Guide Bearings	4.1.1.7							1.5
Mechanical Seal/Packing	4.1.1.8							1.0
Head Cover	4.1.1.9							1.5
Bottom Ring	4.1.1.12							1.0
Discharge/Throat Ring	4.1.1.13							1.5
Weighting Factors for Condition Parameters		2.0	1.0	1.0	1.0	1.5	Data Quality -->	*0.00*
							Condition Indicator -->	*0.00*

Table 1c: typical Pelton Turbine Condition Assessment & Scoring - XXX Hydropower Plant (Unit #)

Pelton Turbine Unit _____	Taxonomy ID	Physical Condition Score	Age Score	Installed Technology Score	Operating Restrictions Score	Maintenance Requirement Score	Data Quality Score	Weighting Factors for Parts
Distributor/Manifold	4.1.1.14							1.5
Housing	4.1.1.15							1.5
Needle Valves/Nozzles	4.1.1.16							2.0
Runner	4.1.1.4							5.0
Discharge Chamber	4.1.1.17							1.0
Deflectors	4.1.1.18							1.0
Main Shaft	4.1.1.6							1.0
Guide Bearings	4.1.1.7							1.5
Weighting Factors for Condition Parameters		2.0	1.0	1.0	1.0	1.5	Data Quality -->	*0.00*
							Condition Indicator -->	*0.00*

5.0 Rating Criteria

Physical Condition - Rating Criteria for Turbine Parts

Physical Condition of turbine parts refers to those features that are observable or detected through measurement and testing. It includes surface roughness from erosion, corrosion or cavitation, cavitation pitting, cracking damage, clearances and leakage, vibrations and noises, oil loss, shaft runout, etc. The surface condition of waterway is important since it affects the efficiency and capacity of the turbine. The excessive clearance and leakage will lead to uncontrolled water losses, vibration and shaft runout may lead to safety issues of turbine operation, and the oil loss may affect water environment. Thus, they should be carefully evaluated. The Best Practices of Francis Turbine, Propeller Turbine and Pelton Turbine can assist in evaluating the physical conditions.

For HAP site assessment, it is important to interview and discuss with plant personnel to score the physical condition of turbine parts. The results of all related information are analyzed and applied to Chart 1 to assign the condition scores of turbine parts.

Chart 1 Turbine Physical Condition Rating Criteria		
Physical Condition Description		Physical Condition Score
Excellent	No noticeable defects. Some aging or wear may be noticeable.	9 – 10
Very good	Only minor deterioration or defects are evident, and function is full.	7 – 8
Good	Some deterioration or defects are evident, but function is not significantly affected.	5 – 6
Fair	Moderate deterioration, function is still adequate, but the unit efficiency may be affected.	3 – 4
Poor	Serious deterioration in at least some portions, function is inadequate, unit efficiency or availability significantly affected.	2
Very poor	Extensive deterioration. Barely functional.	1
Failed	No longer functions, may cause failure of a major component.	0

Age - Rating Criteria for Turbine Parts

Age is an important factor to consider turbine upgrading and also to indicate performance degradation. When turbine ages, it becomes more susceptible to cracks from fatigue and cumulative weld repairs, and increases the likelihood of physical failure. Meanwhile, an older turbine usually has greater potential to gain efficiency and capacity by replacing and using the state-of-the-art turbine design and materials.

Age scoring is relatively more objective than other condition parameters. The detailed scoring criteria developed in Chart 2 allows the age score be automatically generated in the HAP Database by the actual years of the installed part. The turbine parts usually have expected lifespan of 40-45 years, but the seal rings and bearings are considered 20 years between the overhauls or rehabilitations, and a water-lubricated guide bearing has 10 years of expected lifespan. Their scoring criteria will be changed accordingly as shown in Chart 2.

Chart 2 Age Rating Criteria for Turbine Parts

Ages of the turbine major Parts/Items	Age Score	Ages of Oil Bearings and Seal Rings	Age of Water-Lubricated Guide Bearing
<5 years	10	<2 years	<1 years
5-10 years	9	2-5 years	1-2 years
10-15 years	8	5-7 years	2-3 years
15-20 years	7	7-10 years	3-5 years
20-25 years	6	10-12 years	5-6 years
25-35 years	5	12-17 years	6-8 years
35-40 years	4	17-20 years	8-10 years
40-45 years	3	20-22 years	10-12 years
45-50 years	2	22-25 years	12-13 years
50-60 years	1	25-30 years	13-15 years

Installed Technology Level – Rating Criteria for Turbine Parts

The Installed Technology Level indicates advancement levels of designing, machining, installation and materials, which may effect on the unit and plant performance. The outdated technology may bring difficulties for spare parts supply and prolonged outage when it fails.

Scoring the Installed Technology Level requires historic knowledge of turbine technology advancement and familiarity with turbine manufacturing industry. With the computerization of turbine design (CFD) and manufacturing (CNC), the production accuracy and turbine efficiency have been significantly improved since 70'-80', particularly for the water passage parts. So the turbine parts installed before 70' would get lower scores than those in 90'. The material of turbine parts is another factor to consider for scoring the installed technology level. Very old runners in the early 1900's or before, could have been cast from cast iron, later to be replaced with cast carbon steel, and today either cast or fabricated from carbon steel or stainless steel. The most common material being used in is ASTM A743 CA6NM stainless steel. It is cavitation resistant, fairly easy to cast and fabricate, and can usually be weld repaired without post heat treatment. The same is true for wicket gates materials.

The competence, professionalism and reputation of the original suppliers could also imply the installed technology levels. Compared those from large and well-known manufacturers, the turbine parts supplied by small and unnamed companies would get lower scores.

Chart 3 Turbine Technology Rating Criteria	
Technology Levels of the Parts/Items	**Score for Installed Technology Level**
The technology has not been changed significantly since the part 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**

Operating Restrictions - Rating Criteria for Turbine Parts

The turbine operating restrictions refer to the current limitations on the operating ranges of head, flow and power capacity, as well as on the required load ramp speeds, based on the original design and current condition of turbine parts. Either under-sized or under-utilized turbine capacity may reduce the turbine operational efficiencies and accelerate the deterioration of turbine physical condition (e.g., cavitation, vibrations). Operational limitations play a role in determining the serviceability of turbine unit: the greater the limitations, the greater the generation loss and sometimes water spilling.

The operating restrictions may be sourced from two aspects:

1) Turbine itself. To limit the severe cavitation or for the structural safety consideration, the operating ranges of maximum/minimum flows and heads are constrained due to the original design and/or currently deteriorated turbine physical condition (e.g., insufficient main shaft strength, hot bearings, and severe vibrations).
2) Environmental and market changes, including the role change in power grid (e.g., the unit assumed more peaking power with the nuclear and wind capacity added in the grid) and the site flow condition changes due to the climate change or required minimum instream flow change. The environmental constraints do not refer to any limitation from other components in the facility, e.g., if the highest water level in headwater reservoir is limited by the safety concern of dam, then the dam, not the turbine, would get lower score for the operating restrictions.

Another example of turbine design constraint is that many low-head sites with great flow were designed and installed Propeller or Francis turbines before 56-60'. However, today Kaplan turbines with adjustable blades become more economically feasible, which could improve unit efficiencies within wider range of flow/head.

Chart 4 describes the ratings of turbine operating restrictions.

Chart 4 Turbine Operating Restrictions Rating Criteria	
Operating Restrictions or Off-Design Conditions	**Score for Operating Restrictions**
The design standard has no changes, and the original turbine design has no constraints on the required operation.	**8 – 10**
Minimal restraints: Operations to avoid minor rough zones; operation range can be expanded with revised turbine selection and design.	**5 – 7**
Moderate restraints: Operations to avoid large rough zones, high vibrations, and hot bearings. The operation range and performance can be significantly improved with revised turbine selection and design.	**3 – 4**
Severe limitations: The turbine is undesirable to operate anymore; the original design has significantly limited the performance and reliability if it operates under current environment/requirement.	**0 – 2**

Maintenance Requirement – Rating Criteria for Turbine Parts

The amount of corrective maintenance that either has been or must be performed is an indication that how the turbine condition is. No corrective maintenance is an indication that the turbine is in good shape. Severe corrective maintenance requires for scheduled or forced outages to perform.

Other factors to consider for maintenance scoring include:

- The need of maintenance is increasing with time or problems are reoccurring;
- Experience of frequent rough-zone operations;
- Previous failures related to the turbine parts;
- Failures and problems of the turbine parts with similar design.

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

Chart 5 Maintenance Requirement Rating Criteria	
Amounts of Corrective Maintenance	**Maintenance Requirement Score**
Minimum level (normal condition): A small amount of routine preventive maintenance is required (e.g., Runner blade surface cleaning and re-coating). No corrective maintenance.	**9 – 10**
Low level: Small amounts of corrective maintenance (e.g., less than 3 staff days per unit per year). 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 (e.g., runner blade pit welding, seal ring replacement).	**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; re-profiling and machining to OEM specifications is required).	**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 Turbine Parts

The Data quality scores reflect the quality of the inspection, test, and measurement results to evaluate the condition of turbine parts. 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 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 and 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 of turbine parts are developed in Chart 6.

Chart 6 Turbine Data Quality Rating Criteria	
Data Availability, Integrity and Accuracy	**Data Quality Score**
High – The turbine 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 Turbine Condition and Data Quality Indicators

In Table 1a, 1b or 1c, the final condition score of the turbine, 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 turbine Data Quality Indicator, *DI*, will be the weighted summation of all Data Quality scores received for its associated parts/items:

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

Here M = the total number of parts/items associated with a turbine; K = the identification No. of turbine 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 turbine 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 turbine 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 turbine testing, such as the efficiency/index test and paint film quality test, would more directly reveal the condition of turbine.

7.0 References

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