Condition Assessment Manual

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1 Introduction

The Hydropower Advancement Project (HAP) is a systematic approach to best practices implementation to improve the efficiency, capability, water utilization and value of existing U.S. hydropower plants.

The HAP considers three performance levels for hydropower facilities: Installed performance level (IPL), Current performance level (CPL), and Potential performance level (PPL). IPL is that achievable by the facility under design conditions immediately after commissioning (installed name-plate capacity performance in most cases). CPL may be lower than the IPL due to wear and tear or due to the changes in the constraints placed on a facility that prevent it from operating as originally designed. PPL could be achieved under current operating constraints by upgrading technology and implementing best practices for operations and maintenance. HAP assessments will identify equipment and operational process improvements that move the CPL towards PPL.

The HAP will highlight opportunities for improvement of U.S. hydropower value in two categories: (1) Efficiency Improvements and (2) Utilization Improvements. Efficiency Improvements, defined herein as equipment and process upgrades that increase the *efficiency* of generation on an instantaneous and annual average basis, thereby enabling increased energy production from the water passing through turbines. Utilization Improvements, defined herein as equipment and process upgrades that enable a project to *use* more of the available water in streams, which will also increase energy production. The distinction between *efficiency* (generation per unit of water passing through turbines) and *utilization* (generation per unit of water passing the project on an annual average basis) is non-trivial in detecting trends in the results of systematic assessments of the U.S. hydropower fleet, and for modeling the effectiveness of federal or commercial RDD&D[1] investments for hydropower improvement. The potential for increased production and value of grid services resulting from efficiency upgrades in the first category is predictable and scalable according to common design features of the hydropower technology. The potential for increased production and value of grid services from utilization upgrades in the second category is less predictable and more varied because it depends on site-specific hydrologic and environmental contexts. Improvements in unit reliability and availability contribute to both of these categories—first, by enabling increased flexibility to

[1] Research, Development, Demonstration, and Deployment

maintain units at efficient loads, and second, by maximizing the volumetric capacity of the powerhouse.

The HAP is currently a three phase effort to identify and assess performance improvement opportunities at existing hydropower plants. Phase I will focus on the compilation of hydropower best practices and development of standardized assessment methodologies to identify efficiency and utilization improvements. During Phase I, three demonstration and seven baseline assessments will be performed to verify and refine the developed assessment methodologies. Phase II will carry out 40 facility assessments at a diverse selection of existing hydropower plants to identify and catalog the potential for increased generation within the existing hydropower fleet. The results of these assessments will highlight potential upgrade projects that can be further studied in the future. Dependent on program budget and direction, Phase III will assist the hydropower industry to execute detailed feasibility studies of improvement projects including engineering designs and cost-benefit analyses.

This Manual will provide objectives, methodology, and quantitative rating tools for hydropower asset condition assessment; as well the procedure, scope of work, and personal requirement for facility assessment. The Appendices to this Condition Assessment Manual are the crux of information and guidance to which hydropower professionals will refer to ensure that assessment efforts are the HAP standard assessment methodology. They include:

1) Workbooks for quantitative condition rating of individual components;
2) Guides for condition assessment of individual components;
3) Inspection Form and Check List for each individual component.

The scope of assets to be assessed will include all major components in mechanical, electrical, civil, and Instruments & Controls (I&C) systems, as well as some auxiliary mechanical components. Each component to be assessed will have a Guide to describe how its condition will be evaluated and a corresponding Excel Workbook to record and calculate the condition scores, while the Inspection Form and Check List is to provide the assessment team members with a useful notebook used for on-site inspection and data collection.

The intended users of this Condition Assessment Manual (including Appendices) are the hydropower professionals or experts who will execute HAP Phase II assessments. Other potential users include on-site plant staff, technical staff, plant managers, or asset managers who are going to use the assessment tools or assessment results for further analysis supporting their investment decisions at the existing facilities.

Although the calculation of Condition Indices has been embedded in the Excel Workbooks, the overall structure of HAP condition assessment, including the calculation formula, is still provided in this Manual for the assessment teams to better understand how the collected data will be utilized for quantitative condition analysis.

2 Condition Assessment Objectives

The HAP is designed for both performance analysis and condition assessment of existing hydropower plants. The performance assessment is to quantify unit and plant performance and to investigate the opportunities for operations-based, equipment-based, and maintenance-based performance improvements leading to additional generation. The quantitative condition assessment aims to characterize and trend asset and asset component conditions across the U.S. existing hydro fleet. The use of a standard assessment methodology (the HAP methodology in this case) is crucial for comparing and trending the hydro asset conditions across different facilities, owner fleets, regions, and within the overall U.S. hydropower inventory. Such trends will be useful in programming research and development efforts to improve hydropower availability, cost, and value in the future.

This document, as the general section of the Condition Assessment Manual, addresses the methodology and processes of quantitative condition assessments as well as the condition rating tools. One of the condition rating tools is the Excel Workbooks which will be used to standardize the recording of information, scoring based on that information, and calculation of condition ratings. The Guides will provide standard processes and rating scales that produce consistent, repeatable, and objective condition scores. Collectively, these condition results from 50 or so sample plants (around 200 units) will be quantitatively and statistically analyzed to answer questions such as:

1. What is the average condition of existing hydro assets?
2. What percentages of assets (at level of plant, unit, component or part) are in need of investment to achieve a fair or good operating condition?

Combined and correlated with the results from performance analyses, these condition results can be used to answer questions such as:

1. How much capacity, efficiency or annual energy would be gained through an upgrading program? How would the gains correlate to unit/plant condition?
2. How does the degradation of unit efficiencies correlate to the age of runners (or the age of generator winding)?

In addition, the database of performance and condition assessment results, in anonymous form that protects plant-specific data, will provide asset managers with a benchmark to better understand the conditions of their facilities and help make decisions on further assessment and upgrade investment.

3 Condition Rating Framework

In the context of HAP condition assessment, the assets of hydropower fleet are classified hierarchically as Plants, Units, Components (Subsystems, Structures), and Parts/Items as illustrated in Figure 1. More detailed hydropower asset hierarchy can be found in the HAP Taxonomy that is organized by physical and functional layers within a hydropower facility based on several sources (TVA 2010, ASME 1996, Roose and Starks 2006). The Taxonomy provides the basis for the categorization of the hydro assets for HAP condition assessments and also for the documentation of Best Practice Catalog and Condition Assessment Guides.

The power generating units are essentially the core of a hydro plant, but the scope of unit in HAP condition assessment is extended from the turbine-generator equipment to the “water to wire” system; including civil, mechanical, electrical and I&C components (such as intake, water conveyance, turbine, generator, transformer, etc.). The scoring process is a bottom-up aggregation of scoring, with the parts of a component aggregated to a component score, component scores aggregated to unit scores, and unit scores aggregated to facility scores. For example, to assess the condition of a turbine, turbine parts are first scored and the overall turbine condition can then be evaluated based on the turbine parts scores. When all the components are assessed, the overall unit condition and plant condition can be evaluated.

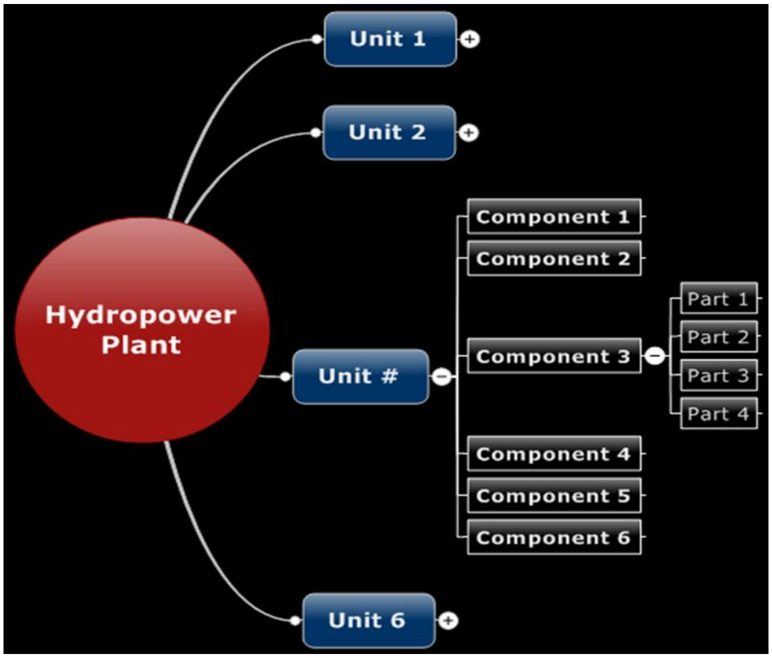

Figure 1: Illustrative Hierarchy of Hydro Assets

The following five condition parameters will be scored for each part:

- **Age** – The years that a part or equipment has been in service since initially commissioned or previously replaced.
- **Physical Condition** – This is a very general term. It refers to those features and performances that are observable or detected through visual inspection, measurement and testing. The meaning of Physical Condition can vary from component to component and from one part to another. For turbine runners, it means surface roughness, cracks, cavitation etc., while for generator windings it may refer to Insulation Resistance and Polarization Index. In the HAP condition assessment, the physical condition is scored based on visual inspections and data collection from previous tests and measurements.
- **Installed Technology Level** – It indicates advancement levels of designing, machining, installation and materials. The technology level may have an effect on the unit and plant performance, and the outdated technologies may bring difficulties for parts replacement and prolonged outage period when it fails.

- **Operating Restrictions –** With the evolution of economy, power market and technology, and the changes of site flow condition and environmental requirements (e.g., DO levels, instream flows), the design standard may have changed or the original design may currently constrain the operations (e.g., Francis turbine aeration devices). In addition, the operating restrictions arising from deterioration of aging assets are also considered.
- **Maintenance Requirement –** It reflects the historical and current demands for the repairs and maintenance, particularly the amount of corrective maintenance.
- For electrical components (e.g., Generator, Transformer), the results from some specific tests and data analyses might be more important than visual inspection as indications of equipment health and condition. Although they could be categorized into Physical Condition, to emphasize their importance to the equipment condition assessment, they are treated as additional condition parameters. For instance, the aggregation of electrical tests for generator Stator including insulation resistance (IR) test, polarization index (PI) test, bridge test for winding resistance and etc. will be treated as one of generator condition parameters. For the I&C system, a different set of condition parameters are developed to better indicate the health and condition of I&C components. The details refer to Appendices, Guides of individual component condition assessment.

Again, the turbine is used as one example of components to illustrate the rating process. Different types of turbines consist of different parts, and the major parts of the three major turbine types (Francis, Propeller/Kaplan and Pelton) are listed in Tables 1a, 1b and 1c, respectively, in Appendix 1.07. Each individual unit in a plant has one table for the turbine parts and turbine scoring. Assuming in XXX Hydropower Plant, Unit 1 has a Francis turbine, the following Table 1 is used for the turbine condition assessment. In Table 1, the matrix of condition scores, $S_C(J, K)$, are assigned by the assessment team to each turbine part and each condition parameter, based on the on-site inspections and collected data/information using the established turbine rating criteria (Charts 1-5, Appendix 1.07).

The Data Quality Score, $S_D(K)$, as an independent metric reflects the quality of available information and the confidence of the information used for the part assessment. In some cases, data may be missing, out-of-date, or of questionable integrity; any of these situations could affect the accuracy of the associated condition scores, where the Data Quality Indicator is used as the means of evaluating and recording confidence in the Condition Indicator (MWH 2010). The data quality scores of each assessed part/item are determined by the on-site evaluators based on the data availability, integrity and accuracy. The rating criteria for Data Quality Indicator are developed for the turbine in Chart 6, Appendix 1.07.

Any score cell in Table 1 (actually, in any component Rating Tables) allows "pass by" if any part does not exist in a particular unit (e.g., draft tube may not exist for some turbines), and "NA" is input to exclude this part from the score processing. Similarly, if any of the condition parameters is inapplicable to one particular part, "NA" will be also input to exclude this parameter (e.g., The Electrical Tests for generator Stator is not applicable for any other generator parts, so "NA" will be input into the cells of other parts for this generator condition parameter). This mechanism permits the necessary flexibilities for the differences among the units and plants while maintaining a standardized evaluation process. In Table 1, two categories of weighting factors, *F*(*J*) or *F*(*K*), are predetermined to reflect the relative importance of each condition parameter or each part to the overall turbine condition assessment.

Table 1: Turbine Condition Assessment & Scoring - XXX Hydropower Plant

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*

In order to assess the "water-to-wire" condition of a unit, a total of 19 components have been tentatively considered to compose a Unit. Each of these components will have one scoring table corresponding to each individual unit, as Table 1 is for Unit 1 Turbine Condition Assessment. Some components (such as Transformer) are often shared by several (or all) turbine-generator units in a plant. If so, this common component is assessed only once and its Condition Indicator (*CI*) would be applicable to all the sharing units (i.e., one scoring Table corresponds to all sharing units). It is also recognized that some parts and components are not immediately attached to one specific unit (not as clear as the turbine and turbine parts), and they have to be mapped and identified for a specific unit. For instance, as shown in Figure 2, the upstream pressurized water conveyance system may be partially shared by several turbine-generator units, in which the penstock sections have to be numbered and all sections/parts are mapped into the different individual units. Table 2 lists the parts/items of the Pressured Water Conveyance for Unit 1 in the scheme shown in Figure 2.

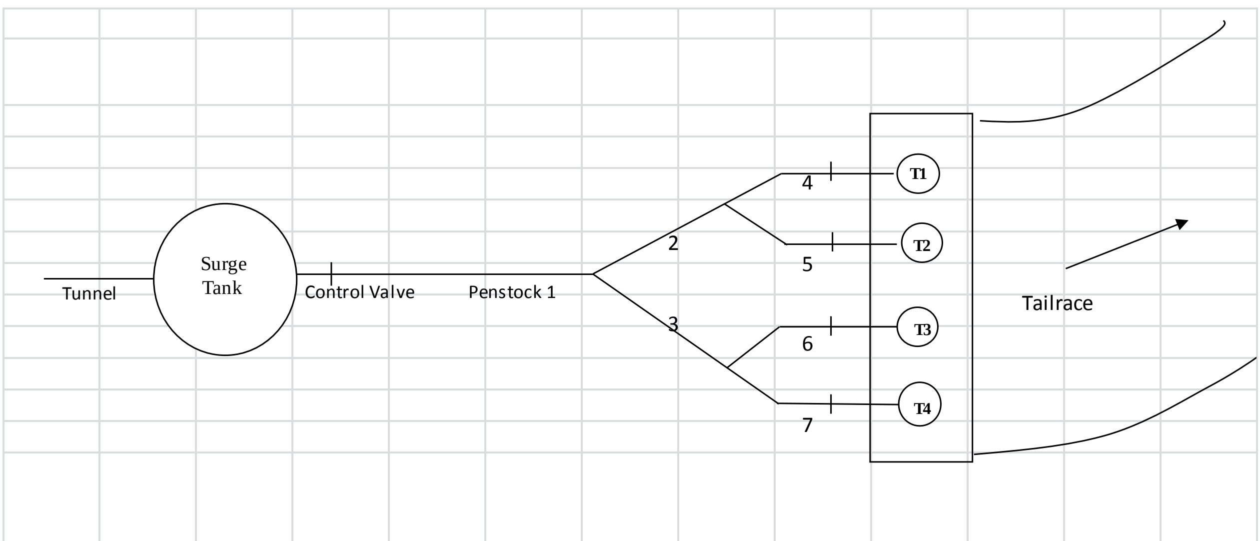

Figure 2: Mapping of Pressured Water Conveyance for Individual Unit

Table 2: Pressured Water Conveyance Condition Assessment & Scoring - XXX Hydropower Plant

Pressurized Water Conveyance 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
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 & Coatings	3.4.3							1.0
Foundation & Supports	3.4.4							1.0
Air Vent/Pressure Relief Valve	3.4.5							1.0
Joints & Coupling	3.4.6							1.0
Surge Tank	3.6							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

For the electrical and I&C components, the parts/items listed in the condition assessment tables might be categorized according to the different functionalities, while for the mechanical and civil components, the parts/items are more likely organized by their physical and structural features.

Once the component parts scoring table is established (such as Table 1 or Table 2) and a matrix of scores S_C (*J*, *K*) are assigned, the final condition score of the component, i.e., the component Condition Indicator, *CI*, can be calculated as follows:

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

Here *M* = the total number of parts/items associated with a component; *K* = the identification No. of Parts/Items (from 1 to *M*); *N*= the total number of condition parameters; *J* = the identification No. of condition parameters (from 1 to *N*, respectively, for the physical condition, age, technology level,…), $S_C(K, J)$ = the condition score of a part/item for a condition parameter; *F*(*J*) = the weighting factor for a condition parameter, determined based on the relative importance of the condition parameter to the overall condition assessment; $F(K)$ = the weighting factor for a part/item, determined by the relative importance of the part/item to the overall condition of the component. All the weighted factors have been pre-determined during the process development stage based on consensus among experienced hydropower engineers and plant O&M experts, but are subject to adjustment later by the HAP core technical team according to the special layout/design of individual hydropower plants and the industry comments that will be received. By the weighted summation, the range of absolute values of weighting factors has no effect on the final score (*CI*) of a component.

The computation results in a value of *CI* between 0 and 10. As shown in Table 3, which is cited from HydroAMP (2006) and subject to verification during the HAP demonstration and baseline assessments, a *CI* of 7 or greater is considered “Good”, 3 to 7 “Fair” and less than 3 “Poor”. Based on the range of *CI*, the operating restriction or decision for further evaluation would be able to make.

Table 3: Condition Indicator (*CI*) and Condition-Based Suggestions

7 ≤ *CI* ≤ 10	**Good**	Continue O&M without restriction
3 ≤ *CI* ≤ 7	**Fair**	Continue operation but re-evaluation suggested
0 ≤ *CI* ≤ 3	**Poor**	Immediate evaluation and O&M adjustment required

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

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

$S_D(K)$ = the data quality score for a part/item, assigned by the assessor based on the developed Data Quality rating criteria for each component; M, K and $F(K)$ are the same as used in equation (1). The *DI* will result in a score between 0 and 10.

Table 4 aggregates all the components *CI*s for Unit #. The Unit Condition Indicator, *UCI*, is the weighted summation of the *CIs* of all components associated with the unit:

$$UCI = \frac{\sum_{i=1,N} CI(i) \times W(i)}{\sum_{i=1,N} W(i)} \tag{3}$$

Similarly, the unit Data Quality Indicator *UDI* is calculated as:

$$UDI = \frac{\sum_{i=1,N} DI(i) \times W(i)}{\sum_{i=1,N} F(i)} \tag{4}$$

Here *N* = the total number of components associated with the unit. Currently, a total of 19 components will be assessed; they are associated with the efficiency, and reliability or availability of generating units. In the future, more components/subsystems for the balance of the plant would be added. *i* = the identification No. of the component (from 1 to *N*); *CI* (*i*) = the condition score of component (*i*), *DI* (*i*) = the data quality score of component (*i*); *W* (*i*) = the Weighting Factor of component (*i*), which is predetermined based on the importance of the component to overall power generation and reliability, but they may be subject to changes later by the HAP core technical team according to the special layout and design of individual hydropower plants. By the weighted summation, the range of absolute values of weighting factors has no effect on the Condition Indicators of the unit and plant.

Table 4: Synthesis of Components Indicators to Unit Indicators
– XXX Hydropower Plant – Unit #

Components	Component Code in Taxonomy	Weighting Factors $W(i)$	Condition Indicator $CI(i)$ (0-10)	Data Quality Indicator $DI(i)$ (0-10)
Trashracks and Intake	3.1/3.2	2.0		
Penstock/Tunnel/Surge Tank	3.3/3.4/3.6	1.5		
Control/Shut-off Valve	3.5	1.0		
Flume/Open Channel	3.7	1.0		
Draft Tube Gate	3.8	0.2		
Leakage and Release	2.1/2.2/2.3	1.5		
Turbine	4.1.1	2.0		
Governor	4.1.2	1.0		
Generator	4.1.3	3.0		
Exciter	4.1.4	1.0		
Transformer	4.1.5	2.5		
Circuit Breaker	4.1.6	0.5		
Surge Arrester	6.1	0.5		
Instruments & Controls	4.3	0.5		
Powerhouse Crane	4.2.1	0.5		
Station Power Service	4.2.2	0.5		
Compressed Air System	4.2.3	0.5		
Raw Water System	4.2.4	0.5		
Lubrication System	4.2.5	0.5		
Unit Indicators			***0.00***	***0.00***

Note: Circuit Breaker, Surge Arrester, Powerhouse Crane, Station Power Service and Compressed Air System will be considered for future additions.

Finally, all the *CIs* of components and units will be aggregated into Table 5 to provide an overview of a plant and units condition. The plant *CI* is simply the average of *CIs* of all assessed units in the plant.

Table 5: Aggregated Plant Condition Indicators

– XXX Hydropower Plant

Components	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Units Average
Trashracks and Intake							
Penstock/Tunnel/Surge Tank							
Control/Shut-off Valve							
Flume/Open Channel							
Draft Tube Gate							
Leakage and Release							
Turbine							
Governor							
Generator							
Exciter							
Transformer							
Circuit Breaker							
Surge Arrester							
Instruments & Controls							
Powerhouse Crane							
Station Power Service							
Compressed Air System							
Raw Water System							
Lubrication System							
Unit Condition Indicators (*UCI*)							
Plant Condition Indicators (*PCI*)							

4 Survey Methodology and Sampling Techniques

As aforementioned, upon completion of the 50 facilities assessments, the collective results will be used to trend the current performance level and characterize the improvement potential of the U.S. conventional hydropower fleet (Note: the HAP assessments at current stage are focused on the U.S. large hydro fleet, that is the individual plant capacity is not less than 30 MW.) However, statistically valid estimates of nationwide opportunities will require survey techniques that support expansion of the results from the 50 assessments to the entire fleet. Simple selection of a range of representative facilities will provide useful insights to the industry, but may not provide a statistically valid basis for expansion of the results.

In addition, consistency and comparability across assessment teams will be important for this nationwide assessment. Aggregation of unit and facility level results across the multiple assessment teams will require a high degree of standardization of methodology, which the Assessment Manual addresses. Inter-team consistency can be enhanced by on-site training, including mock assessment of a single facility by all assessment teams followed by inter-team comparison and alignment of results. Additionally, to minimize the unavoidable inter-team variability, the aggregated assessment results will be replicated and compared by using a random subset of the assessed facilities to characterize the remaining.

4.1 Characteristics of the U.S. Large Conventional Hydropower Fleet

To design a valid sampling technique, it is necessary to review the "population" of this study, that is, the U.S. fleet of large conventional hydro facilities. Based on FY11 NHAAP database, there are total 395 large hydro plants in the U.S., in which 357 are conventional hydro plants, 24 pumped storage hydro plants, and 14 combined plants. The following is a summary of the unit and plant level statistical information for large conventional hydro facilities:

a. **The number of large CH plants is 357**, which is the population size of large conventional hydro plants in the U.S. Among this population of plants, the numbers of plants with different ages:
   Number of CH plants built before 1990 = 320
   Number of CH plants built before 1980 = 294
   Number of CH plants built before 1970 = 271
   Number of CH plants built before 1960 = 198

b. **The number of units at the 357 conventional hydro plants is 1521**, in average 4-5 units per plant. This is the population size of the units in the fleet of large conventional hydro.

c. **Number of Turbine types**

Turbine Type	**Number of Units**	**Percentage (%)**
Francis	864	51.9%
Francis (H>300ft)	241	14.5%
Kaplan	312	18.7%
Propeller	130	7.8%
Pelton	39	2.3%
Axial Flow Turbine (Bulb, Pit or Tubular)	34	2.0%
Pump-Turbine (Pumped storage)	67	4.0%
Unknown or other types	220	13.2%
Total No. of units	1666	100.0%

d. Number of Plants per 18 Hydrologic USGS Regions and Alaska

Region	Region Name	Number of Hydro Plants	Percentage
1	New England	19	5%
2	Mid Atlantic	15	4%
3	South Atlantic-Gulf	58	15%
4	Great Lakes	11	3%
5	Ohio	21	5%
6	Tennessee	28	7%
7	Upper Mississippi	6	2%
8	Lower Mississippi	5	1%
9	Souris-Red-Rainy	0	0%
10	Missouri	27	7%
11	Arkansas-White-Red	23	6%
12	Texas-Gulf	7	2%
13	Rio Grande	2	1%
14	Upper Colorado	5	1%
15	Lower Colorado	7	2%
16	Great Basin	3	1%
17	Pacific Northwest	75	19%
18	California	80	20%
19	Alaska*	3	1%
	Total Number of Plants	395	

Note: Several large plants in Alaska were not included in the FY11 NHAAP summary

e. Number of Conventional Hydro Plants per Ownership Type

Owner Types	Number of CH Plants	Percentage of CH Plants	Number of CH Units	Percentage of CH Units	CH Capacity (MW)	Percentage of CH Capacity
1. Federal	110	31%	508	35%	30,657	49%
2. Public/Municipal	63	18%	214	15%	11,527	18%
3. Private/Corp	179	51%	736	50%	20,356	33%
Sum	352	100%	1,458	100%	62,540	100%

Notes: 1. The info in NHAAP database is not so detailed and complete yet.

2. The difference between Public (Type 2) and Private (Type 3) ownerships is made by judging if the organization is nonprofit or profit oriented.

4.2 Rationale of Sample Size for Nationwide Assessments

The number of assessments is the issue of sample size determination, which is important for economic reason: an under-sized study can lead to incapability to produce useful results, while over-sized one uses more resources than are necessary. The 50 facilities (or around 200-220 units) would be the minimum required sample size for supporting expansion of the assessment results to characterize and estimate the status and improvement opportunities in the entire fleet of large conventional hydropower.

From the theory of statistics, for a certain confidence level (i.e., how sure you can be for the statistic results) and confidence interval (i.e., the margin of error), the needed number of random samples can be calculated:

(a) The sample size for an infinitely large population:

$$n_0 = \frac{z^2 p(1-p)}{c^2}$$

Here Z= Z value (1.645 for 90% confidence level; 1.96 for 95% confidence level)
p = percentage (50% for unknown participation level prior to sampling)
c = the confidence interval (margin of error, plus-or-minus of precision), expressed as decimal (e.g., 0.05 for 5% confidence interval)

(b) The sample size needed for a finite population:

$$n = \frac{n_0}{1 + \frac{n_0 - 1}{N}}$$

Here N = the population size.

Considering the 357 facilities as the population size of large hydro, the 154 facilities assessments (random sampling) would be required to gain 90% of confidence level and plus-or-minus 5% of precision level for assessment results. While for a given 90% of confidence level, 11% plus-or-minus of precision levels can be expected from 50 facilities assessments.

Considering the 198 facilities built before 1960 as the population size of large hydro, the 115 facilities assessments (i.e., random sampling from the group of 50-year-old plants) would be required to gain 90% of confidence level and plus-or-minus 5% of precision level. While for a given 90% of confidence level, 10% plus-or-minus of precision levels can be expected from 50 facilities assessments. This indicates the reduction in population size won't significantly help to reduce the effort of assessments.

However, considering the unit-level of population size, that is, the total 1521 units at the fleet of large conventional hydro, the 230 units' assessments (i.e., random sampling) would be required to gain 90% of confidence level and plus-or-minus 5% of precision level. Furthermore, when the units at the 198 facilities built before 1960 (i.e., around 840 units) is considered as the population, the 205 units' assessments (i.e., random sampling from the 50-year-old units) would be required to gain 90% of confidence level and plus-or-minus 5% of precision level. Therefore, the assessment efforts at the unit-level for the 50 facilities (i.e., 200-220 units) will be quite sufficient in terms of the validity of sample assessments. It is true that HAP condition assessment is both unit and plant levels, but performance assessment is at plant level only.

4.3 Sampling Techniques

To validate the 50 assessment results at the facility level, the assessment sites must be selected carefully with consideration to cover different technologies, ownerships, geographical regions, power markets, ages and sizes of the projects. Firstly, the HAP is a nationwide project effort, aimed to provide a fact-based quantitative estimate of additional energy available through improvements and expansions of hydro plants. This objective of HAP has determined the assessed facilities need to be good representative for the nationwide hydro fleet. Moreover, the hydro facilities are nationwide populated, distributed in all major river basins and 18 UDGS regions in 50 States. A more representative geographical distribution of assessments would indicate more states and congressional districts will be positively affected by the HAP. In addition, there are six classes of hydro plant ownerships in the US: federal, municipal and other non-federal public, private utility, private non-utility, industrial and cooperative. Different ownerships may represent for different power markets and O&M philosophies. All the hydro population and engineering features call for the diversity in the sample assessments. Therefore, the concept and techniques of "Stratified Sampling" will be applied during the process of nationwide facility selection and assessment. This sampling technique can decrease variances of sample estimates and use partly non-random method to sample individual facilities where easily accessible. For example, more facilities will be selected from the regions with dense hydro plant populations; and also at least half of selected facilities should have Francis turbine installed based on the proportion percentages of turbine types in the U.S. large hydro fleet.

5 Condition Assessment Scope and Process

The scope of work for the effort of a hydropower facility assessment will include Facility Selection, Assessment Planning, Site Visit, and Analysis and Reporting. The technical scope, information needs, and required expertise are summarized in Table 6. Workshops will be organized for selected assessment teams to attend to ensure complete understanding of interpretation and use of the BPC and Assessment Manual.

Facility Selection – It is anticipated that diversity of facilities will be selected for HAP assessment in Phase II, which consider:

- The geographic regions (across U.S. nation);
- The project purposes (power generation, flood control, water supply, etc.);
- Turbine technology types (Francis, Kaplan, Propeller, Pelton, Bulb);
- The project sizes (MWs) and components (from intake to tailrace);
- The project types (water storage, run-of-river);
- Water conveyance types (open channel, pressurized tunnel, fabricated penstock);
- Facility ages.

The assessment facilities will have been determined for each assessment team at the time of contracting. The BPC and Assessment Manual will be available publically to provide guidance in the data and resources that will be required to assess facilities.

Assessment Planning – The work will begin well in advance of site visits to solicit, collect, and analyze configuration and operation data to understand how the facility functions. The objective of this effort is to estimate the IPL, CPL, and PPL to the greatest extent possible in advance of the site visit. There should be a shared understanding by the assessment team and the facility staff as to what facility information will be made available to the team, including condition monitoring data, layout and design drawings, equipment specifications, O&M manuals, operation logs, maintenance records, and previous/historic condition assessment reports. Assessment team will also conduct interviews with O&M staff. The Performance Assessment portion of the effort will require multiple years of hourly generation, flow, and water surface elevation data for the facility and units. However, absence of such data does not necessarily eliminate a facility from eligibility, since it is older facilities with limited data that may benefit most from assessment and upgrades. The collected data will be reviewed and studied to determine the focus of on-site assessment for the specific plant, and that the planned level of effort and personnel are adequate for the on-site assessment. This phase of the effort will require focus and insight from the Assessment Team Leader (Table 6), who must possess experience in hydropower design, operation, and inspection.

Site Visit – The site visit is a critical component of the overall assessment process because it (a) allows the assessment team to validate, through direct observation, their understanding of how the facility operates and performs; and (b) allows the assessment team to address any remaining information needs (data gaps, quality assurance, anomalies, etc.) directly with facility staff. Preparation for the site visit will be extensive and will begin and end with ensuring the health and safety of the team and facility staff. The assessment team must establish a common understanding with facility staff of the schedule for assessment, support functions the facility staff will be expected to perform during the assessment, and any disruptions to normal operations that the assessment may produce. Senior and junior members of the assessment team will arrive at the facility with a site-specific understanding of the design and layout of major components of the powertrain, balance of plant equipment, water conveyances, structures, and interconnection equipment so that on-site interactions can focus on condition and performance assessment rather than explanation of design and basic operations. The assessment team leader will oversee the development of a site-specific assessment work plan, to be provided to the facility staff and ORNL in advance of each site visit. The work plan will include detailed schedules; environmental health, and safety requirements; and the roles, responsibilities, authorities, and accountabilities (R2A2s) of team members and facility staff involved in the assessment. A detailed site visit report will be required to provide to the facility owner and to DOE within two weeks of the conclusion of the site visit.

An example of on-site activities and sequence is as follows: introductory meeting with health and safety briefings; confirm schedule and support staff requirements; discuss remaining information needs; confirm or adjust estimates of IPL, CPL, and PPL; examine plant systems and discuss conditions with facility staff; prepare interim report; and conduct exit meeting to discuss preliminary findings with facility staff. The need for engineers with deep theoretical and practical understanding and experience in hydropower design and operation to lead the on-site efforts cannot be overstated.

Analysis and Reporting – For each facility assessment there are four deliverables:

- Site Visit Report
- Non-public Assessment Data Report

- Draft/Final HAP Assessment Report
- Public Assessment Report

A Site Visit Report will be submitted within two weeks of the conclusion of the site visit. The assessment team will compile and document information obtained prior to and during the site visit into a Non-public Assessment Data Report. This report will not be made public without specific approval from the Facility owners/operators.

The team will complete the analyses required to document the IPL, CPL, and PPL for the facility and will produce a Draft HAP Assessment Report that prioritizes:

- Process (primarily related to performance monitoring, unit commitment, and load allocation) upgrades that move the CPL toward the PPL and
- Equipment improvements and design changes that align the IPL with the PPL.

The report will include estimates for the potentially increased energy and other benefits, the order of magnitude cost estimate to implement, the recommendations for additional studies to resolve uncertainties in prioritization, costs, and benefits of improvement activities. The report will also include a description of the facility and the site-specific environmental and operating constraints that impact the IPL, CPL, and PPL.

Examples of improvement activities that could be recommended include:

- Advanced instrumentation and control upgrades, online condition and performance monitoring
- Runner replacement or turbine upgrade (e.g., propeller upgrading to Kaplan),
- Generator re-winding and up-rating,
- Wicket gate adjustments to minimize leakage,
- Tuning of blade and gate cams in double-regulated machines,
- Intake and trash rack upgrades, online fouling monitors, and optimized cleaning schedules
- Water conductor system from intake to tailrace upgrades and modifications that could improve the plant performance (such as reduction in conveyance losses)
- Spillway gate sealing upgrades for leakage control,

- Dam and reservoir remediation for seepage control,
- Repair and recoating of water conveyances to minimize leakage and friction losses,
- Incorporation of environmental mitigation-induced efficiency losses in unit commitment and load allocation,
- Adding small generating units to use minimum flow releases and maximize plant efficiency,
- Remediation for major safety and reliability issues if any observed, and
- Rehabilitation for prolonged generation years.

6 Condition Assessment Outcome

The condition assessment results will be used to analyze three impact indices: Reliability Impact Index, Efficiency Impact Index, and Cost Impact Index. The Reliability Impact Index represents the risk level of an asset (the asset could be a part, a component, a unit, or a plant). Bad condition of an asset means high reliability impact (i.e., more likely to fail and cause more severe impact once it fails). This index can be purely correlated to the asset *Condition Indicators*.

The second outcome from the condition assessment is the Efficiency Impact Index, representing the potential of generating performance improvement. Bad condition usually implies the great potential for efficiency improvement. The analysis of Efficiency Impact Index at a facility will combine the results from both Condition Assessment and Performance Analysis, which could be based on the incremental power production pertaining to a year or long-term timeline.

The third outcome from the condition assessment is the Cost Impact Index, representing the level of dollar cost for upgrading the process or asset in terms of $/kW or $/kWh. Usually, bad condition indicates high cost level for the same type of asset. A preliminary cost estimate will be combined with the condition rating results to obtain the Cost Impact Index.

These three impact indices will be analyzed when the condition and performance assessment reports have been generated for 50-60 facilities, so they can be evaluated consistently for all the facilities. The impact analysis results will be assembled to provide a baseline condition and trend the improvement opportunities within the nationwide existing U.S. hydropower fleet.

For an individual facility, the three Impact Indices can collectively provide a base for the decision-making on further assessment or studies and for prioritizing the investment opportunities. Meanwhile, the individual index (Reliability Impact, Efficiency Impact or Cost Impact) would also make sense individually – e.g., if an asset owner concerns of reliability issue more than efficiency potential, the owner may focus on the reliability impacts and even look into the reliability impacts from the most-concerned parts or components of a generating unit.

7 Plant General Data Collection

7.1 Plant General Assessment

Plant general information includes the Name, Location/Coordinates, River name, Ages, Purposes of project, Type of project, histories of project design, construction, operation, maintenance and rehabilitation. This part of data collection should include any information may not be covered in the Inspection Form and Check List for each individual component. The Plant General Inspection Form and Check List is provided as in a separate document.

7.2 Data List for Performance Analysis

Data can be obtained from plant personnel, central engineering staff (if any), and load control personnel (if applicable):

1. Operating Data: Do a data survey; find out what is measured (and how well); and find out what archival data are available.
   a. Get snapshot data not averages
   b. Hourly sampling frequency
   c. For most cases, a few years' data is plenty to capture operating patterns. However, for others, more years may be appropriate to capture longer term events (e.g., market effects on dispatch, excessive outages due to reliability problems, hydrology-related patterns, etc.).
   d. Essential items for schedule analyses and operational efficiency analyses
      i. Unit power
      ii. Head Water Level
      iii. Tail Water Level
      iv. Air on or off for aerating units
   e. Other important data

i. Winter-Kennedy Differential, Acoustic Flow Meter Output, or Other Unit Flow Rate
ii. Spill flows
iii. Wicket gate opening
iv. Trash rack differential (if available)
v. Blade angle for Kaplan units
vi. Air flow rates
vii. Reservoir bathymetry (for pumped storage plants)
viii. Unit status (available/unavailable)
ix. Environmental flows (e.g., sluice flows)

2. Test Results: Get unit index test results and/or efficiency test information
   a. With aerating units, unit characteristics while aerating are very important
   b. Winter-Kennedy (or other) flow rates are very important
3. Determine how units are dispatched (e.g., generation, ancillary services, both)
4. Determine environmental constraints
5. Determine unit operating constraints
   a. Minimum flow
   b. Cavitation and vibration constraints
   c. Generator constraints

Table 6: Scope of Assessment and Personnel Requirement

Role	Qualifications	Scope of Assessment (Major Components to be Assessed)	Required Condition Inspection and Data Collection	Preparation (hours)	On-site Assessment (hours)	Post-Assessment (hours)
Assessment Lead	ME, EE, CE with 15+ years of hydropower design or operations experience	Systems coordination, main POC with asset owner, scheduling master, safety analysis	Basic and general info regarding facility and major equipment (ages, layout and design drawings, major problems experienced and maintenance/upgrade records, historic/previous assessment reports, etc.)	40	8-24	80
Power Train & Balance of Plant Expert	ME with 5+ years of hydropower experience	Turbine, shaft, bearings, seals, lubrication, governor, cooling water system, drainage system, SCADA	Turbine model, design parameters and characteristic curves; cavitations inspection and measurement data, gaps in the seal rings; WG/blade angle settings; index tests or other testing data records; any water or oil leakage inspection & measurement data, and etc.	16-40	8-24	24
Electrical Expert	EE with 5+ years of utility experience	Generator, exciter, transformers, switchgear, circuit breakers, relays, SCADA and etc.	Generator model, design parameters and efficiency curves; Regular tests and EL CID tests data for condition assessment of generators insulation; oil testing data for transformer condition assessment; inspection/data required for efficiency assessment of other components.	16-40	8-24	24
Civil Structures	CE with 5+ years of hydraulic structure experience	Trash racks, intakes, gates and interfacing surface, stoplogs, tunnels/canals, penstocks, draft tubes, tailrace, valves, dams, reservoirs and buildings	Observed corrosion, blockage & other physical conditions, quantified head losses for each component of water conveyance system; measured flow through turbine & released to downstream; leakage, seepages, sedimentation and condition check for reservoir and other civil works. Visional, ROV, dewatered or diving inspections required if no recent records available.	16-40	8-24	24
Performance Specialist	Specialist with experience in hydropower plant efficiency analysis and optimization	Scoring efficiency-related data and processes (availability & soundness), unit and plant controls, operational simulations	Unit performance characteristics, unit operation logs, generation scheduling/dispatch, historic testing data including head water elevation, tailwater elevation, power, flow rate, water temperature, gate opening (blade angle), and etc.	40-80	8-16	40
Clerical Staff				40		24
SUB-TOTAL (hours)				**168 - 280**	**40 - 112**	**216**

Note: The on-site assessment hours include traveling time.

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