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.