

IEEE Guide for the Rehabilitation of Hydroelectric Power Plants

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Abstract: This guide is directed to the practicing engineer in the field of hydroelectric power plant design for the purpose of providing guidance in the decision-making processes and design for the rehabilitation of hydroelectric power plants. It covers general assessment considerations, rehabilitation of waterways, and rehabilitation of equipment. An extensive bibliography is included.

Keywords: hydroelectric power plant, rehabilitation

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Foreword

(This Foreword is not a part of IEEE Standard 1147-1991, IEEE Guide for the Rehabilitation of Hydroelectric Power Plants.)

This document is a guide for the hydroelectric power industry to assist hydroelectric power plant owners, operators, and designers in the economic (Feasibility) and technical evaluation (electrical aspects) of existing hydroelectric installations for rehabilitation. Feasibility study results may indicate redevelopment of the site. Redevelopment will not be treated in detail in this guide.

This guide is intended to be used as a reference document for practicing engineers in the hydroelectric power industry.

The Working Group on Hydroelectric Power (P1147) was formed at the 1986 IEEE Summer Power Meeting. Its members represent a cross-section of the hydroelectric power industry that includes power plant owners, engineers, and equipment manufacturers.

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IEEE Guide for the Rehabilitation of Hydroelectric Power Plants

1. Scope and Introduction

1.1 Scope

This guide is directed toward the practicing engineer in the field of hydroelectric power plant design for the purpose of providing guidance in the decision-making and design processes for the rehabilitation of hydroelectric power plants.

1.2 Introduction

Owners of hydroelectric power plants have four options to consider after evaluating the performance and operation of plants and individual units in the plant. These options are

- 1) Retirement
- 2) Continuation of operation as-is
- 3) Redevelopment
- 4) Rehabilitation

The first two options are self-explanatory. Option (3), *redevelopment*, involves the construction of an essentially new plant by replacement of all or a major part of the plant equipment and structures in order to make optimum use of the hydro resource.

This guide will address option (4), *rehabilitation*. Rehabilitation should result in extended life, improved performance, increased reliability, reduced maintenance, and improved operations. This guide covers all equipment up to and including the main transformer.

All aspects of the power plant should be considered for rehabilitation including the typical structural, electrical, and mechanical systems shown in Fig 1. For example, improved performance can be achieved by replacement of the turbine runner with a modern design, by upgrading the generator, or by improving auxiliary support systems. Increased reliability, reduced maintenance, and improved operations can be achieved by the rehabilitation of appurtenant electrical equipment such as exciters, regulators, governors, transformers, and control systems. These and related subjects are addressed in this guide.

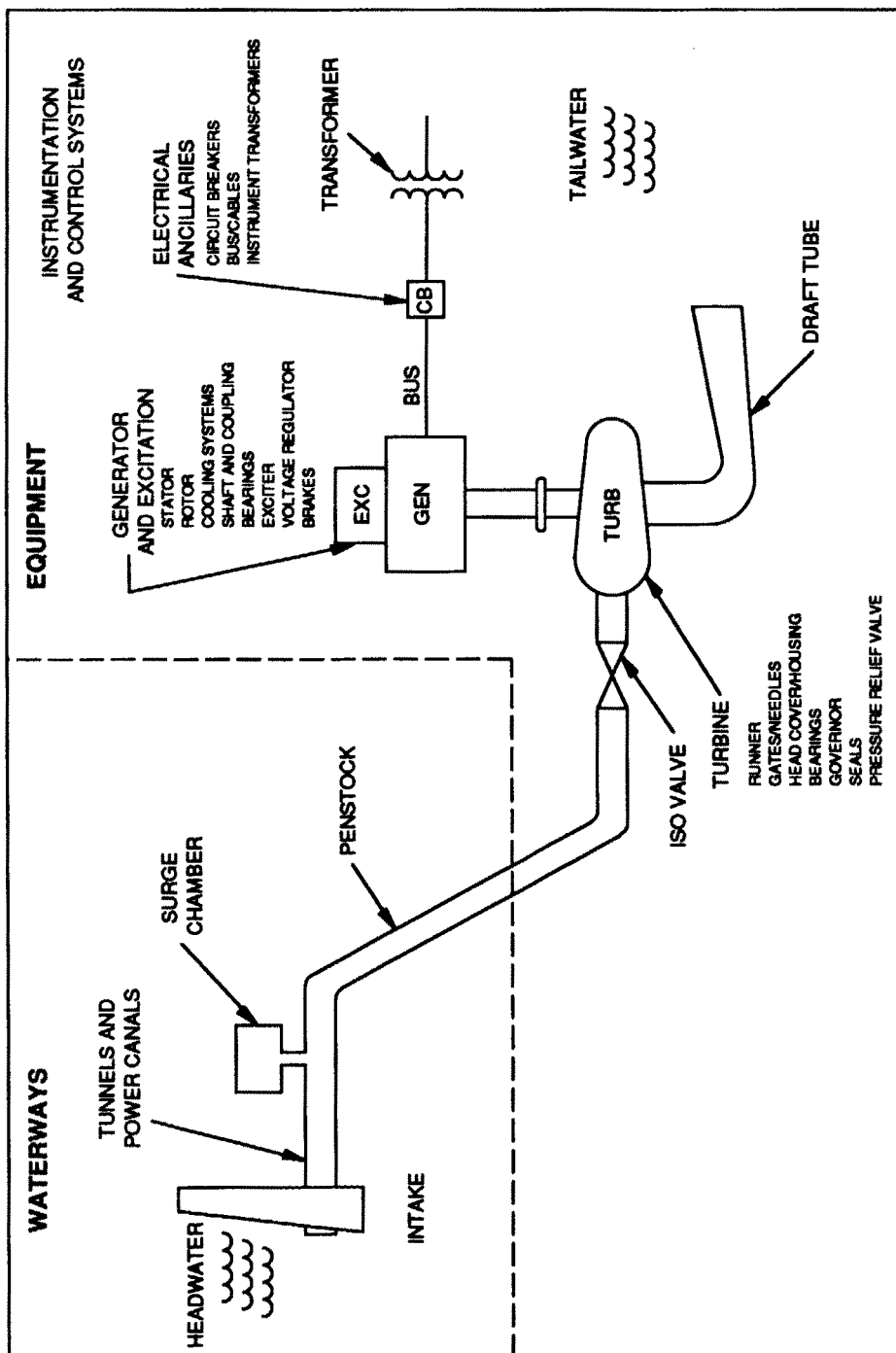


Figure 1—Typical Power Plant Systems Considered for Rehabilitation

This guide addresses conventional hydropower. Portions of this guide are relevant to pumped storage, however, the unique features of pumped storage are not covered.

The plant owner should be aware of current safety codes and standards during the plant assessment and rehabilitation.

The plant owner should be aware that the rehabilitation of the plant may require the need for amending the license with the appropriate regulating agency. The owner should also investigate historical preservation regulations that may impact the rehabilitation program.

This guide contains a bibliographical listing of industry standards, recommended practices, and guides that may be used as a resource by the engineer engaged in power plant rehabilitation. The review of those documents that apply to the desired area of rehabilitation is encouraged. The listing is not complete, but is meant to be an aid in starting the review process.

2. General Assessment Considerations

2.1 General Conditions for Rehabilitation

Rehabilitation of equipment in a hydroelectric power plant may be appropriate when any of the following conditions prevail:

- 1) Declining unit availability
- 2) Potential for improved performance
- 3) Changes in plant or unit operating conditions
- 4) Opportunity for plant automation
- 5) Reduced output capabilities
- 6) Failure of major equipment
- 7) Inability to withstand the effects of seismic forces during earthquakes

It is desirable to perform an appraisal of each of the above conditions as they apply to all major equipment in hydroelectric power plants. Inspection and testing is an integral part of this appraisal process. A tabulation of suggested items to be evaluated is given in Table 1.

Table 1—Items to be Considered in Assessment of Plant and Equipment

The following is a list of items that should be considered in the assessment of equipment. The left column lists general items, and the right column gives more specific factors to be considered.	
Operating Conditions	Factors
Availability of water	Expected changes in water flows could have major effect on rehabilitation.
Addition of new unit(s)	A new unit at a plant could relegate operation of existing units to short-time peaking, which could affect the benefits of rehabilitation of the existing units.
Need for increased capacity	Experience shows that increasing capacity by uprating requires minimum capital and produces the lowest cost in dollars per kW for increase.
Review Operating Records	Factors
Plant/unit flows, head, and energy production	Look for trends that could indicate degradation in performance, such as reduction in head due to high penstock losses or less energy produced by the same water.
Forced outages	Reveals major problem areas, types of outages, and their frequency.
Equipment operating data	Loadings, flows, temperatures, and cooling — all of which have an effect on life expectancy.
Review Maintenance Records	Factors
Past and present maintenance programs	Reveals if equipment has been maintained, which can influence the condition of equipment.
Repairs — what and when	Identifies problem areas if repairs are frequent. For example, frequent turbine runner repairs due to cavitation could indicate the need to change runner design or material or tailwater elevation. Another example would be frequent generator thrust bearing repairs, which could mean that a high-pressure lubrication system should be added, or an effort should be made to reduce the hydraulic thrust.
Equipment Design Data	Factors
Age and materials	Can be useful in predicting expected life.
Design performance and ratings	Is original consistent with present use? (For example, the turbine was designed to have a maximum efficiency rating at 80% rating, but is now operating at 110%; or, the unit was designed for 50 Hz, but is now operating at 60 Hz.)
Inspection of Equipment	Factors
General condition	Dirt, corrosion, leaks, cracks, cavitation, loose wedges, tape separation, etc.
Obvious problem areas	Leaks, vibration, high operating temperatures, lack of cooling, etc.
Equipment Tests	Factors
Test Data	Comparison of previous test data with new tests that can identify degradation in performance and reliability. Some tests are Turbine — efficiency tests Generator — insulation tests Switchgear — insulation tests Transformer — oil tests for degradation

2.1.1 Declining Unit Availability

This causes increased costs and reduced revenues. Declining unit availability can be recognized by the occurrence of the following conditions:

- 1) The end-of-life expectancy of the individual components should be analyzed, and the expected timing, cost of replacement, and availability of spares should be included in the analysis.
- 2) Poor reliability of equipment may be evidenced by frequent outages. Outages and their frequency should be analyzed to determine the real cause; and corrective actions should be undertaken to improve the performance.
- 3) Maintenance activity that is over and above the routine activity necessary to keep the equipment in reasonable operating condition is another indicator. Causes for the increased maintenance activity should be investigated.

2.1.2 Potential for Improved Performance

The performance of major equipment such as output and efficiency was determined by the technology and state-of-the-art available at the time that the equipment was designed and built. Since significant advances in engineering and materials have occurred, older equipment can now be rehabilitated to obtain important gains in performance.

2.1.3 Changes in Plant or Unit Operating Conditions

Major equipment is designed to provide optimum performance for a specific set of operating conditions. The fact that these operating conditions can change with time often will justify rehabilitation of the equipment to improve its performance for a new set of operating conditions. Some examples are

- 1) Changes in water usage and availability for the generation of power can result in the need to increase the power output requirements of the turbine, generator, and ancillary equipment.
- 2) Changes in the method of operation of the unit can result in the need for higher outputs.

2.1.4 Plant Automation

Plant automation programs that are intended to achieve unattended operation of a unit or to convert from local to off-site control often require extensive modifications to equipment. Although plant automation is beyond the scope of this guide, it is recommended that rehabilitation of equipment be included as part of the automation studies.

2.1.5 Reduced Output Capabilities

Major equipment that have restrictions that prevent operation of the unit at its full capacity or curtail its energy production due to changes in plant conditions are candidates for rehabilitation. Examples of operating restrictions are

- 1) Reduction in available water flow
- 2) Temporary repairs to maintain limited equipment operation

2.1.6 Failure of Major Equipment

Unscheduled outages due to failure of major equipment during operation often result in substantial economic losses, especially if water can not be stored or diverted to other units. When the severity of the failure results in a prolonged outage, it is appropriate to consider the uprating of the failed equipment as an alternative to simple repair or replacement in kind. The following examples illustrate situations in which uprating could be considered:

- 1) *Failure of a main unit transformer.* Procurement of a new transformer that has lower losses and is designed for current and future operating conditions could be appropriate.
- 2) *Failure of a turbine runner such that its repair is not feasible.* Upgrading the runner with a new design that features improved performance under the current and future operating conditions could be appropriate.

2.1.7 Seismic Considerations

It is appropriate to review the capability of plant structures and equipment to withstand the effects of earthquakes. This involves establishing ground motion levels (peak horizontal and vertical acceleration and velocity) for the maximum credible earthquake (MCE) for the area, then assessing the ability of plant structures and equipment to withstand these levels. Assessments can be made using a combination of computerized (dynamic) and manual analysis techniques and physical inspections.

Examples of modernizations that improve seismic withstand capabilities are

- 1) Automatic flow shut-off by unit shutdown or intake gate closure initiated by seismic triggers
- 2) Anchoring of critical equipment necessary for safe and reliable shutdown, such as battery racks, governor equipment, and control and protection switchboards
- 3) Strengthening of control and protection switchboards to prevent buckling or collapse
- 4) Reinforcement of structures near critical equipment to prevent damage from falling debris
- 5) Installation of flexible metal hose in place of rigid pipe for governor pressure piping
- 6) Modifications to control and protection circuits to ensure safe shutdown in the event of failure of dc power supply during a seismic event

2.2 Systems Approach to Rehabilitation

In the above text, general conditions were reviewed that could lead to the rehabilitation of major equipment. It is important to realize that changes in external system parameters or criteria, or the rehabilitation of one major piece of equipment, can have a significant impact on other systems in the plant. A systems approach is needed to fully evaluate most rehabilitation.

To illustrate this point, consider a case in which a turbine runner is uprated to produce greater power output and to operate at improved efficiency. Such improvements are not uncommon, but the impact on other parts of the plants should be considered, such as

- 1) Passing greater water flows through the turbine can have an impact on the penstock in that larger flows will produce higher pressure transients due to load acceptance and rejection. Changes in governor stroke and timing and changes in pressure regulating valves (if applicable) are often required.
- 2) The increase in turbine shaft output power requires an assessment of the shaft coupling, generator shaft, and rotor structure to safely transmit the increased torque.
- 3) The increase in generator power output requires an assessment of the stator winding, stator core, and field to determine their ability to generate the increased power and the possible need to uprate. The ability of the excitation system to provide the required field current, to provide the necessary voltage control, and to meet reactive power requirements should also be determined.
- 4) The capability of the generator leads and circuit breaker (if applicable) to carry the increased current should be evaluated.
- 5) The main unit transformer and associated transmission lines should be evaluated to determine if they can carry the increased power.
- 6) The rating of the current transformers and associated metering and protective equipment should be evaluated based on the upgraded capacity of the generator.
- 7) The generator cooling system and components should be evaluated for adequacy.

Because rehabilitation of major equipment in the plant can require prolonged unit outages, the impact of the outage on the water system and on the electrical power system should also be considered. Two examples of the impact due to outages are

- 1) A prolonged unit outage for rehabilitation could mean that water must be stored or diverted to other units or plants. If this cannot be accomplished, then the power and energy production from that water could be lost, which would have an important economic impact on the feasibility of the rehabilitation.
- 2) A prolonged unit outage also results in the loss of generating capacity on the electrical power system. If this loss in capacity occurs during system peak loads, then the loss of capacity could have an economic effect on the feasibility of the rehabilitation.

The above examples illustrate the importance of planning major rehabilitations so that they will have a minimal impact on the water and power systems associated with the plant.

2.3 Feasibility Study

2.3.1 Introduction

A feasibility study of the various alternatives is performed to determine a possible course of action for plant rehabilitation. Consideration is given to project staffing, operation, and maintenance of the plant. Alternatives are developed for repair, replacement, rehabilitation, modernization, and automation, as well as the addition of functionally new equipment. The alternatives are then studied and compared for performance and economic justification. The resultant mix of most favorable alternatives is then incorporated into a program for plant rehabilitation.

This section does not discuss the details of making a feasibility study but does emphasize the need for one. A concise plan for the anticipated work is a product of the study, and is a very useful tool in implementing any rehabilitation.

A rehabilitation project should result in an economic benefit. Other projects implemented for safety, environmental, or regulatory reasons may have little, if any, economic benefit.

The feasibility or benefit-to-cost analysis may be very simple or quite sophisticated, depending on the size of the project and the number of optional features involved. The study evaluates the various options, most often using a present worth computation, to include those features that show favorable economics and delete those that fail the economic justification.

The feasibility analysis is essential to the development of an informed basis for action and a concise scope of work.

2.3.2 Anticipated Benefits

2.3.2.1 Increased Plant Output

The means of increasing output, either capacity or energy, cover practically every aspect of the plant. Some cost more than others, and some have greater benefits than others. The need, during the feasibility review, is to determine those modifications that are economically justifiable. The present day expense of modernization should be balanced against the long-term gains. For example, it may seem like a significant expense to rewind a 40 year old stator. However, if the gain in output, which may be small, is evaluated over the future life of the plant, it may be a highly desirable expenditure. Similarly, increased operating head or water storage should be evaluated with the intent of increasing plant output or load factor.

2.3.2.2 Reduced Manpower Requirement

Substantial returns, when evaluating rehabilitation programs, emerge quite often after an analysis of the manpower requirements. A “before and after” review of personnel requirements can show dramatic economic benefits. This is particularly evident in those cases where 24-hour manned positions can be eliminated or reduced to single-shift requirements.

2.3.2.3 More Efficient Water Use

Increased efficiency in the hydraulic equipment and water passages is a topic that should be subjected to critical review with the intention of obtaining long-term gains. Improved designs for turbines, gates, seals, governors, and controls offer an opportunity to make more efficient use of the water. Small efficiency gains turn into substantial economic benefits when evaluated over the life of the plant.

2.3.2.4 Improved Operation and Increased Availability

Benefits can be realized by reducing the forced outage rate and increasing the unit availability, thereby improving the reliability of the plant. Fiscal values can be assigned to these improvements and used in the feasibility analysis when weighing costs against benefits.

Operation can be improved by incorporating modern control schemes, reducing the number of control devices, eliminating unnecessary recording functions, or similar methods. Unit availability can be increased by replacing or refurbishing equipment that has become or will soon become failure prone. Reliability improvements can be equated to better operation and will result in improved revenues for the plant.

2.3.2.5 Reduced Operating and Maintenance Costs

The use of supervisory control and automated data acquisition can reduce many of the manual operations normally associated with the older plants. Also, improved operation data can assist in determining maintenance requirements and reducing forced outages.

2.3.3 Costs

Feasibility studies cover the costs associated with rehabilitation. The costs fall into several categories.

2.3.3.1 Direct Costs

- 1) Cost to purchase and install new equipment or modify existing equipment
- 2) Loss of revenues during outages caused by the rehabilitation program

2.3.3.2 Indirect Costs

- 1) Costs for planning, engineering, purchasing, etc.
- 2) Supervision and inspection

2.3.3.3 Investment-Related Costs

- 1) Depreciation and salvage
- 2) Return on capital
- 3) Taxes
- 4) Insurance
- 5) Cost of funds used during construction

The feasibility stage of hydroelectric plant rehabilitation quite often requires testing of the equipment, water passage losses, and river levels and flows to confirm the existing conditions prior to plant modifications. The establishment of benchmark values are necessary before an economic evaluation can be completed and a program can be defined.

3. Rehabilitation of Waterways

3.1 General

Energy losses in the waterways system of the hydroelectric power plant are due to wasted water flow and loss of head. These losses are associated with the operating practices of the plant and with the physical equipment included in its waterways systems. A brief discussion of these losses is contained herein. The discussion does not attempt to address possible improvements and their implementation unless significant electrical content is involved. Appropriate civil and mechanical engineering society (ASCE¹ and ASME²) guides can be referred to for consideration and in-depth treatment of the rehabilitation of many of these components. Items such as spillway and intake gates are of paramount concern to a power plant owner because major plant and facility safety issues are involved.

3.2 Leakage Losses

Leakage from various power plant components decreases available flow to the turbines. The leakage is usually minor in nature. EPRI EM-2407 [B126]³ estimates the average leakage loss at a typical plant at less than 0.5 % of available stream flow. Leakage, for purposes of classification, can originate from three general sources: intake gate systems, flood control systems, and structural sources such as foundations, power tunnels, and penstocks. Leakage from sources up to the turbine shut-off valve, together with their causes, are discussed briefly in the following paragraphs.

3.2.1 Intake Gate Systems

3.2.1.1 Gate Seals

The intake gates may lack gate seals or have defective seals.

3.2.1.2 Gate Position Indication Systems

Some plants have remote indication systems that allow intake gates to be controlled from the power plant control room or other remote locations. Miscalibration or inherent design limitations of the indication system may give false indication of gate closure.

3.2.1.3 Gate Hoist Equipment

Erratic or unpredictable operation of gate hoist equipment can be a cause of gate leakage. If rehabilitation of intake gate systems is being considered, many of the electrical features discussed in 4.22 are applicable to the electrical systems of the gates and hoists.

¹American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017, USA.

²American Society of Mechanical Engineers, 22 Law Drive, Fairfield, NJ 07007, USA.

³The numbers in brackets, when preceded by the letter "B," correspond to the Bibliography in Section 5.