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Technical Letter
No. 1110-2-550 30 May 1997

Engineering and Design
RELIABILITY ANALYSIS OF HYDROPOWER EQUIPMENT

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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

ETL 1110-2-550

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1. Purpose

This engineer technical letter (ETL) provides basic guidance for assessing the reliability of hydropower equipment and establishes an engineering basis for rehabilitation investment decisions. The methodology, concepts, and background information are briefly stated with further explanation and examples in the appendices. This letter also references the hydropower benefits analysis and the economic models as they relate to hydropower rehabilitation projects.

2. Applicability

This ETL applies to all HQUSACE elements and USACE commands having responsibilities for civil works hydroelectric power plant projects.

3. References

Required and related publications are listed in Appendix A.

4. Background

Reliability analyses are a required and significant part of the economic justification for funding of rehabilitation and major maintenance projects.

a. In FY 1992, major rehabilitation projects began being budgeted under Construction, General, and Flood Control, Mississippi River and Tributaries, appropriation accounts. Total implementation costs of hydropower rehabilitation projects must be in excess of $5.3 million for FY 1998 submittals, and the work must extend over two full construction seasons to qualify under the major rehabilitation program. The cost threshold amounts are adjusted annually for inflation as published in the Annual Program and Budget Request for Civil Works Activities, Corps of Engineers, EC 11-2-172. Proposals for these projects are subjected to a much more rigorous economic analysis than in the past. Not only is it necessary to show that the monetary benefits of major rehabilitation work exceed the cost, but it must also be demonstrated that each component in a rehabilitation plan is incrementally justified and that the combination of components proposed yields the maximum net benefits. In short, proposals for major rehabilitation work must be supported by the same level of economic analysis as that for new water resource development projects. The Chapter 3 of the ER 1130-2-500 establishes the policy for major rehabilitation at completed Corps projects. The Chapter 3 of the EP 1130-2-500 established guidance for the preparation and submission of Major Rehabilitation Projects Evaluation Reports for annual program and budget submissions. They should be consulted for the most recent policy on types of improvements that can be pursued under the Major Rehabilitation program

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This technical letter supersedes ETL 1110-2-337, dated 30 June 1994.

and the basic assumptions for the economic analysis. Currently, reliability is the key factor in determining whether there is a Federal interest in a proposed replacement. If an equipment replacement is reliability-driven, the investment is generally Federally funded. An increase in output which is primarily incidental to the reliability work may also be included in such a project. However, non-Federal funding is required to fund the project if there are no reliability problems and the proposed project purpose is only to improve output beyond the original design. Contact CECW-B for current policy on non-Federal funding of generation improvements.

b. Hydropower major maintenance work items also require reliability analysis and economic justification. Major maintenance includes projects, such as a generator rewind, with total estimated costs that exceed $3 million and do not qualify as Major Rehabilitation. Specific guidance on hydropower major maintenance evaluation requirements is being drafted by CECW-B.

5. Reliability Concepts

There are some basic reliability concepts which arise from statistics and are utilized in evaluating reliability. The definitions of the terms used to represent these concepts and the definitions of terms more specific to hydropower equipment reliability analyses follow.

a. Risk. The exposure to a chance of loss or injury; the likelihood of adverse consequences. Expressions of risk are composed of the following two parts:

(1) The existence of unwanted consequences.

(2) The occurrence of each consequence expressed in the form of a probability.

b. Certainty. A condition where determinacy exists in the elements that characterize a situation. The likelihood of an event occurring and its consequences are known absolutely.

c. Uncertainty. A condition where indeterminacy exists in some of the elements that characterize a situation. Uncertainty may exist from either probability uncertainty or outcome uncertainty or any of the pathways between the initiating event and the consequences.

d. Variability. The existence of differences in the numerical quantities within the same population. Uncertainty and variability have some of the same connotations. With variability, the range of possible values is usually known, perhaps along with other information such as the distribution. However, uncertainty allows the values for a quantity to retain an element of vagueness that is not characterized in quantities exhibiting variability. This suggests that if placed on a continuum from complete randomness to complete determinacy, variability is somewhere closer to certainty than uncertainty is.

e. Reliability of power plants. There are risks associated with the possible failure of operating power plants. The risks include repair costs and higher power generating costs. A generating unit that has been derated because of previous problems is not capable of producing the same amount of power that it could originally produce. That is a certainty. The exact amount of power the unit can produce in the derated condition is uncertain. The probability that a generating unit will fail after it has been on line for 20 years has variability. The engineering reliability analysis required for a major maintenance rehabilitation proposal needs to consider these reliability concepts.

f. Equipment reliability. Hydropower equipment reliability is defined as follows:
The extent to which the generating equipment can be counted on to perform as originally intended. This encompasses the confidence in soundness or integrity of the equipment based on forced outage experience and maintenance costs, the output of the equipment in terms of measured efficiency and capacity, unit availability, and the dependability of the equipment in terms of remaining service life (retirement of the equipment).

6. Engineering Reliability Analysis

This section discusses the many facets of reliability of hydropower equipment in relatively broad terms. Appendices B through E go into further detail by exploring a theoretical project and applying an analysis to that project. The overall engineering reliability analysis consists of four independent analyses to determine the following equipment reliability factors: (a) forced outage experience and maintenance costs; (b) efficiency and capacity; (c) availability; and (d) dependability. The life-cycle costs of each segment are compiled for use in the economic analysis. Benefits for each alternative are calculated by subtracting the average annual equivalent life-cycle costs for the alternative from the average annual equivalent life-cycle costs for the base condition. The following paragraphs briefly summarize each segment of the reliability analysis.

a. Forced outage experience and maintenance costs. A forced outage occurs when a power plant component fails to perform satisfactorily and causes an interruption in power production. A planned outage occurs when a unit is intentionally taken out of service to perform planned repairs, replacements, routine inspections, and rehabilitations.

(1) The life-cycle cost of equipment maintenance and repair includes labor and material costs as well as lost energy and capacity benefits associated with forced or planned outages. Therefore, reliability is a determining factor in estimating life-cycle costs. Decreased reliability may be represented by a large increase in labor and materials costs over time. Certainly, increasing maintenance costs and unit outage hours can both be used to indicate a need for equipment replacement or rehabilitation. Project records for the equipment in question can be used to document past trends and as a basis to make future projections. Currently, such documentation may be the only justification required for replacing relatively low cost items that are critical for power production. In the near future, economic justification that incorporates reliability will be required. The economic justification will be conducted using the Hydropower QUADRANT model, HYD-QUAD. CECW-B should be contacted on the requirements for justifying relatively low cost items below the main rehabilitation and major maintenance threshholds and for using HYD-QUAD. HYD-QUAD is discussed in Appendix F.

(2) Caution must be exercised when relying on maintenance costs as indicators of reliability because they do not necessarily reflect equipment reliability. Explanations of costs and maintenance efforts should be presented in the evaluation reports. Maintenance and repair records should be tabulated and charted to show the trends over the past few years. Projections for future years can be made using sound engineering judgment to extrapolate these costs and should be made for each of the alternatives being considered. Lost energy and capacity are discussed below under the topic of availability.

b. Efficiency and capacity. This portion of the reliability analysis can be applied to any piece of equipment that has an effect on the ability of the generating unit to produce rated power at rated efficiency. However, this approach is primarily applicable to the turbines, generators, and transformers. Turbines will be used as an example in the following explanation.

(1) Part of the aging process of turbines is the development of cracks, corrosion, erosion, scaling, and cavitation damage. Much of this damage is corrected by welding, which induces material stresses and can change the shape of the turbine water passage thereby lowering the efficiency of the turbine. Thus, degradation of turbine performance occurs as a result of the aging process and can be exacerbated by repairs which are necessary to keep the turbine operational.

(2) The first step in quantifying the performance degradation is to determine current and original levels of performance. Current efficiency and power output must be determined by field testing at similar settings used in the original field tests. The current performance must then be compared with the original level of performance to establish the amount of performance degradation that has occurred. Original levels of performance

can be established from model tests and acceptance test data. It is important to fully investigate the calibrations and calculations of the data in order to truly compare the original and current performance.

(3) The information derived from this testing and analysis is provided as input to the hydroelectric power benefits analysis, which is discussed in Appendix D. The benefits analysis estimates the power system production costs using a full range of unit availability which can be applied to the base case and each alternative.

c. Availability. Availability is the annual percentage of time that the generating equipment is available for power production. Records of availability are maintained by each project on a unit-by-unit basis. The current level of availability must be compared with previous data to establish the extent of degradation. Historical trends can be extrapolated to project future changes in the unit availability rate. Availability data are also used as input to the hydroelectric power benefits analysis.

d. Dependability (reliability).

(1) The final area of consideration concerning equipment reliability is dependability. Dependability is ascertained by a risk analysis that determines the probability that the equipment will not perform satisfactorily in any given year. The output from this risk analysis is used in the probabilistic life-cycle cost analysis. One way to graphically represent the probabilistic life-cycle cost model is with event trees. A discussion of event tree models is presented in Appendix E. Two methods of probabilistic risk analysis are frequently used. The first method uses historical data and an evaluation of the condition of the equipment to determine a statistical distribution of age at retirement. This method is characterized by the use of reliability curves. The second method is similar to that used in structural evaluations. It extends the safety factor concept by using a probabilistic approach to determine a reliability index. The method that is most appropriate depends upon the type of equipment being evaluated and the specific situation.

(2) Hydropower equipment is typically operated until it fails or is retired for some other reason. Failure meaning that it ceases to function properly under the stresses applied. Replacement and refurbishment are both considered as constituting the effective retirement of a piece of equipment. The first major reason for equipment retirement is physical condition, which includes deterioration with time, wear from use, and failure in service. The second reason for retirement is related to functional situations, which include inadequacy to perform required functions, potential for improvement (uprating), and obsolescence. These may occur due to a change in environment, operating conditions, or load requirements. The first category, physical condition, is the primary reason that the Corps developed the Major Rehabilitation Program. This program establishes a standardized method of considering and evaluating the deterioration and wear of equipment in an effort to optimize rehabilitation actions. Failures in service are generally not evaluated under the Major Maintenance and Rehabilitation Programs, but are funded through reprogramming Operation and Maintenance funds. Reliability is the key factor in determining whether there is a Federal interest in a proposed replacement. As previously stated, if there are no reliability problems and the proposed project purpose is to solely improve output beyond the original design (improvement in functional situations), non-Federal funding is required to fund the project. It also may happen that a replacement is reliability-driven, Federally funded, and there is increased output which is primarily incidental to the reliability work.

7. Risk Analysis Using Reliability Curves

Historically, engineering judgment has been used to predict remaining unit life and determine the probability that the unit will perform unsatisfactorily. The Corps has embarked on a program to attempt to structure these predictions and determinations. Methods of determining reliability are well established for many types of physical properties. A useful way of expressing reliability for the Corps' economic evaluations is the annual probability that a piece of equipment will fail to perform satisfactorily. The following discussions explain the terms and their applications used in this process.

a. The following two functions are used in the development of reliability curves.

(1) The reliability of equipment can be considered a continuous variable with a probability density function (pdf) of *f*. A pdf is a theoretical model for the frequency distribution of a population of measurements. In this case regarding reliability, the pdf is the rate of change of the equipment dependability. Therefore, if the dependability of the equipment at age *a* is defined as:

$D(a) = P(A > a)$

where

A = age of the equipment at retirement

and

$P(A > a)$ = probability that $A > a$ (Ayyub, Kaminskiy, and Moser 1996)

Then the pdf of *D(a)* is

$$f(a) = \frac{dD(a)}{da} = D(a)$$

This simply states that the dependability of a piece of equipment is equal to the probability that the equipment is still functioning at age *a*.

(2) The hazard function H(*a*), or incremental failure rate associated with the random variable *A*, is given by:

$$H(a) = \frac{d\,\text{In}\,D(a)}{da} = -\frac{D\,(a)}{D(a)}$$

That is, the incremental failure rate is equal to the probability of the equipment life being age *a* divided by the probability of the equipment surviving to age *a* in the first place. It is the probability that the failure occurs at age *a*.

b. The Corps is continuing to assemble a large database of equipment histories to establish the reliability characteristics of various categories of equipment. The initial work in this area focused on generator stator windings because there have been a significant number of stator retirements in the form of rewinds (Ayyub, Kaminskiy, and Moser 1996), but a significant turbine database is also being developed. The historical data include many attributes such as year installed, age at failure, and rated capacity. Appendix F presents a review of recent research in hydropower reliability analysis. The raw data are compiled and reduced into annual summaries of exposures and failures.

c. The raw retirement data can be fitted using any number of means. One method is the application of Iowa Curves developed in the 1930's by the Engineering Experiment Station at what was then Iowa State College (Winfrey 1935). Other distribution functions that may be used include normal, exponential, log-normal, and Weibull. The Weibull distribution is one of the most widely used reliability functions. It has been shown that the differences between the Iowa Curves and a Weibull distribution are statistically insignificant. The Weibull distribution is much easier to adapt to computer analysis techniques. Research to develop new and more refined reliability functions continues.

d. The practice in Corps evaluation reports has been to use the hazard function directly if the condition of the specific equipment in question is considered average. If, however, the equipment has exhibited signs of premature or accelerated deterioration, the hazard function has been adjusted to account for the evident higher probability of failure. Similarly, the hazard function can be modified to account for lower failure probabilities for equipment that is in better condition than average. Contact the Hydroelectric Design Center (HDC) for the current details on modifying hazard functions.

e. Figure 1 is a plot of generator raw data showing the number of units performing satisfactorily given years in service or age. Figure 2 shows these data plotted as a reliability curve, with percent in service as the ordinate. Figures 3 and 4 then show these data fitted to a Weibull curve and the resultant hazard function, respectively.

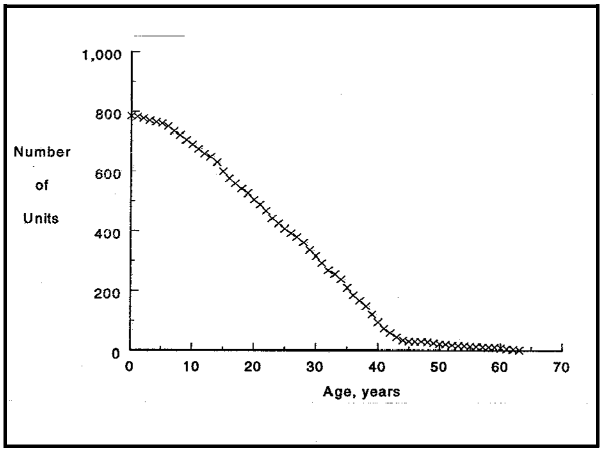

Figure 1. Generator stator windings. Number of units performing satisfactorily versus years in service

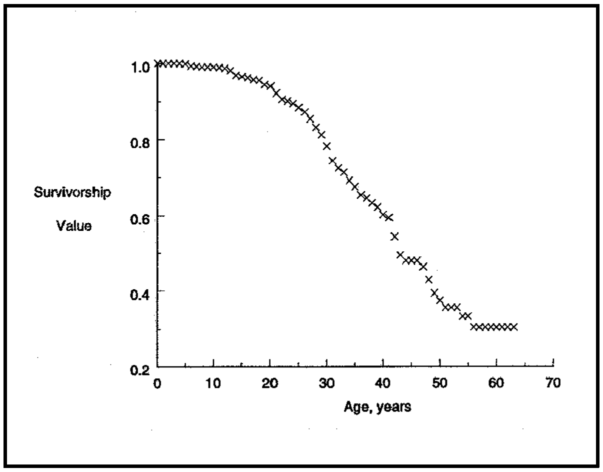

Figure 2. Generator stator windings. Reliability curve

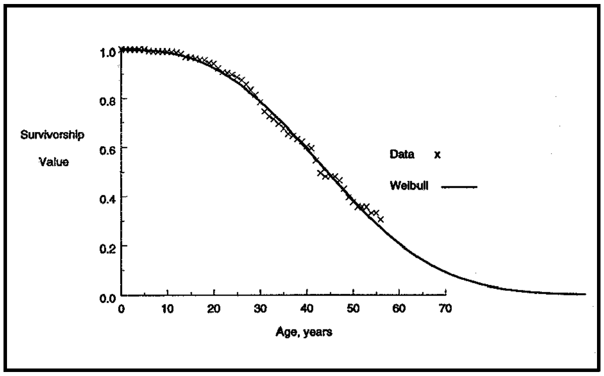

Figure 3. Generator stator windings. Weibull distribution

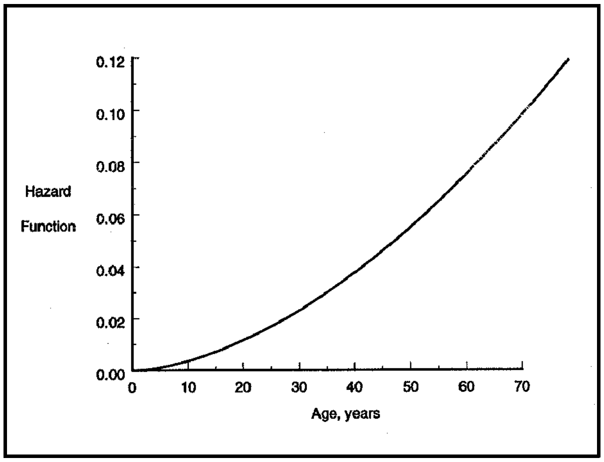

Figure 4. Generator stator windings. Hazard function from Weibull distribution

f. The factor being used by the Corps to evaluate equipment condition and modify the frequency curve data is the condition indicator (CI). Condition indicator evaluation methods have been developed by the Corps for many types of equipment and structures (USACE 1993). CI's are a screening tool which provides a uniform method of evaluating condition through testing and inspections. Inspection and test data are gathered and condition index numbers assigned for each unit in accordance with the latest guidance. Equipment with CI values from 70 to 100 is considered to be in very good to excellent condition. CI values in this range, when applied to the survivor curve, will tend to show increased reliability. Equipment with CI values in the midrange, from 40 to 69, is considered fair to good. The best prediction of this equipment's reliability is the statistical baseline data of similar equipment. Therefore, there is no cause to adjust the baseline frequency curve for equipment that falls into this category. Equipment with a CI below 40 is considered to be in poor condition or worse. CI values below 40 will tend to increase the probability of failure and the baseline frequency curve is adjusted. It is important to note that the methodology to be used in applying CI's to the reliability analysis is continuing to be developed. Current guidance should be sought by contacting HDC.

8. Risk Analysis Using Capacity and Demand

This method of determining the dependability of equipment uses a statistical approach toward determining both the demands placed on the equipment and its ability to handle those demands. This method is an adaptation of the structural reliability assessment methods described in ETL 1110-2-532. In this procedure, limiting states of hydropower equipment performance are written as a factor of safety equal to the quotient of the capacity and demand. The variables describing this capacity and demand are considered random, and estimates of means and standard deviations are made based upon experience. Estimates of the mean and standard deviation of the factor of safety are then made using a Taylor Series Finite Difference procedure. The reliability index of the equipment can then be estimated by approximating the distribution of factor of safety as log-normal. Mlaker (1993) and Mlaker and Bryant (1994) present technical details of this approach, along with an example. Their work is summarized in Appendix F.

9. Recommendations

It is recommended that the procedures contained herein be used as guidance toward assessing the reliability of hydropower equipment. This ETL should be utilized in a team effort involving Operations, Engineering, Planning, Project Management, and the HDC to contribute to the evaluation of rehabilitation or upgrade alternatives.

10. Additional Information

Much of the work that is covered by this ETL is still under development. The latest information can be obtained from the HDC in Portland, OR, telephone (503) 808-4225. Also, worldwide web sites containing information relating to the hydroelectric power industry are listed in Appendix G.

FOR THE COMMANDER:

7 Appendices
APP A - References
APP B - Reliability Study Process
APP C - Example Problem Description
APP D - Hydroelectric Power Benefits Calculations
APP E - Economic Models
APP F - Review of Recent Research in Hydropower Reliability Analysis
APP G - Worldwide Web Sites

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Chief, Engineering Division
Directorate of Civil Works

Appendix A
References

A-1. Required Publications

ER 1105-2-100
Guidance for Conducting Civil Works Planning Studies

ER 1130-2-500
Partners in Support (Work Management Policies)

EP 1130-2-500
Partners in Support (Work Management Guidance and Procedures)

EC 5-1-50
Corps-wide Centers of Expertise

EC 11-2-172
Annual Program and Budget Request for Civil Works Activities

ETL 1110-2-321
Reliability Assessment of Navigation Structures—Stability of Existing Gravity Structures

ETL 1110-2-532
Reliability Assessment of Navigation Structures

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Mlaker and Bryant 1994
Mlaker, P. F., and Bryant, L. M. 1994. Turbine Reliability. Final report to Contract DACAW39-94-C-0101 for U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

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U.S. Army Corps of Engineers. 1993. Condition Rating Procedures/Condition Indicator for Hydropower Equipment, REMR Management Systems; Hydropower Facilities. Washington, DC.

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A-2. Related Publications

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Appendix B
Reliability Study Process

B-1. A reliability analysis of hydropower plant equipment requires the following three basic steps: (a) data collection and investigations; (b) identification of specific reliability issues; and (c) calculations and evaluation. Figures B-1 and B-2 show the basic steps in a reliability study and the typical hydropower equipment analyzed for reliability.

a. The data collection and investigations need to be extensive and cover all aspects of the equipment design, use, history, and future demands. This step should include historical unit availability and operation, any equipment derating, accident reports, operation and maintenance records, equipment performance tests (original, interim, and current), periodic inspection reports, design and construction reports, the operation and maintenance manual, and turbine model test reports. During this step it is also important to identify the priorities and concerns of the project personnel and utilize engineering judgment in evaluating equipment condition. A thorough site investigation should be conducted by hydropower technical experts and should include equipment inspections and project personnel interviews.

b. The data should then be compiled and the primary equipment weaknesses and project concerns identified. The equipment condition may be quantified with the Condition Indicator (CI) value as defined in the REMR Condition Rating Procedures (USACE 1993). In addition to the CI value, the equipment operation, demands, and maintenance practices should be considered in evaluating the reliability. Experience and historical data of like equipment should be utilized in the determination of the equipment condition and future reliability.

c. Once the condition of the equipment has been identified, the calculations and evaluation should be performed. For equipment with extensive life databases, such as generators and turbines, standard time-dependent reliability and hazard functions should be used. These functions are under development by Institute for Water Resources (IWR) and HDC. Any of the weaknesses and concerns identified in the previous steps should be fully explained and addressed separately if required.

B-2. There may clearly be a failure history of specific equipment which warrants a reliability analysis separate from the remainder of the equipment. The generators at The Dalles powerhouse demonstrated a specific failure mode (coil failure from turn-to-turn faults) and a severe decline in reliability after fifteen years of age. Weibull curves were developed for the generators since the historical data of the fourteen units, for which there had been thirteen coil failures, constituted a sufficient database (USACE 1995). Specific equipment curves can be developed by adjusting the standard equipment curves if the equipment demonstrates accelerated degradation, such as was found at the Buford powerhouse. A reliability study of the Buford turbines found that the condition of the main unit turbines was typical for their age, but the station service unit showed severe degradation (USACE 1996). Therefore, it was reasonable to use the standard reliability and hazard functions for the main units and adjust these functions to reflect the poor state of the station service unit. If the equipment has a specific reliability problem but lacks a statistically significant base of data, a capacity versus demand analysis may be done. This approach was appropriate for the reliability analysis of the Walter F. George powerhouse. The turbines were found to have two areas which warranted further assessment, the shaft sleeve and hub, so JAYCOR was contracted to provide a full report (Mlaker and Bryant 1994).

B-3. To obtain the most current time-dependent reliability research results, contact the HDC.

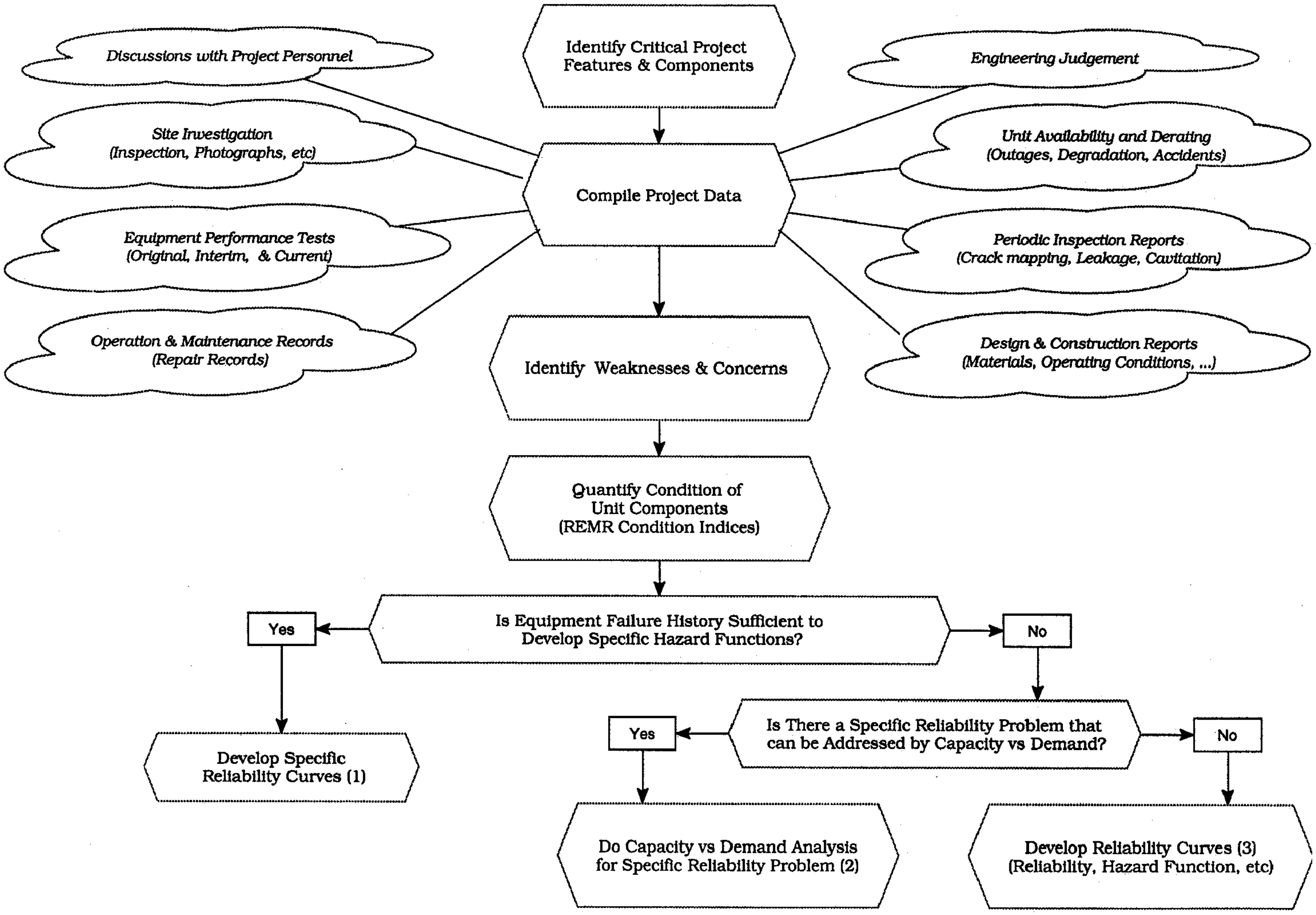

Figure B-1. General process for evaluating hydropower equipment reliability

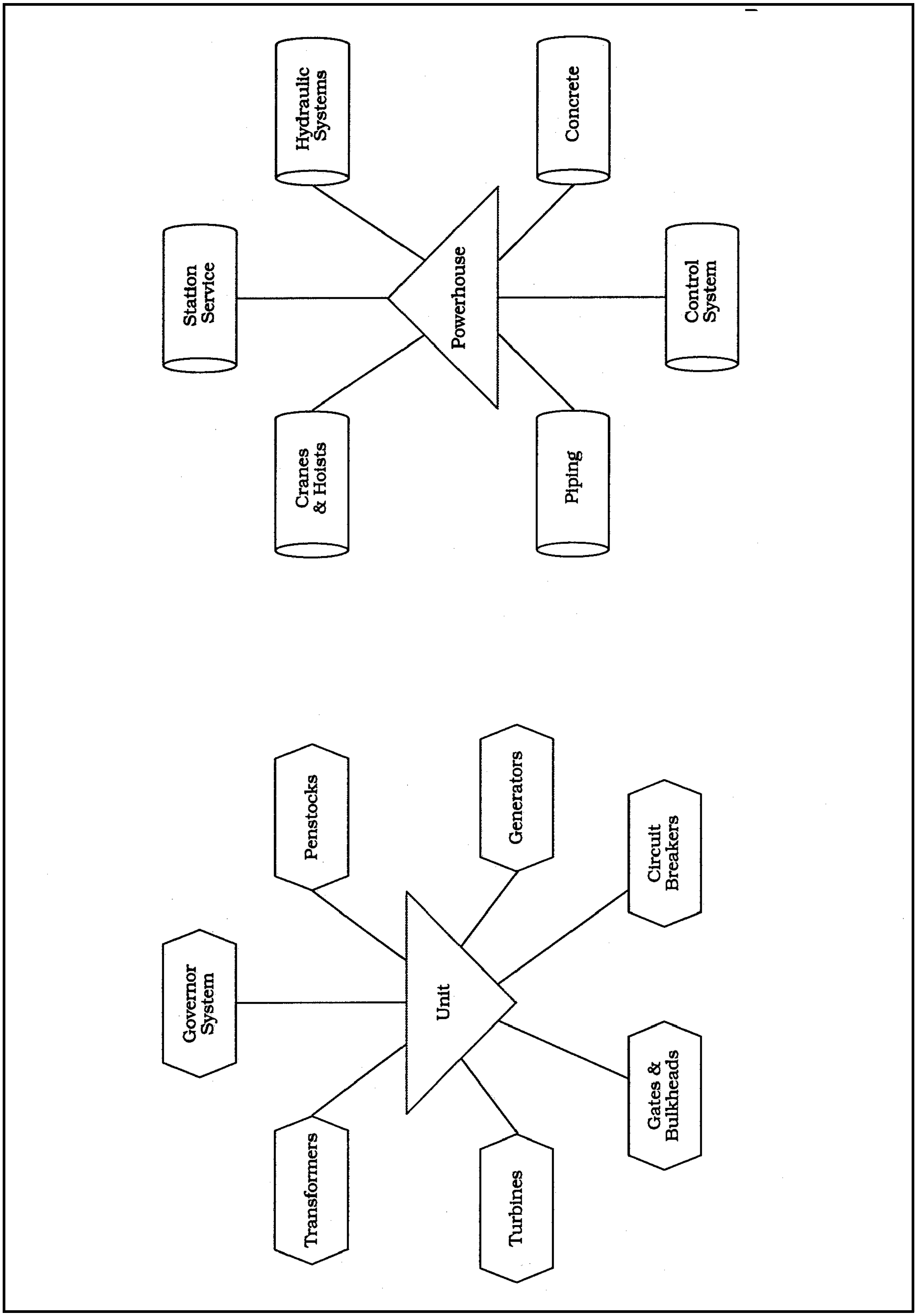

Figure B-2. Typical hydropower equipment analyzed for reliability

Appendix C
Example Problem Description

C-1. In order to discuss the engineering reliability analysis, the hydroelectric power benefits analysis, and the economic modeling process, a brief overview of an example rehabilitation project is warranted.

C-2. The "Chapman Hydroelectric Power Project" consists of a single powerhouse with four Francis turbines that were placed into service beginning in 1947. The total rated capacity is 200 megawatts (MW). There are two three-phase generator step-up transformers, each serving two generating units. The plant is a storage project located in the southeast portion of the United States. There is a relatively small variation in lake elevation due to seasonal flows and the need for flood protection. The storage in the lake is very large in relation to the flow in the river. Therefore, all of the flow into the lake either evaporates or passes through the turbines for power production. The plant factor is 25 percent.

C-3. Problems include turbine runner cracking, severe cavitation damage, generator coil degradation, and deterioration of the generator step-up transformers. Over the past 10 years, the turbine runners have exhibited increased cracking. On three separate occasions, pieces of the buckets have broken off. An enhanced maintenance program was instituted. This program, which includes more frequent inspections and welding repair, has prevented further breakage. However, cracking and cavitation damage continue to increase at an accelerated rate. Deterioration of coil insulation has caused coil failures in three of the four generators in the last two years. Spare generator coils are not available, and there is no spare transformer. Unsatisfactory performance of either the generator or turbine runner will cause a unit outage. Unsatisfactory performance of a transformer will cause an outage of two units. Field testing has shown that the units have experienced an efficiency loss from their original condition. Average unit availability has also deteriorated from 95 percent 10 years ago, to 93 percent 5 years ago, and to 88 percent this year.

Appendix D
Hydroelectric Power Benefits Calculations

D-1. General

Traditionally, the economic feasibility of a hydroelectric project is determined by comparing the cost of the hydroelectric project to the cost of the most likely thermal alternative. In other words, is the cost of constructing and operating a hydroelectric project less than the cost of obtaining the power from the thermal power plant(s) that would be the most likely source of that power if the hydroelectric plant were not built?

D-2. Energy vs. Capacity Benefits

The following two parameters define hydroelectric project output: energy (the total amount of generation in a given time period, expressed in megawatt-hours (MWh)); and capacity (the maximum amount of power that can be delivered at any given moment, expressed in megawatts (MW)).

a. Energy benefits are measured by the cost of producing an equivalent amount of generation in the power system with the hydroelectric plant replaced by the most likely thermal alternative. The energy benefits represent the variable costs associated with producing the alternative thermal generation, which are primarily fuel costs.

b. Capacity benefits are measured as the cost of constructing an equivalent amount of thermal power plant capacity. The capacity benefits represent the capital costs and other fixed costs associated with the most likely thermal alternative.

D-3. Gain in Output Resulting from Rehabilitation Projects

The Chapter 3 of the ER 1130-2-500 establishes the policy for major rehabilitation at completed Corps projects. The Chapter 3 of the EP 1130-2-500 established guidance for the preparation and submission of Major Rehabilitation Projects Evaluation Reports for annual program and budget submissions. They should be consulted for the most recent policy on types of improvements that can be pursued under the Major Rehabilitation program and the basic assumptions for the economic analysis. The following discusses the benefit computations for the various types of improvements.

a. The first step in estimating the benefits is to determine the gain in power output that will be realized from the proposed rehabilitation plan. Rehabilitation measures can be grouped into five categories, based on the way in which they increase hydroelectric power project output:

(1) Those which restore lost efficiency.

(2) Those which restore lost capacity.

(3) Those which restore lost availability.

(4) Those which increase the remaining service life (reduce the probability of retirement).

(5) Those which increase a plant's operating flexibility.

b. Replacing the worn turbine runners is a measure that restores lost efficiency. The primary benefit of this type of rehabilitation is increased energy production. Incidental increases in efficiency can also be included in the benefits calculations. Increasing efficiency beyond that of the original equipment can be part of a rehabilitation project, but current guidance limits it to incidental or funded by non-Federal sources. Contact CECW-B for current policy regarding non-Federal funding of generation improvements.

c. Rewinding the generators with state-of-the-art materials often permits the units to operate at higher output levels. This would be an example of a capacity-increasing measure. Current guidance should be consulted to determine to what extent increased capacity can be funded under Major Rehabilitation funding. The incremental costs of improving generator capacity beyond the original project level are often very small and can in many cases be supported under the Major Rehabilitation program.

d. Replacing runners and rewinding the generators will also improve the unit availability and increase remaining service life. All of these benefits should be taken into consideration.

e. Replacing a Kaplan unit with an unreliable blade adjustment mechanism can improve the unit's response to changes in load and increase plant's flexibility.

D-4. Example

The easiest way to describe the benefit evaluation process is to walk through an example of a typical rehabilitation project. The proposed plan for the fictional "Chapman"project includes replacing all four worn turbine runners with new runners and rewinding the generator stators (Appendix C).

a. It will be assumed that when the original runners were new, the units had an average overall efficiency of 87 percent, and tests have shown that, in their current condition, the overall efficiency has dropped to 84 percent. With new runners, it is estimated that an average efficiency of 89 percent could be achieved. However, the rated capacity of the turbines remains the same.

b. The rated capacity of the original generators was 50 MW. By rewinding the generator stator with state-of-the-art materials, the rated capacity of the generators can be increased to 60 MW, which now matches more closely the maximum capability of the turbines.

D-5. Duration Curve

To graphically display the amount of energy that could be gained from a rehabilitation measure, a generation-duration curve will be used. The curve could be developed using historical records or output from a sequential streamflow routing model such as HEC-5.

a. Table D-1 shows the output of the plant by unit, and Figure D-1 shows the annual generation-duration curve for the example plant for the available period of streamflow record based on the existing condition of the plant. The duration curve in this case is based on weekly average streamflow data from a 60-year simulated operation study. Since this is a weekly average it does not reflect the effect of peaking operation. This would require an hourly generation-duration curve, which would have the same area under the curve but would show more operation at or near full output and less operation at low output levels.

b. However, for purposes of estimating energy output, a curve based on average daily, weekly, or monthly output should be used rather than an hourly curve. The use of average values is necessary to measure the amount of energy that would otherwise be spilled if the rehabilitation measure were not implemented.

c. The horizontal line at the top of the duration curve defines the maximum capacity of the plant,

Table D-1
Plant Output

Unit	Unit Capacity MW	Cumulative Capacity MW	Unit Energy MWh	Cumulative Energy, MWh
1	50	50	412,000	412,000
2	50	100	254,000	666,000
3	50	150	112,000	778,000
4	50	200	23,000	801,000

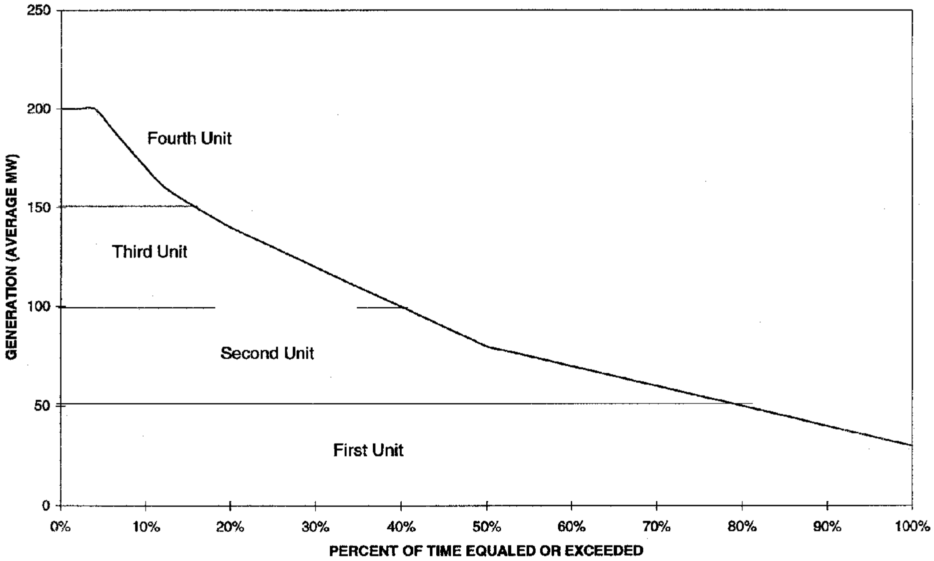

Figure D-1. Annual generation-duration curve

which in this case is 200 MW, the combined capacity of the four existing generators.

D-6. Energy Gained by New Runners

Figure D-2 describes the gain in energy achieved by replacing the worn existing turbine runners with new state-of-the-art runners. The middle curve shows the output when the original runners were new (overall efficiency of 87 percent), and the lower curve shows the output with the original runners in their existing, worn condition (overall efficiency of 84 percent). The upper curve shows the output with new state-of-the-art runners (overall efficiency of 89 percent). The area between the upper and middle curve represents the gain in energy creditable to the new runners. The upper and middle curves were derived by applying efficiency adjustment factors to each of the points that were used to derive the existing case (Figure D-1) generation-duration curve. They could also be derived through additional simulation studies with a routing modelsuch as HEC-5.

Energy output with original runners when new	828,000 MWh
Energy output with existing original runners	801,000 MWh
Energy output with new runners	<u>845,000 MWh</u>
Gain in energy output	44,000 MWh

Note that the capacity of the existing generators limits output to a maximum of 200 MW. So, even if the new runners had a somewhat greater megawatt capability, it would not be possible to take advantage of that capability.

D-7. Energy Gained by New Generator Windings

a. Figure D-3 describes the gain in energy achieved by rewinding the stators with state-of-the-art insulation materials. The new materials make it possible to place more copper in the windings, which increases the capacity of the generators. In this example, it is assumed that the

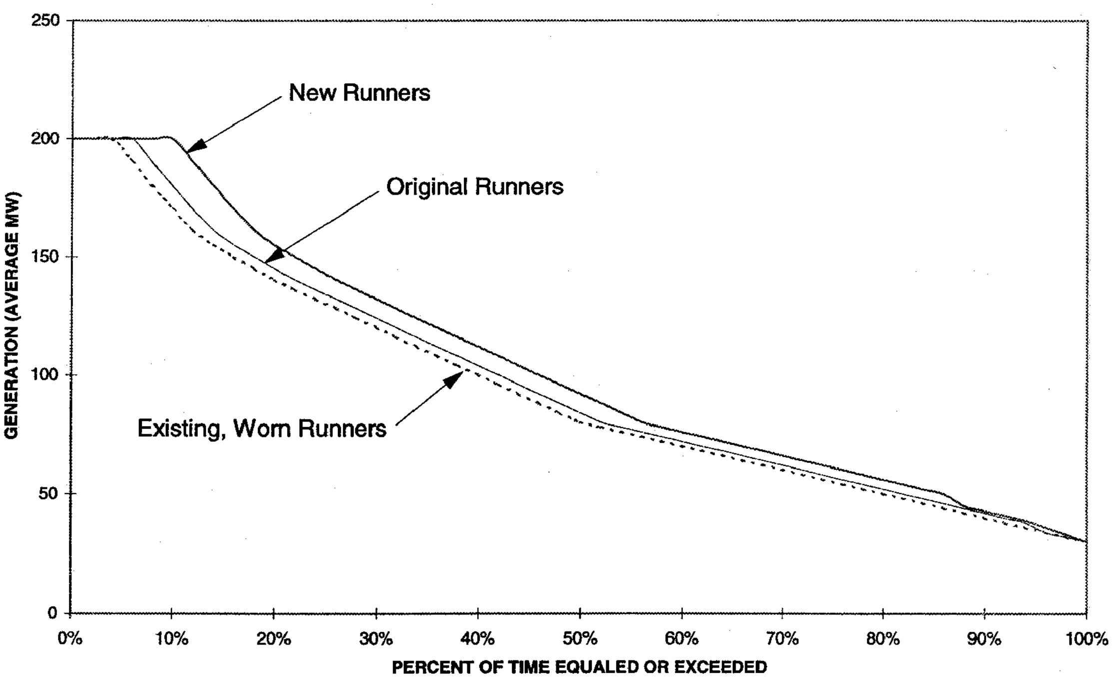

Figure D-2. Energy gain, replacing runners

new runners are in place and the capacity of the generators can be increased to match the full output of the new runners. As a result, the capacity of the plant is increased to (4 units × 60 MW) = 240 MW.

b. The upper limit (which truncates the duration curve) is increased from 200 MW to 240 MW, so the generation-duration curve was extended to the new upper limit. The upper hatched area on Figure D-3 defines the gain in energy output realized from adding a generator rewind to turbine runner replacement.

Energy output with existing generators	845,000 MWh
Energy output with generator rewind	861,000 MWh
Gain in energy output	16,000 MWh

Note that a gain in generation could also be realized by rewinding the generators but retaining the existing turbines. The upper hatched area would be smaller, being defined by an extension of the lower curve on Figure D-2 rather than the upper curve. The gain in energy for this scenario would be 4,000 MWh instead of 16,000 Mwh.

D-8. Energy Gained by Improved Availability

a. The major rehabilitation guidance prescribes the approach to evaluating the unit availability. Major elements in this analysis are the assumptions that are used to define the base condition, or the “without major rehabilitation” condition. The base condition assumes that the project will be operated in the most efficient manner possible without the proposed rehabilitation. Should the project experience unsatisfactory performance (e.g., a hydroelectric power unit outage), it is assumed that emergency funds will be available to fix the feature. The timing, frequency, and consequences of system disruptions are all unknown and must be estimated for both the with and without project conditions.

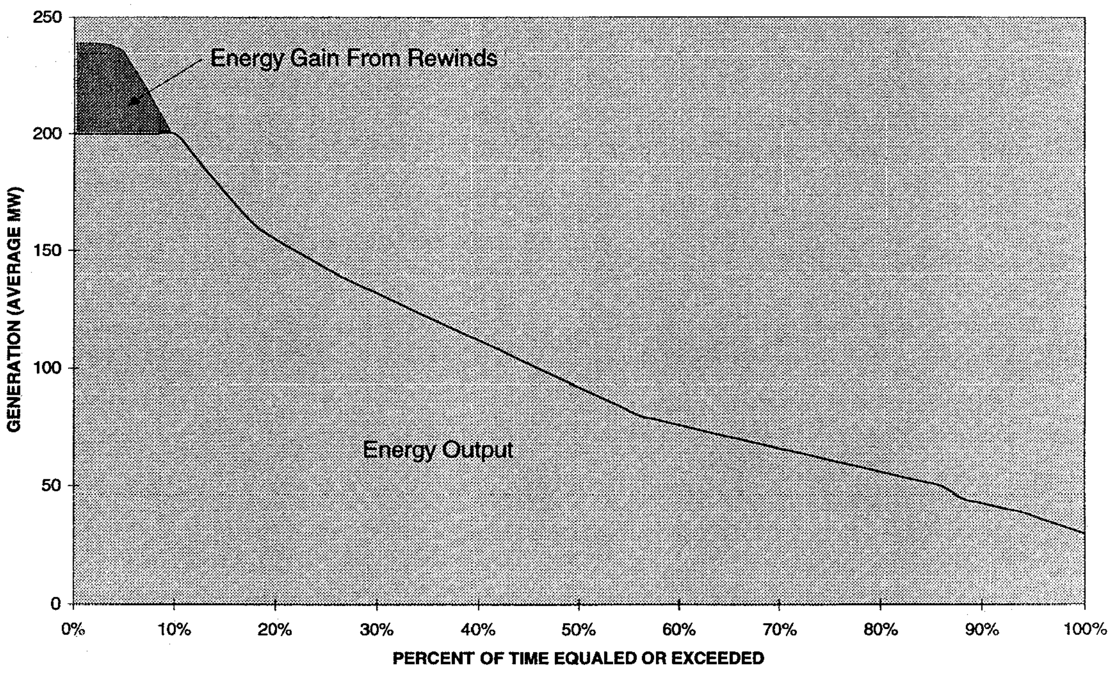

Figure D-3. Energy gain, rewinding stators

b. Both the new runners and the generator rewind could contribute to improved availability for the plant. Replacing old, failure-prone components with new components usually reduces the amount of time generating units are out of service due to forced outages. This in turn increases the amount of generation the plant can produce.

c. Figure D-4 illustrates the concept of generation loss due to forced outages. The shaded area represents the generation that would be lost if forced outages kept one unit out of service one-third of the time (high value assumed for illustrative purposes only; forced outage rates for hydroelectric plants are typically less than 10 percent). A rehabilitation measure which reduces the outage rate would reduce the size of this area, thus increasing energy output. The process of computing the loss in energy due to outages is rather complex because it is necessary to account for the combined probability characteristics of multiple components (turbine runners and generator windings, for example), the combined probabilities of different numbers of units being out of service, and the fact that component reliability tends to decrease with age. In addition, it is necessary to account for the length of the outage and the cost of repair. In order to account for all of these factors, event tree models have been developed for estimating the energy benefits attributable to reliability improvements. This topic is discussed in more detail in Appendix E. However, for purposes of illustration, it is assumed that the combined gain in average annual energy benefits due to improvement in the availability of the turbines and generators is $750,000.

D-9. Computation of Energy Benefits

The average annual gain in energy benefits that accrues to a rehabilitation plan is computed by applying a unit energy value to the gain in energy creditable to that plan. Assuming an energy value of $28/MWh, the gain in energy benefits for the runner replacement and generator rewind measures would be as follows:

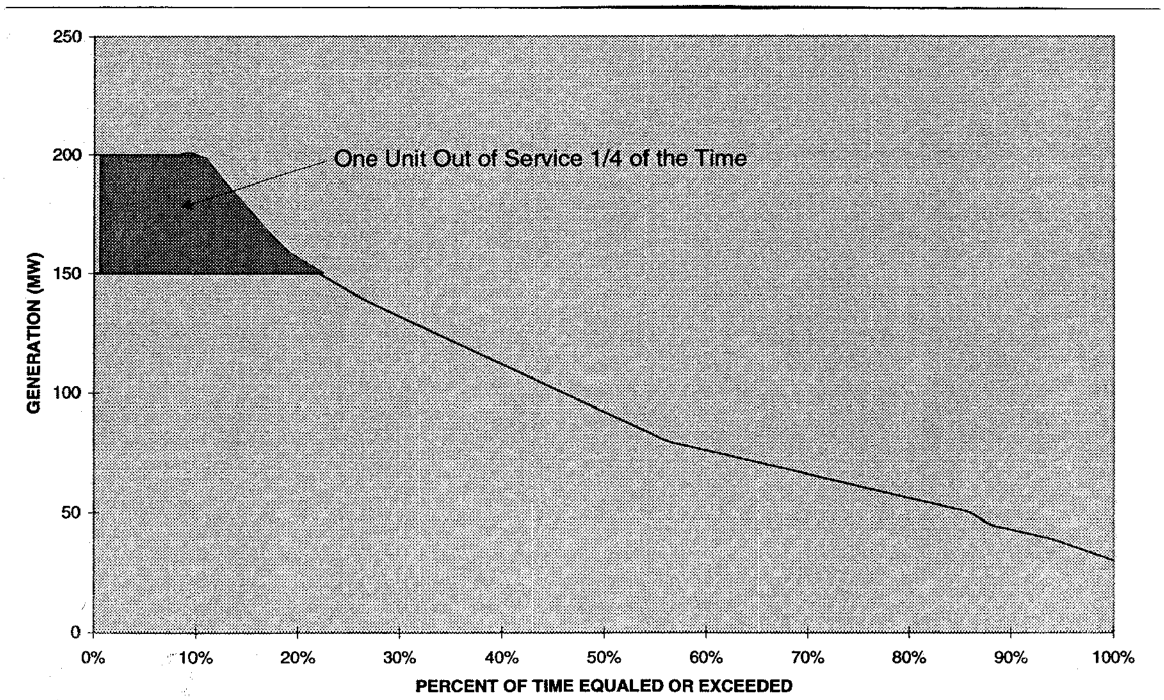

Figure D-4. Generation loss due to forced outages

Runner replacement benefits		
(44,000 MWh x $28/MWh)	=	$1,232,000
Generator rewind benefits		
(16,000 MWh x $28/MWh)	=	448,000
Availability benefits	=	750,000
Total energy benefits	=	$2,430,000

The unit energy values represent the energy cost associated with producing the generation with the most likely thermal alternative or alternatives. The energy value of $28/MWh is based on the energy values provided from the Federal Energy Regulatory Commission (FERC) for coal-fired steam, and gas-fired combustion turbines and combined cycle plants. The value is based on weighted national values by fuel source and inclusion of estimated real fuel cost escalation. The energy value is in terms of October 1995 price levels. The Corps usually develops these values using a system production cost model, simulating the operation of a particular power system twice: once with the hydroelectric plant in the system, and once with the hydroelectric plant replaced with an equivalent number of megawatts of thermal capacity. The different nature of power systems, loads, and fuel costs throughout the nation requires site-specific evaluation for each major rehabilitation study.

D-10. Dependable Capacity

a. The dependable capacity of a hydroelectric power plant is an estimate of the amount of thermal generating capacity that would carry the same amount of peak load in a power system as the hydroelectric power plant. It is intended to account for the variables that affect the amount of hydroelectric power capacity that can be used effectively in the system load, including the following:

(1) The variability in the maximum capacity that a hydroelectric power plant can deliver caused by variations in head.

(2) The variability in usable capacity caused by variations in the availability of streamflow, which in turn causes variations in the amount of energy available to support the capacity.

b. A variety of different techniques are used to estimate dependable capacity. The Corps presently uses the average availability method for projects which operate in thermal-based power systems and the critical month method for projects in hydroelectric-based power systems.

c. For this example, the average availability method was used. Space does not permit a detailed discussion of the procedure, but, in brief, it involves computing the amount of capacity that can be supported with the available energy for each week in the peak demand months for each year in the hydroelectric period of record. The average capacity that can be supported over that period defines the project's dependable capacity.

d. Supportable capacity is defined as the amount of capacity that can be supported for a specified number of hours per week. The number of hours required varies from project to project and from system to system, depending on the system resource mix and hourly load shape. A typical example might be 4 hours per day, 5 days per week (or 20 hours per week).

e. Some examples will illustrate this concept. Taking the 200-MW example project and using the 20-hr/week criterion, assume that in a particular month, sufficient stream flow is available to produce 5,000 MWh/week. Applying the 20-hr criteria, (5,000 MWh)/(20 hr/week) = 250 MW could theoretically be supported. However, the installed capacity of the plant is only 200 MW, so the supportable capacity for that month is limited to 200 MW. However, if the generators were rewound to 240 MW, the supportable capacity would increase to 240 MW. Assume that in another month, 3,000 MWh/week can be generated. In this month, only (3,000 Mwh)/(20 hr/week) = 150 MW can be supported, either with or without the rewind.

D-11. Dependable Capacity Gained by New Runners

The amount of energy available in each week will be increased due to the higher runner efficiency. In some weeks, sufficient energy is already available to support the existing capacity. But in some of the lower flow weeks, this additional energy will permit more capacity to be supported. The average gain in capacity over all of the peak demand weeks in the period of record defines the gain in dependable capacity attributable to the new runners. Typically, this gain is relatively small for runner replacement, and for this example, the new runners increase the dependable capacity from 185 MW to 190 MW (compared with an installed capacity of 200 MW).

D-12. Dependable Capacity Gained by Generator Rewind

The generator rewind increases the maximum capacity of the plant. This in turn permits more capacity to be supported in those weeks where more energy is available than is needed to support the existing capacity. In the example case, if the generator capacity is increased by 40 MW, the dependable capacity increases from 190 MW to 226 MW (compared with the new installed capacity of 240 MW).

D-13. Computation of Capacity Benefits

a. The average annual gain in capacity benefits that accrues to a rehabilitation plan is computed by applying a unit capacity value to the gain in dependable capacity creditable to that plan. Assuming a capacity value of $95/kW-year, the gain in capacity benefits for the runner replacement and rewind measures would be:

Runner replacement benefits		
(5,000 kW x $95/kW-year)	=	$ 475,000
Generator rewind benefits		
(36,000 kW x $95/kW-year)	=	<u>$3,420,000</u>
Total capacity benefits	=	$3,895,000

b. The unit capacity values represent the investment cost associated with delivering the replacement capacity with the most likely thermal alternatives. The $95/kW-year capacity value is based on a mix of coal-fired steam plants, gas-fired combined cycle plants, and gas-fired combustion turbine plants, weighted by the Energy Information Administration's projections of future capacity additions nationwide. The Corps usually obtains these values from the FERC, although they can be developed from data published by the Electric Power Research Institute (EPRI) and other sources.

D-14. Increase in Capacity Benefits Realized by Increased Availability

a. Although improving the electrical-mechanical reliability of hydroelectric generating units clearly increases the peak load-carrying capability of the units, it has proven difficult to quantitatively estimate the benefits realized from this gain. However, a relationship of generating unit average availability to effective load-carrying capability has been developed.

$$ELCC = C - \{M * \ln[(1 - R) + (R * e^{C/M})]\}$$

where

ELCC = effective load-carrying capability of unit, MW

C = rated capacity of that unit, MW

M = system characteristic (typically, 3 percent of total system capacity), MW

R = unit's equivalent forced outage rate, percent

e = 2.718

b. Using this equation, effective load carrying capabilities (ELCC's) can be developed for each unit size and each forced outage rate associated with the different proposed rehabilitation measures or plans. Ratios of ELCC are developed by dividing the ELCC for a proposed measure by the ELCC for the capacity value developed by FERC. The ratios of ELCC can then be applied to the unit capacity values to estimate the gain in capacity benefits that apply to the proposed rehabilitation measure or plan. The capacity values, as developed by FERC, already include a factor which accounts for the average availability of a typical hydropower unit compared with a thermal generating unit. For the example study, assume that the $ 95/kW-year FERC capacity value is based on a typical hydro unit availability of 93 percent, and the availability of the units in their existing condition is 91 percent. Assume that the turbine runner replacement increases the availability to 93 percent, and adding the generator rewind increases it to 95 percent. These availability values would be obtained from reliability studies.

c. While these capacity value adjustments are small, they apply to the entire dependable capacity of the plant, so they result in substantial benefits. Table D-2 summarizes the calculation of the increase in capacity unit values based on the ELCC ratios. The table also provides total benefits attributable to both the increases in dependable capacity and increases in reliability.

Table D-2
Increase in Capacity Benefits

Case	Dependable Capacity MW	Capacity Value $/kW-year	Total Benefits ($1,000)	Incremental Benefits ($1,000)
Existing	185	93	17,200	--
New Runners	190	95	18,050	850
+ Rewind	226	97	21,900	4,700

d. Subtracting out the previously calculated benefits for the gains in dependable capacity, the gain in capacity benefits as a result of improved reliability is $375,000 ($850,000 - 475,000) for the new runners alone, and $805,000 ($4,700,000 - 3,895,000) for the combined plan of new runners plus rewind.

D-15. Benefits from Increasing Remaining Service Life

The hydroelectric power benefits accruing from replacing equipment before it fails are limited to the differences in unit outage times. A planned rehabilitation program will substantially reduce the time that a unit is out of service when compared with waiting for a major equipment failure.

D-16. Flexibility Benefits

a. An additional area where benefits might accrue to power plant rehabilitation is in the area of flexibility—the ability of a power plant to come on-line quickly and to respond rapidly to changes in load. An example might be a plant with aging Kaplan units which have deteriorated to the point where the turbine blade adjustment mechanism can no longer be operated reliably. In such cases, the blades may have to be welded in a fixed position so that they lose their ability to follow load. Rehabilitating the units would restore this capability, and this in turn would generate some benefits which could be used to help support the investment in the rehabilitation work.

b. Unfortunately, while it is widely agreed that flexibility benefits are an important hydroelectric project output, it is difficult to quantify such benefits. EPRI and others have done some work in this area, but so far an accepted procedure for quantifying flexibility benefits does not exist. However, if a proposed rehabilitation project does improve a project's flexibility, this should at least be addressed qualitatively in the rehabilitation project feasibility report.

D-17. Total Gain in Benefits

The total annual power benefits attributable to the combined runner replacement/stator rewind plan would be as follows:

Energy benefits	=	$2,430,000
Capacity benefits	=	<u>$4,700,000</u>
Total benefits	=	$7,130,000

D-18. Last-Added Test

a. Standard economic practice requires that separable components of multi-component plans be incrementally justified on a last-added basis. For instance, the example rehabilitation plan includes two components. For the plan to be economically feasible, both runner replacement and generator rewind would have to be individually justified on a last-added basis. This assures that the plan with the highest net National Economic Development benefits (i.e., benefits-costs) is identified, as called for in ER 1105-2-100.

b. Last-added analysis refers to a comparison of the incremental benefits gained by one component of a plan on a last-added basis, with the incremental costs of including that component in the plan. The last-added benefits for a component are determined by deducting the benefits of a plan with that component excluded from the benefits of the plan with all components included. Again referring to the example, the last-added benefits of the generator rewind would be the benefits of the total plan minus the benefits of runner replacement alone. A similar process would be followed to determine the incremental benefits of the runner replacement. Once incremental benefits are determined, they are compared to the incremental costs of including the component. If the incremental benefits exceed the incremental costs, the component is justified on a last-added basis.

D-19. Analysis Tools

Various computer analysis tools have been developed to assist in the evaluation of Major Rehabilitation and O&M repair projects. Examples of these are Hydroelectric power-REPAIR and HYDROELECTRIC POWER QUADRANT being developed through the Corps of Engineers Institute of Water Resources (CERD-IWR-R). Life-cycle, risk models have been developed by other districts such as the Portland District and Mobile District, for evaluation of Major Rehabilitation projects. These models are conceptually described in Appendix E that follows. Assistance in evaluation of the potential project benefits can be received from the Power Branch (CENPD-ET-WP) of the North Pacific Division, which is the designated Corps-wide Mandatory Center of Expertise for Hydroelectric Power System - Economic Evaluation (EC 5-1-50).

Appendix E
Economic Models (Event Trees)

E-1. General

Engineering reliability analysis coupled with traditional engineering judgment offers a more effective and objective way of identifying future events and consequences than engineering judgment alone. Detailed economic studies including risk and uncertainty analysis provide decision makers with a more comprehensive picture of the range and likelihood of the economic consequences of any particular project proposal. This appendix provides guidance for the use of event trees and incorporating engineering reliability and hydropower benefits studies in the economic analysis of major rehabilitation projects.

E-2. Event Trees

An event tree is simply a diagram of the potential events and outcomes that could occur to a given component or group of components in one time period or in subsequent time periods.

a. Event tree diagrams are used to identify possible occurrences of satisfactory or unsatisfactory performance and their consequences, given specific events. For example, a mechanical/electrical component such as a turbine runner or a generator, during any time period, may be fully operational, out of service from a prior period, or exhibiting unsatisfactory performance.

b. These possible events or branches of the tree identify all of the pathways that may occur during each time period. The event tree is developed for each component to be evaluated for each time period of the analysis.

c. The consequences of each pathway are also identified. The consequences may consist of changes in system hydropower generation costs due to unit outages or changes in unit generating efficiencies, increases or decreases in operation and maintenance costs, or changes in repair or replacement costs.

d. The event tree also facilitates coordination of the engineering reliability analysis with the economic evaluation. In the Corps' planning framework, the event tree assists in developing a clear definition of the without-project condition. For major rehabilitation studies, the without-project condition is a description and evaluation of the consequences that are expected to occur during the period of analysis in the absence of rehabilitation. Use of event trees requires planners (and project engineers) to graphically depict what is expected to happen to various components in any given time period. This process helps clarify critical elements and possible solutions. It highlights any apparent data gaps and serves as a road map for building the economic spreadsheet model.

E-3. The Economic Model

In its most simplistic form, the economic model that is developed for a major rehabilitation analysis could be described as a basic accounting spreadsheet. In its final evolution it can span many megabytes of computer disk space and devour hundreds of hours of computer time. The Institute for Water Resources (IWR) has developed, and is continuing to improve, a PC-based program that will handle the economic modeling requirements much faster and easier than using spreadsheet-based software. The basic spreadsheet model is described below because it is relatively easily understood.

a. The spreadsheet model is first created to mirror the single unit event tree diagram for the without-project condition. This incorporates both the physical and economic consequences of possible events and the engineering reliability analysis for each component. A Monte Carlo simulation procedure is used to calculate variance and expected values.

b. Monte Carlo simulation is a process in which random numbers are generated from a range of possible values, usually between zero and one,

Appendix F
Review of Recent Research in Hydropower Reliability Analysis

F-1. Introduction

This appendix presents a summary of recent research related to hydropower reliability analysis that may be useful in conducting maintenance and rehabilitation studies.

F-2. Reliability Analysis of Hydroelectric Power Equipment

a. In this study an assessment method of the time-dependent reliability and hazard functions of hydropower equipment is developed (Ayyub et al. 1996). Life data of equipment can be classified into several types. For hydropower equipment, complete data or right censored data are commonly encountered. The 1993 inventory of generators as provided by the Corps includes records of failure and replacement. A preliminary examination of these records revealed that the average age at failure is 28 years. Also, the average age of equipment based on this 1993 inventory is 24 years. Generators were grouped by plant-on-line date and power into 12 groups. The life data of generators within each group were analyzed. Survivorship functions were developed, and models based on nonlinear numerical curve fitting using an exponential function with a second-order polynomial tail were proposed. Early-life special models and late-life prediction (extrapolation) models were also developed. The effect of manufacturer on generator reliability was investigated. It can be concluded that the differences between the survivorship values of the General Electric Corp. and the Westinghouse Corp. generators are, in general, statistically insignificant.

b. The above-mentioned reliability and hazard functions can be viewed as marginal functions that do not account for the particular condition of a piece of equipment, but they provide average or generic results for a group or stratum. In the practical use of hazard functions in investment decision analysis, a generic function might not be sufficient for a particular piece of equipment. Hence, the generic function needs to be modified by conditioning on a particular piece of equipment, resulting in a modified hazard function. By conditioning on a particular piece of equipment, the physical or performance condition of the equipment is introduced as a factor for modifying the generic function. The Corps maintains information on test results of a particular piece of equipment that are aggregated to obtain a condition index. The test results and the condition index are needed to perform this modification.

c. Once a generic hazard function and a condition index are obtained for a particular piece of equipment, they can be combined to obtain the modified hazard function using Bayesian techniques. Reliability functions were developed for groups of generators that were defined by the date of having the plant on line and the power rating of the generators. The resulting reliability functions are called herein the group reliability functions. These reliability functions can be used as prior information in the Bayesian techniques to obtain plant-specific reliability functions by utilizing new plant information on generator failures or censoring to obtain plant reliability functions as posterior reliability functions. Alternately, plant reliability functions can be developed using the same methods that were used for the groups to obtain prior plant reliability functions. Then, new plant information on generator failures or censoring can be utilized to obtain updated plant reliability functions as posterior reliability functions. These two cases have the common objective of obtaining plant-specific reliability functions and updating these functions using new life or censoring data. Then, a method is presented to obtain a unit (i.e., generator) specific reliability function based on a plant (or group) reliability function based on obtaining either censoring information or the condition index of the unit. Examples were used to demonstrate the use of these methods.

d. The suggested methods in this study were demonstrated using hydropower generators. Other similar hydropower equipment types can be treated using similar methods.

F-3. Repair, Evaluation, Maintenance and Rehabilitation (REMR) Program

a. The REMR research program is a 13-year, $67M research effort undertaken from 1984 through 1997. The objective of the program was to identify and develop effective and affordable technology for maintaining and extending the service life of civil works structures. REMR products are useful in both major rehabilitation and nonroutine maintenance studies. The paragraphs below summarize some of the REMR products that have been used in reliability studies (U.S. Army Corps of Engineers 1993).

b. The REMR Management System is a computer-based system for managing REMR activities. It is designed as a planning tool and an information system for project-level management. It establishes procedures to inspect and evaluate the conditions of civil work structures, provides data management capabilities, and facilitates some economic analysis of maintenance alternatives. The REMR Management System was designed to help prioritize REMR activities based on equipment condition, select maintenance alternatives based on performance, and compare the costs of maintenance alternatives.

c. Any decision which determines how to allocate rehabilitation dollars should be based on reliability data. An attempt to collect these data in the past was made by collecting data on the current condition of equipment. This collection process, if continued over time, could be used to develop life history data and could then be used to develop failure rate and reliability data. The Hydroelectric Power Equipment Condition Indicators program was developed as the methodology used to collect equipment condition data (Norlin et al. 1993). This program established a measure of equipment condition called the condition index with an associated REMR Condition Index (CI) scale (see Table F-1) which may be a key step in the development of a reliability centered nonroutine maintenance program. The program also developed the methodology used to objectively determine the CI for (1) generator stators, (2) excitation systems, (3) circuit breakers, (4) main power transformers, (5) powerhouse automation systems, (6) turbines, (7) thrust bearings, (8) governor systems, (9) cranes and wire rope gate hoists, (10) hydraulic actuator systems, (11) emergency closure gates, and (12) power penstocks.

d. The CI for a piece of equipment is determined by evaluating a “condition indicator” which consists of standard tests or visual or other nondestructive examinations. The CI for a component or system ranges from 0 to 100, where 0 index indicates the component/system is in completely deteriorated condition, and an index of 100 indicates the component/system is in new condition.

Table F-1
REMR Condition Index Scale

Zone	Condition Index	Condition Description	Recommended Action
1	85 to 100	Excellent: No noticeable defects. Some aging or wear may be visible.	Immediate action is not required.
	70 to 84	Very Good: Only minor deterioration or defects are evident.	
2	55 to 69	Good: Some deterioration or defects are evident, but function is not significantly affected.	Economic analysis of repair alternatives is recommended to determine appropriate action.
	40 to 54	Fair: Moderate deterioration. Function is still adequate.	
3	25 to 39	Poor: Serious deterioration of at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, rehabilitation, or reconstruction.
	10 to 24	Very Poor: Extensive deterioration. Barely functional.	Safety evaluation is recommended.
	0 to 9	Failed: No longer functions. General failure of a major structural component.	

e. The CI does provide objective information about the current condition of the equipment, but it is difficult to determine a failure rate from a CI. In addition to the CI value, there are other measurements (such as hours of usage, severity of usage, routine maintenance practices, and manufacturer) that are important in accurately determining service life and predicting failure rates.

F-4. Reliability of Hydroelectric Power Equipment Study

A reliability study of hydroelectric power equipment was conducted by JAYCOR at the request of the COE (Mlakar 1993). In this study, a Weibull distribution was fitted to survivor data to produce failure rate estimates of generator stators. A Bayesian analysis with the COE condition indices was performed. The results suggest that the CIs contribute little additional reliability information. For equipment lacking a statistically significant base of data, a capacity and demand formulation was used to estimate reliability.

a. Survivor Data Analysis.

(1) In this study, a survivor curve presents the percentage of units in a given group which are surviving as a function of the age in service. The survivor curve can be represented by the reliability function of probability theory which describes the probability of satisfactory performance as a function of age. The Weibull distribution was used to describe the reliability distribution. The characteristic age and shape parameters were found for a data set by performing an algebraic transformation to the data and fitting the transformed data with a line. The scale and shape parameters were found from the slope and intercept of the line. Once these parameters are known, the associated hazard function can be obtained. This hazard function provides the failure probability as a function of age for the component.

(2) To investigate the accuracy of the CI to predict whether a component is “sat” or “unsat,” CIs for 15 units in a known satisfactory condition and 3 units in a known unsatisfactory condition were estimated. The statistics of this evaluation showed that there is no significant difference between the condition indices for the stator in the two different conditions. Based on this evaluation, it is concluded that the CI would not improve the reliability information given by historical data for the 15 units examined. The CI estimations were based on only 4 of the 13 tests needed to fully determine the CI. Had all tests been performed, the results may have shown that the CI could be used to improve the reliability estimates.

b. Capacity and Demand Analysis.

(1) For equipment lacking a statistically significant base of data, a capacity and demand formulation can be used to estimate reliability. The reliability of the previous section can be used to estimate the reliability of an item if statistically significant data exist. For most hydroelectric power equipment, these data do not exist. In these cases, the reliability can be estimated using probabilistic techniques to describe deterministic design parameters.

(2) In summary, the proximity to a limiting state of performance is quantified as the factor of safety, F. This measure is defined as the ratio of capacity to resist, C, to the applied demand, D, and is also a function of a set of variables, Xi describing the components geometry, material, and boundary conditions. Typically the logarithm of the random variable (F) is considered, and the reliability index (b) is defined as the ratio of the mean and standard deviation of ln(F). The reliability index represents the number of standard deviations from the limiting state to the mean. Generally, the mean and standard deviation of the ln(F) are not known but information may be known about the means and standard deviations of the Xi variables. If so, the mean and standard deviation of the ln(F) can be approximated using a Taylor Series Finite Difference estimation. Finally, the reliability index can be used to estimate the reliability by assuming that ln(F) is normally distributed in which F(b) is the cumulative normal distribution function. This formulation can be used to estimate the reliability as a function of component age, R(t), because as a component ages the underlying variables Xi change. Having

estimated R(t), the hazard function can be derived and the failure rate as a function of age can be found.

(3) The methodology used to conduct this part of the study was excellent but the results are expected to have larger uncertainties associated with them. Additionally, the method is generally more difficult to apply especially when considering the age effects of random variables. A capacity and demand formulation could be used, but fitting historical survivor data with a probility density function (e.g., Weibull or log-normal distribution) is preferable.

F-5. Turbine Reliability

JAYCOR prepared this report which documents the development of quantitative measures for the reliability of turbine features using capacity and demand analysis (Mlaker and Bryant 1994). The results can be used in economic models which optimally allocate limited resources for project rehabilitation. The second report section introduces general approaches to reliability estimation that are used in the study. In the third section, deterministic models for three modes of unsatisfactory performance of the turbine hub are described. In section four, a probabilistic-based, reliability formulation is explained for application to these three models of unsatisfactory performance. The resulting probabilistic models are then applied to turbine unit number 3 at the Walter F. George Power Plant. In the fifth and closing section of the report, observations about the reliability of these features of hydropower equipment are summarized and recommendations are made for broadly applying the method to Corps hydropower projects.

F-6. Hydroelectric Power Quadrant Prototype

a. The QUADRANT model for hydroelectric power (HYD-QUAD) is being developed specifically for field use on nonroutine maintenance studies to support project budget decisions (Russell et al. 1995). The HYD-QUAD development is based on the NAV-QUAD work (Russell et al. 1993). The purpose of the HYD-QUAD is to develop a program that can be used to assist Corps managers in allocating maintenance funds. The project develops and uses an analytical process based on economics to make maintenance investment decisions. HYD-QUAD is generally applicable to maintenance items that are not a baseline budget item, have a cost greater than $100,000 and less than $5,000,000, and have an impact on the probability of plant outage.

b. For a given project or facility, the HYD-QUAD framework evaluates an initial maintenance condition, impact on maintenance condition, and leads to a maintenance project ranked on economic impact. The HYD-QUAD model was developed using the existing NAV-QUAD model, a literature review, interviews with field professionals, workshops, and focus group meetings. Generally, the HYD-QUAD methodology was developed around the following four steps:

Step 1 - Determine the current condition of the facility for which maintenance is being considered using the CI method developed under the REMR program (Norlin et al. 1993). The CIs for each component/system are combined to produce an overall indicator of the facility condition, called a summary condition index (SI). This SI value is obtained by taking a weighted average of each of the components that comprise the unit or facility. These weighting factors were determined by averaging 38 estimates made by hydroelectric power managers. Each manager was asked to distribute 100 points among the components/systems of the facility or unit. Hydroelectric equipment included in the initial evaluation are generator, transformer, circuit breaker, governor, and voltage regulator.

Step 2 - Each proposed maintenance alternative is listed and the associated change in SI is estimated to produce a “change in SI.” Information on current unit or facility condition and the expected improvement on condition is provided by districts or projects.

Step 3 - Given the baseline SI and improved SI, outage frequency and duration are calculated as a function of SI. A simple arithmetic weighting scheme was used to estimate the SI for a unit. Estimates of frequency and duration of outages as a function of SI were developed through opinions of five hydroelectric power experts. This outage information was collected by distributing a series of worksheets to hydroelectric power experts. The worksheets collected judgments of outage frequency and duration for units with SIs of 90, 80, 60, and 40. Respondents were asked to estimate the 25, 50, 75, and 99 percentile probabilities at each SI level. Five respondents successfully executed the exercise and their estimates were used to develop frequency SI and duration SI functions to estimate outage frequency and duration given an SI. Finally, this information was converted into an estimated cost.

Step 4 - The difference in costs with and without the proposed maintenance are compared to determine the net benefit of performing the maintenance. QUADRANT's output includes costs and damages for all years, rankings, and cumulative initial project costs. A PC version was developed for quantification. A dynamic programming technique was used to compare projects.

c. In addition to current unit condition and expected improved condition, HYD-QUAD input includes cost of outage (energy and capacity costs), interest rates, bowing factors, target SI, zero maintenance age, years to horizon, and total cost of work items. Input information is provided either by the district or project office or HQUSACE. Other intermediate input may include the energy value plant factor. The QUADRANT methodology is based on a CI adapted from the REMR program. Generally, the CI presents a "snapshot" representing the absolute condition of a piece of equipment regardless of its age or maintenance history. CIs are received from the field and are based on testing, field observations, and inspector opinion. The CIs are combined into an SI through a simple weighted average process of five systems. The weighting factors were determined by an opinion poll of 38 hydroelectric power managers.

d. The process described above could be improved by determining the weighting factors in a more objective fashion. For example, the weighting factors could be determined through a fault tree analysis technique that would interrelate the various systems/components and rank them based on the risk associated with a failure of the system/component. Systems/components with higher risk to the facility would be assigned a higher weighting factor based on the relative magnitudes of the risks.

e. Estimates of frequency and duration of outages as a function of SI were developed through opinions of only five hydroelectric power experts. Historical data were either not available or not used. This process is critical to the accuracy of the overall QUADRANT process but is based on the sampling of only five experts. This process should be improved or at the very least the number of experts should be increased to reduce the uncertainties associated with expert opinion. Although the SI does provide useful information, it may not be definitive enough to use alone in this analysis. There is no substitute for solid historical reliability data. Outage frequency should be based on historical reliability data, not SI values. The SI values could be used to adjust the historical reliability information (combined with failure rate data) to provide a better estimate of the reliability of the actual piece of equipment under consideration.

f. Finally, the cost estimations are somewhat simplistic and should be improved. QUADRANT results only show highly summarized, cumulative project costs. There is no consideration given to repair/construction costs of collateral damages that could occur from a given failure or the interest costs associated with construction costs.

F-7. Risk Assessment for Nonroutine Closure/Shutdown of Hydroelectric Generating Stations

a. The Department of Energy Pacific Northwest Lab under contract with the Corps is performing a reliability and risk analysis for evaluating nonroutine turbine shutdown scenarios at

Columbia and Snake Rivers hydroelectric station powerhouses (Vo et al. 1995a,b). The purpose of the analysis is to evaluate the risks associated with events that would require a nonroutine shutdown at hydroelectric stations and involve an inability to close the intake gates within the time normally allotted to close. The Corps guidance for rapid closure of the intake gate is the 10-minute closure rule which requires intake gates to be capable of closure within 10 minutes in the case of a flooding or overspeed event. The ability to meet the 10-minute closure rule is questionable for hydroelectric stations that have their intake gates removed or raised from the original design position. The intake gates at some hydroelectric stations on the Columbia and Snake Rivers have been removed or raised to improve fish guidance.

b. This project provides a general probabilistic risk assessment (PRA) for hydroelectric stations. The results of the PRA are being synthesized with an economic consequence analysis to produce results in terms of economic risk. Results of this study can be used for policy and decision making. This project was broken down into four phases. A separate report was or will be issued for each phase. Each phase offers information and/or processes that individually could be useful to rehabilitation evaluations.

Phase 1 - This phase involved collection and analysis of relevant hydroelectric power equipment failure data. Reviews of failure data from generic sources were conducted and data were collected from a survey of hydroelectric stations and an expert panel elicitation. For each component the sources were combined using a Bayesian process. The resulting failure rate values are generic for the components over their expected life. Failure rate functions (i.e., failure rate vs component age) were not developed. Failure rate functions would need to be developed to support both major maintenance and rehabilitation programs. In addition, the failure information for electrical components generally came from nuclear related sources. Further research into the applicability and possible development of hydroelectric-specific electrical component failure rates could be warranted.

Phase 2 - Probabilistic risk analysis techniques and software were used to complete this phase. The postulated initiating events (loss-of-load, internal flooding upstream of the wicket gates, and internal flooding downstream of the wicket gates) were modeled in event trees. Systems required to respond to these events were modeled in fault trees. The fault tree component failure rate information was taken from the Phase 1 database. The model accounted for the minimum time that a component could operate, the minimum time that a component could fail, and time-based recovery actions. In addition, the model accounted for the different plant conditions which exist in the field (i.e., differences in design, operations, etc.). This latter feature allowed 48 different field conditions to be modeled. The results of this phase were “frequency profiles.” These profiles reflect the frequency of remaining in a potentially damaging event versus time after initiation (e.g., frequency of having loss-of-load conditions which last 5 minutes, 10 minutes, 15 minutes, etc.). At present the model only handles the three events of concern for the project. Other events are possible/plausible which could have application to a rehabilitation evaluation. Only systems and components required to mitigate the events of concern were modeled. With the addition of new events, more system models and components could be required. The existing system models may also require additional detail. As noted above, the model can handle 48 major design features (based on governor type, intake gate design, emergency wicket gate closure, etc.). The selected design features were found to be adequate for differentiating between possible plant response to the events of concern. With the addition of new events, more design features may be required.

Phase 3 - Given an event occurring for a specific time, there is a certain probability that damage of a certain level (a damage state) will occur. There is an economic cost associated with each level of damage. Phase 3 collected information to (1) delineate the different damage states, (2) quantify the probability of entering a damage state given an event lasting a set time, and (3) estimating the cost associated with each damage state. This information was collected from a combination of expert elicitation and deterministic and probabilistic calculations. The above information was combined to produce “economic consequence curves.” These curves provide an economic cost versus time in an event. The economic consequence curves were then combined with the frequency profiles from Phase 2 to produce an economic risk. This is a single value for each field condition that reflects the dollars at risk for that field condition. Comparisons between the different field conditions were provided, as were importance values for the components from Phase 1. This latter information is useful for identifying components important to risk. In addition, the importance values were evaluated to predict changes in risk to specific components. The risk values and associated importances would have to be re-quantified for any model and/or data changes as discussed in Phases 1 and 2, but the general process should be applicable to rehabilitation projects. A detailed uncertainty analysis was included in the Phase 3 analysis using a Latin-Hypercube process and a Monte Carlo simulation. This process discerned the overall uncertainty associated with each of the intermediate steps as well as for the final result (economic risk). The uncertainty values would have to be requantified for any model and/or data changes as discussed in Phases 1, 2, and 3, but the general process should be applicable to the rehabilitation projects.

Phase 4 - The results of Phase 3 will be used as input to the decision analysis in Phase 4. This analysis will be based on various economic analyses such as cost-benefit ratios. The cost-benefit ratios and economic analysis of Phase 4 are composed mainly of comparisons between designs and proposed changes to designs. They are not expected to concentrate on changes in individual component reliability improvements. However, the process could lend itself to modification for rehabilitation studies.

F-7. Engineering and Design Reliability Assessment of Navigation Structures (ETL 1110-2-532) and Stability of Existing Gravity Structures (ETL 1110-2-321)

a. Engineer Technical Letter (ETL) 1110-2-321 supplements ETL 1110-2-532 and provides guidance for assessing the reliability of existing gravity structures founded on rock and establishing an engineering basis for rehabilitation investment decisions. ETL 1110-2-532 provides guidance for assessing the reliability of navigation structures and establishing an engineering basis for rehabilitation investment decisions. The guidance provided by these ETLs is intended to provide (1) an engineering method for assessing the reliability of structural features based on their current condition; (2) a consistent uniform method for prioritizing the investments needed to restore or modernize projects which are approaching or have exceeded their design life; and (3) an initial step in defining the detailed engineering studies needed to estimate the remaining service life of structural features.

b. The methodology in these ETL guidance documents uses reliability indices as a relative measure of the current condition and provides a qualitative estimate of the structural performance. Structures with relatively high reliability indices will be expected to perform their function well. Structures with low reliability indices will be expected to perform poorly and present major rehabilitation problems. If the reliability indices are very low, the structure may be classified as a hazard. Working from a sufficiently large experience base, it should be practical to make some estimates of expected structural performance with some engineering judgment. The reliability indices will be calculated using the performance function, capacity, divided by demand. The results of the reliability analyses may be used to identify deficient structures in need of stabilization and to prioritize investment decisions. Target reliability indices that may be used in evaluating and comparing structures are given in these ETLs.

F-8. Electric Power Research Institute Studies

The Electric Power Research Institute (EPRI) has conducted/sponsored research in the hydroelectric area and, specifically, in reliability, modernization, and risk. Some of the research potentially relevant to reliability and or rehabilitation studies are documented in the following reports:

a. GS-6419, Hydropower Plant Modernization Guide (EPRI 1989) helps utility managers to evaluate, plan, and coordinate the modernization of the major plant components that extend plant life, reduce power loss, increase availability, and boost power output. This guide provides information, methodology and data for developing reasonable expectations of new equipment. It demonstrates how to synthesize these requirements into a comprehensive plant modernization plan. A second volume deals with turbine runner upgrading and generator rewinding, and a third with plant automation.

b. EM-3435, Hydropower Reliability Study (EPRI 1984), develops recommendations for improving the reliability and availability of hydroelectric generation plants in the United States. The two-part project used statistical analysis and a field survey as the basis for documenting historical performance and present-day practice in hydroelectric generation. The project team selected the North American Electric Reliability Council's Generation Availability Data System (GADS) database as its historical source. In addition, a multidisciplinary survey team used questionnaires to obtain information on component ratings, materials, manufacturers, O&M practices, failure modes and causes, and other issues from a representative group of U.S. hydroelectric plants. Project personnel made recommendations for improvements to GADS. Those modifications, along with greater utility participation, are expected to produce a more complete and statistically significant database for future users.

c. EM-2407, Increased Efficiency of Hydroelectric Power (EPRI 1982), presents the results of a project that examined the potential for increasing hydroelectric generation efficiency at existing plants. The physical factors studied include the uprating of turbines and generators, leakage control, and the use of flashboards. The study concluded that excluding pumped storage, there is a potential for a 17% increase in capacity and approximately a 5% increase in energy from existing conventional plants.

d. AP-4714, Inspection and Performance Evaluation of Dams: A Guide for Managers, Engineers, and Operators (EPRI 1986), provides project owners, managers, engineers, and operators with useful guidelines for dam inspection and for monitoring and evaluating dam performance. This guide was prepared to assist utilities in the design, operation, maintenance, and modernization of hydroelectric projects. The guide includes information on the concept and organization of inspection-evaluation programs as well as recommendations for establishing reporting procedures and developing communication channels.

e. TR-103590, Reliability Centered Maintenance (RCM) Implementation in the Nuclear Power Industry: Guidelines for Successful RCM Implementation (EPRI 1994), provides information which could be used to develop an RCM program. RCM programs help utilities optimize preventive maintenance efforts while improving plant safety and economy through increased dependability of plant components. This guide details the factors that influence a positive outcome in an RCM program and lists success criteria that can be used by RCM program managers early in the process.

f. TR-100320, Reliability Centered Maintenance (RCM) Technical Handbook: Volumes 1 and 2 (EPRI 1992), provides reference material and technical guidance to support RCM evaluations at electric utility power plants.

g. EPRI has recently initiated a Reliability Centered Maintenance program for hydroelectric power application. In addition, EPRI has researched risk, engineering, and economic issues associated with hydroelectric facilities. EM-3435 (EPRI 1984) includes statistical analysis of historical performance data from the GADS database. The report recommended changes to the GADS system. GS-6419 (EPRI 1989), EM-2407 (EPRI 1982), and AP-4714 (EPRI 1986) all contain valuable information for evaluating dam and system performance and modernizing equipment. TR-103590 (EPRI 1994) and TR-100320 (EPRI 1992) both deal with RCM. EPRI has other reports and documents available on these and related topics. The reports are available at no additional cost to EPRI members, and at a nominal cost for nonmembers.

F-9. Waterpower Conference Proceedings of the International Conference on Hydropower

a. The Proceedings of the International Conference on Hydropower, San Francisco California, July 1995, Volume 2 includes a few papers that describe various aspects and cases of rehabilitation program implementation to dams, navigation locks, and hydroelectric power stations.

(1) The paper, “Steel Penstock Rehabilitation Strategies” (Kahl 1995), describes three important deterministic design considerations that can influence alternatives for rehabilitation of older steel penstocks. The three design considerations that need to be addressed arise primarily from potential changes in operation or use of the penstock and/or changes in the rigor of analytical techniques. These considerations may justify alterations from the original design that would be appropriate under the rehabilitation effort. The paper does not address issues of risk, reliability, or economic analysis of potential rehabilitation alternatives.

(2) The paper, “Feasibility Studies to Rehabilitate TVA’s Chickamauga Navigation Facility Due to the Effects of Concrete Growth” (Niznik and Conner 1995), summarizes the four alternatives considered by a multidiscipline team in evaluating the feasibility of options for rehabilitating the Chickamauga Navigation Facility. The paper describes the work involved in the four options and the estimated costs as well as some of the advantages and disadvantages that are associated with each option. The paper does not address the issues of risk or reliability, and does not include details regarding the considerations included in the economic assessment.

(3) The paper, “Hiwassee Dam Rehabilitation to Combat Concrete Growth” (Newell et al. 1995), summarizes the deterministic analysis effort used to evaluate alternatives and project the performance of these alternatives over time. The decision among the rehabilitation alternatives considered was selected based on the output from this time-based analysis and associated economic analysis that was not described in the paper. The paper also summarizes the construction effort involved in performing the rehabilitation project. The paper does not address the issues of risk or reliability, and does not include details regarding the considerations included in the economic assessment.

(4) The paper, “The Use of Object-Oriented Monte Carlo Simulation to Analyze Hydropower Rehabilitation Proposals” (Moser et al. 1995), describes the underlying concept of economic risk analysis as prescribed for the major rehabilitation program. The development of a computer program to conduct the economic analysis of rehabilitation proposals is described. Of particular interest is the graphical user interface that facilitates the entry of economic and reliability data and allows the user to develop and analyze many alternatives. The guidance for major rehabilitation proposals requires use of a risk-based probabilistic analysis of unsatisfactory performance and the resultant economic consequences. The HYDROPOWER REPAIR (Risk-Based Economic Program for the Analysis of Investments for Rehabilitation) is designed to model the distribution of life-cycle costs associated with the operation and maintenance of a hydroelectric power plant. The benefits of a major rehabilitation are inferred from the reduction in the expected life-cycle costs, both expenses and operation costs, associated with the rehabilitation. Reduction in the expected life-cycle costs are due to reduction of the likelihood of unplanned outages,

reduction of the costs from unplanned outages, reduction of future O&M costs, and various combinations of these. The model provides a probabilistic treatment of the hazard function (likelihood of unsatisfactory performance) and loss function (likelihood of costs accruing for the various feature losses considered) that are based on use of historical data. The estimated costs from the loss function incorporate the amount of excess capacity that may exist within the facility or system. Monte Carlo simulation techniques are used to calculate the distribution of the life-cycle costs for the facility considering the maintenance, repair, and operation cost categories as well as investment costs for all alternative rehabilitation strategies evaluated.

(5) This paper (Moser et al. 1995) describes the underlying concept of an economic risk analysis prescribed for the major rehabilitation program and the development of a computer program by the Institute for Water Resources for use in conducting the economic analysis of rehabilitation proposals. The paper describes the economic framework used in the computer program for performing these analyses as well as the approach for incorporating probabilistic risk-based analysis into the computer program through Monte Carlo simulation using historical data. The paper also addresses the figure of merit incorporated into the computer program for assessing the rehabilitation alternatives and making rehabilitation decisions. The user interface for this program is presented with an example application. This paper addresses implementation of risk, reliability, and economic considerations that are mandated for evaluations of rehabilitation options under the major rehabilitation program. The methodology described is technically comprehensive and should be considered the standard for economic analyses.

b. The Proceedings of the International Conference on Hydropower, Denver, Colorado, July 1991, Volume 2, includes a few papers that describe various aspects or risk analysis uses in the hydroelectric power industry and cases of rehabilitation program implementation to various stations.

(1) The paper, “Engineering Risk Assessment for Hydro Facilities” (Laurence 1991), describes a risk assessment which evaluates the risk in terms of dollars to hydroelectric facilities due to earthquake, tsunami, flood, wind, and other natural perils. The methodology included initially evaluating facility design criteria to determine how well various systems and structures would hold up to the catastrophe. Next, varying degrees of catastrophe severity were established and probabilities of each catastrophe were estimated using historical/meteorological data. Damages (in dollars) for each catastrophe were estimated based on the design criteria of the structures/systems and the codes to which the structures/systems were built. Finally, the risk (in dollars) was calculated based on the probability of the catastrophe occurring and the damage consequences.

(2) The paper, “Risk Analysis Applications for Dam Safety” (Moser 1991), presents the principles and issues of risk analysis as they have evolved in the evaluation of dam safety improvements. The paper also reviews some results of the Corps’ Dam Safety Research program in applying risk analysis and risk-based methods to dam safety evaluations. This paper describes several risk-based methods that have been used to evaluate the effects on risk of widening spillways and raising dams in an effort to minimize the effects of floods. These discussions include both economic costs as well as human life considerations.

(3) The paper, “Evaluation of Rehabilitation Alternatives for Small Hydropower Plants” (Prakash and Sherlock 1991), describes methods for comparative evaluation of alternative rehabilitation measures for aging small-scale hydroelectric power plants. The evaluation criteria include both dollar-denominated and nondollar denominated impacts associated with different rehabilitation options. The comparative evaluation is performed using a combination of the delphi and fuzzy-set approaches. In the delphi approach, a panel of experts determine the factors for comparative evaluation of rehabilitation alternatives, and assign weights to each factor. Next, the experts score each alternative. The evaluation factors form the

columns and the alternatives form the rows of the fuzzy-set evaluation matrix. The weight factors are applied to the alternative score through matrix multiplication to determine the best alternative.

F-10. Pacific Engineering Study on Hydroelectric Risk Analysis

a. Pacific Engineering Corporation (PEC) investigated the current status of risk analysis as applied to hydroelectric power generation equipment and facilities (PEC 1995). Attention is focused on the use of probabilistic methods to predict changes in equipment reliability and to prioritize and schedule predictive maintenance. The study consisted of a literature search using online electronic databases and phone interviews with individuals familiar with risk management techniques in hydroelectric power applications.

b. The literature search located 19 articles that contained subjects of interest to the project. These articles were briefly summarized in the report. Interviews were conducted with a cross-section of individuals representing manufacturing interests, hydroelectric power plant owners and operators, and research and development (R&D) and academic interests. The results of the interviews were summarized in the report. Finally, this report presented a section describing its investigative findings. This section summarized where to find the best sources of technical articles dealing with probabilistic risk analysis.

c. Although this report does not provide any useful technical risk analysis information, it could be used to locate additional sources of risk analysis publications.

with any number in the range having an equal likelihood of occurrence. Each random value is input into the spreadsheet, and the spreadsheet is recalculated to arrive at an associated outcome. Each random trial or iteration of the spreadsheet represents an independent “what-if” game. By generating hundreds, or in some cases, thousands of “what-if” games, Monte Carlo sampling will generate the input distribution and the entire range of potential outcomes.

E-4. Model Requirements

Basic functional requirements are established for the model. These requirements allow for flexibility in the analysis, incorporation of basic assumptions, and the ability to change parameters as needed. Some of these requirements are described below.

a. The model must accurately reflect the without-project condition. The without-project condition establishes a base condition from which all other alternatives are to be evaluated.

b. The model must be flexible enough to evaluate a full range of alternatives. Alternatives considered in the analysis often include: enhanced maintenance, use of spare parts, a full array of rehabilitation scenarios, and, subsequently, appropriate timing of any rehabilitation strategy.

c. The model must distinguish between individual operating components, and economic consequences of various alternatives, and the timing of events.

d. The model must be able to incorporate incremental analysis of each unit and its separable components.

e. The model must account for a project life (35 years is recommended) and for near-term events that could impact future rehabilitation strategies.

f. The model must be able to incorporate the engineering reliability and risk and uncertainty analysis for each time period and each functional component under evaluation.

g. For each alternative, the model must be able to incorporate routine and nonroutine O&M costs for each component over the period of analysis.

h. The model must be able to account for changes in generating unit efficiencies with various rehabilitation scenarios.

i. The model must be able to incorporate the consequences of events and repair/rehabilitation scenarios in terms of changes in hydropower system benefits and alternative construction costs. Each alternative produces different hydropower outputs, system benefits, and O&M costs.

j. The model must be able to accommodate other economic calculations such as present valuation and amortization of costs and incorporation of interest during construction.

E-5. Model Operating Characteristics

a. For each alternative considered, the spreadsheet is modified to simulate the specific engineering, operational, and economic consequences relative to the alternative. Monte Carlo simulation techniques are incorporated into the spreadsheet. This approach uses random number generation to compute an expected result given a combination of probabilities and events. The program sums the results of multiple iterations of the simulation and produces expected values and variance. Each simulation should include a minimum of 300 iterations. Up to 5,000 iterations may need to be computed in some simulations.

b. Separate simulations are conducted for the without-project and for each alternative considered in the analysis. Simulations for the Chapman Powerhouse example (Appendix C) should include: rehabilitation of one to four turbines; rehabilitation of one to four generators; rehabilitation of one or two transformers; and all reasonable combinations of these alternatives. The appropriate timing for rehabilitation should also be evaluated. Another alternative that should be considered is one that uses an enhanced maintenance strategy. In many cases this may already be implemented in the without-project condition. A spare parts alternative should also be considered where reasonable. Incremental analysis of the alternatives should be performed to allow for optimization of the number of components to be rehabilitated.

c. This process permits consideration of the physical condition of the individual components and the potential sequencing of repairs.

d. Each simulated outage incorporates consequences, in the form of cost resulting from increased frequency of repair, increased maintenance effort, and having to resort to more expensive means of energy production (hydropower benefits calculations).

E-6. Incorporation of Physical and Economic Consequences

a. Several columns of the spreadsheet model are needed to account for the engineering reliability analysis. The engineering reliability analysis establishes the probability of unsatisfactory performance for each component for current and future conditions. This probability, over time, is inserted for each year in the modeling sequence. Current conditions and probabilities of unsatisfactory performance vary for each individual turbine, generator, and transformer.

b. Within each iteration, a random number is generated for each component in a given time period. Based on the probability of unsatisfactory performance in that time period, the unit either incurs an outage or continues to operate. For example, if the probability of unsatisfactory performance for turbine unit number one in the year 1993 is 2.19 percent, then any random number generated between 0 and 1 that is less than 0.0219 will cause an outage to occur; any number greater than 0.0219 will indicate that the unit is still available for operation. If the unit remains operational, then the probability of unsatisfactory performance in the next time period increases. A random number is generated for each successive time period, and the consequences are recorded. Should a unit incur an outage, depending on the alternative being modeled and the type of outage, the unit will either be repaired or rehabilitated. If the unit is repaired, then the probability of unsatisfactory performance in each successive time period continues to increase. If a unit is rehabilitated, then the probability of unsatisfactory performance is returned to a new condition as the equipment is considered to be restored.

E-7. Types of Unsatisfactory Performance

a. The analysis can include multiple types of unsatisfactory performance with different probabilities of occurrence. For example, in the Chapman hydropower example, the first type could be considered to be a catastrophic outage. For a generator stator, this type of outage could occur if a significant number of coils failed, and a rewind was the only possible repair. The second type of outage is less debilitating. This outage mode consists of a repairable coil failure.

b. For each type of unsatisfactory performance, outage times and costs for repair are computed. For the Chapman generators, a repairable coil failure may cause an outage of 1 month at an estimated repair cost of $25,000. For a catastrophic outage, the Chapman unit is estimated to be out of service for a period of 24 months at a repair cost of $1,500,000.

c. For each alternative considered, routine annual O&M costs are also estimated. Under existing conditions, the Chapman turbine units are dewatered, inspected, and repaired once every 6 months. If a unit is rehabilitated, inspections are assumed to decrease in frequency with a resulting reduction in O&M costs. The time associated with inspections and routine maintenance must also be accounted for in each iteration.

d. Subsequent columns in the spreadsheet sum all unit outages for a given year. Subroutines should be incorporated in the model to prevent double counting of outage time if two interrelated components are out concurrently. If the unit is considered to be out of service in excess of 12 months, outage times must be carried over into the next time period.

e. Additional columns are required to sum O&M, repair, and rehabilitation costs for any given year. Again, subroutines must be used to prevent double counting of normal maintenance costs if the unit is considered to be out of service for an extended period of time.

f. Columns must be added to the spreadsheet to account for specific alternatives and conditions. For example, in an alternative that includes a planned sequence of rehabilitation, if a unit outage occurs within a year of the planned rehabilitation, the unit would not be repaired or returned to service prior to the rehabilitation. This would be the proper sequence of events assuming that it is more cost effective to leave the unit off-line than to return it to service and then shut it down later for a permanent rehabilitation.

g. Another column needs to account for whether or not existing spare parts are available for a given unit. In any simulation, if a unit with spare parts experiences a catastrophic outage, the existing spare parts should be assumed to be put into service.

E-8. Cost of Replacement Power - Hydropower Benefits

a. The without-project condition must first be modeled as discussed in Appendix D. This produces an annual system production cost assuming all four of the Chapman powerhouse units are available for production. Next, the without-project condition is modeled assuming that only three units are available. Subsequent scenarios are run removing a unit at a time until all four units are considered to be off-line. This process results in construction of a system production cost curve assuming a full range of unit availability in the without-project condition. This production cost curve is then used in the economic model to quantify the production cost consequences of unit availability for any potential combination of randomly generated unit outages.

b. Additional production cost curves are constructed to assist in modeling the alternative rehabilitation and repair scenarios. As units are rehabilitated, unit efficiencies increase, hydropower production increases, and system production costs decrease.

c. Once all of the separate cost curves and previously described input values are established, the without-project and all of the with-project conditions are simulated. For each iteration of a simulation, potential outages are generated; O&M, repair, and rehabilitation costs are calculated; and system production costs are estimated. The economic consequences for each alternative over the period of analysis are summed and described in present values terms. Net benefits are computed for each alternative, and the plan that maximizes net benefits is recommended for implementation. Additional statistics are generated to describe the range and distribution of values for each component.

Appendix G
Worldwide Web Sites

There is a significant amount of data on the world-wide web relating to the hydroelectric power industry. This appendix lists worldwide web sites that were found to contain information that could be useful to reliability studies:

a. Institute of Electrical and Electronics Engineers (IEEE): **http://www.ieee.org/**

b. Electric Power Research Institute (EPRI): **http://www.epriweb.com/**

c. North American Electric Reliability Council (NERC): **http://www.nerc.com/**

d. Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program: **http://www.wes.army.mil/REMR/remr.html**

e. U.S. Army Corps of Engineers, Hydroelectric Design Center (HDC): **http://www.npd.usace.army.mil/hdc/**