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, 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.