APPENDIX F

EXAMPLE OF COMBINING RISKS AND CONSEQUENCES

F-1. Introduction. The evaluation procedures for major rehabilitation require the Districts to use risk-based benefit-cost analysis incorporating the existing and future risk of "unsatisfactory performance" of structures and equipment. These risks are then combined with estimates of the costs of unsatisfactory performance to generate an expected reliability based cost. Alternative rehabilitation strategies are then proposed to reduce this cost. Each alternative can either change the risk, change the cost of unsatisfactory performance or both. A complicating difficulty is that the analysis must be carried out over the "life-cycle" to the project, up to 50 years. That is, the cost estimated is the present value of all costs associated with the operation, maintenance, and repair of the facility where each cost is weighted by the probability of occurrence.

F-2. Description of Simplified Evaluation Problem. Suppose that the rehabilitation problem is the potential unsatisfactory performance of a hydropower plant. For simplicity, assume that the plant is composed of two generating units. Each of these units, in turn, is composed of two components: a turbine and a generator. The information available for each component of each unit is shown in Table F-1. Table F-2 shows the system energy and capacity opportunity costs as a function on the number of units out of service simultaneously. It is assumed that all the units provide the same contribution to system energy and capacity. Sometimes, the energy and capacity contributions will differ across the units. In addition, a rehabilitation strategy may include efficiency improvements on a unit by unit basis.

Table F-1: Example Hydropower Rehabilitation Assumptions

	Unit 1		Unit 2	
	Turbine 1	Generator 1	Turbine 2	Generator 2
Initial Risk	.01360	.01176	.01510	.02520
Annual rate of change in risk	.00017	.00042	.00017	.00042
Risk after repair	.00017	.00042	.00017	.00042
Risk after rehabilitation	.00017	.00042	.00017	.00042
Number of months to repair	24	12	24	12

a. As noted in Appendix E, the calculation of system energy and capacity values should be undertaken only by individuals trained in hydroelectric benefit evaluation. One particular issue in economic evaluation is the industry response to temporary versus permanent interruptions due to the unsatisfactory performance on individual hydropower units. The question to be answered is whether temporary losses in generating capacity will result in the electric generating industry building permanent replacement capacity. If so, there is a "capacity loss avoidance benefit" from major rehabilitation; if not, there is no capacity restoration as a source of benefit from rehabilitation. The issue arises since the system contains some percentage of excess capacity to compensate for unplanned outages. This issue is currently the subject of research. Until procedures are established for calculating capacity losses due to unreliable performance, care should be taken in including a capacity loss avoidance as a benefit from major rehabilitation. For the purposes of this example, Table F-2 shows the assumed opportunity costs of unsatisfactory performance.

b. At any point in time, either or both of the components of each unit could perform unsatisfactorily or satisfactorily. The probability of the first occurrence of unsatisfactory performance for a component is dependent on the initial risk, the degradation in reliability (increase in risk), and the number periods since the beginning of the analysis. Following this initial event for each component, the probability of unsatisfactory performance for the component is dependent on the risk of the repaired component, the degradation in reliability and the number of periods since the last episode of unsatisfactory performance.

Table F-2: Energy and Capacity Opportunity Costs

Units Down	Opportunity Cost per Year
0	0
1	300,000
2	10,000,000

c. If the turbine or generator performs satisfactorily, deterioration or degradation occurs and is represented by the annual rate of change in the risk. This degradation rate may be a constant added to the risk each year the component doesn't fail. The level of risk over the life-cycle could be a linear or nonlinear function of time.

d. Figure F-1 shows the level of risk over the life-cycle of a component assuming a linear degradation pattern. Figure F-2 shows the level of risk for the same component assuming a nonlinear degradation. There are more than 1.1259 x 10^{15} (2^{50}) possible risk based life-cycles for a single component.

e. At the end of each period, the unit is either in service, or is out of service due to the failure of one or both of the components. The number of units out simultaneously is important in terms of the cost of energy losses and possibly system capacity losses. These losses are generally increasing functions of the number of

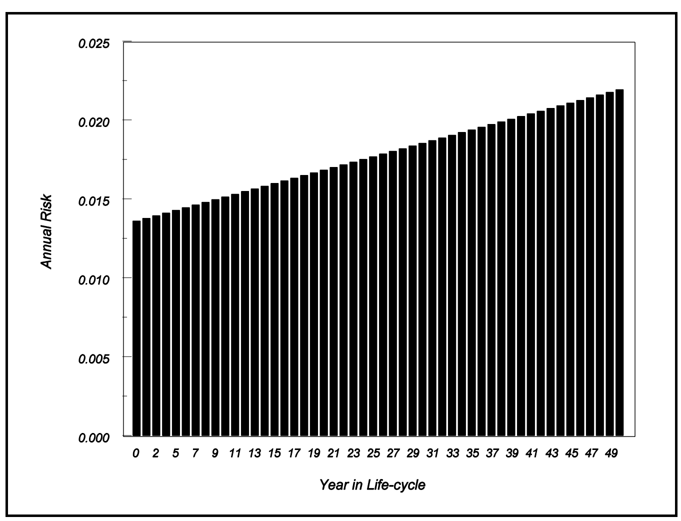

Figure F-1: Linear Risk Function

units out simultaneously since all units are typically not in operation simultaneously even when all are available. Values assumed for this example are shown in Table F-2.

f. Since the repair costs and opportunity costs can occur in future years, the analysis requires discounting the costs in each year to the base year. A discount rate of 8.5% is used in this example. The current year Federal discount rate should be used in an actual evaluation, (8.00% in FY94).

g. The evaluation problem is modeling the possible pathways or sequences of performance that each component for each unit can take, including resetting of the risk after failure of a component. In addition, the model must be flexible to deal with situations with multiple power units and multiple components. The model must account for:

(1) the change in reliability of a component (increases in risk) over time from the start of the analysis,

(2) the changed reliability of a repaired component, (see Figure F-3),

(3) the possible change in degradation rate of the repaired component,

(4) the present value of component repair costs when a component fails,

(5) the present value of foregone project outputs (energy and capacity) when some units are out of service due to component unsatisfactory performance,

(6) the time necessary to repair components,

(7) the present value of regular O&M costs while repairs are undertaken, and

(8) the present value of regular O&M costs after repairs are made.

h. Once these values are determined, they can be used in a risk-

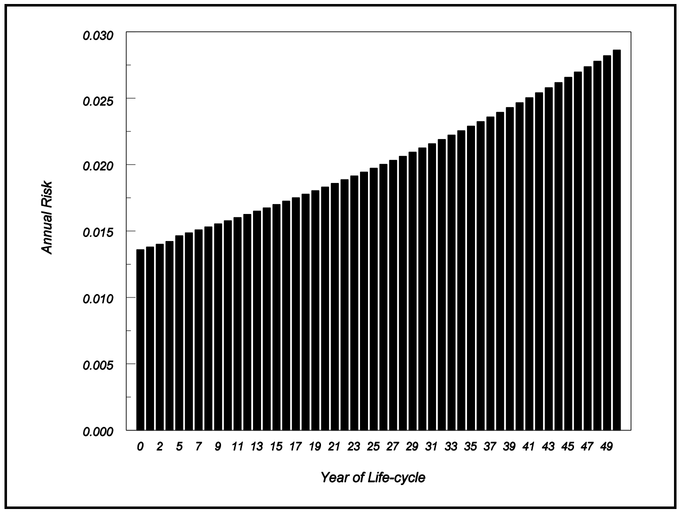

Figure F-2: Non-linear Risk Function

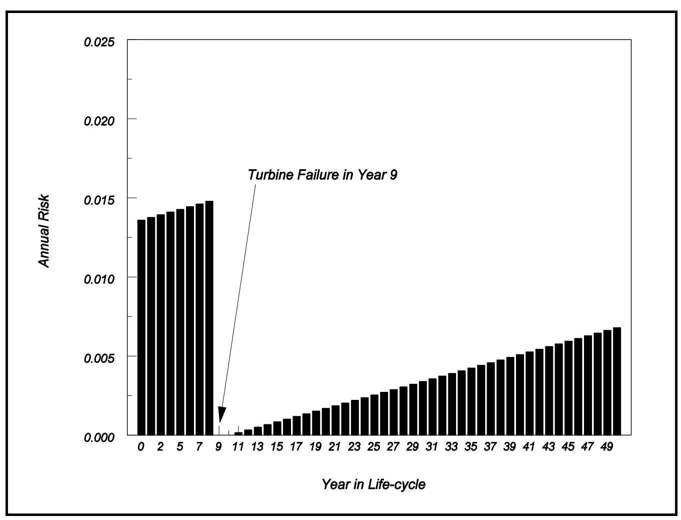

Figure F-3: Life-cycle Risk with One Repair based model to estimate the base condition reliability costs. Any major rehabilitation strategy changes at least some of the above listed values. The risk-based model can be rerun with the revised values. Reductions in reliability costs resulting from the rehabilitation strategy represent reliability benefits of the rehabilitation investment.

F-3. Description of Monte Carlo Simulation. The values shown in Tables F-1 and F-2 were entered in a LOTUS macro written as a Monte Carlo simulation. In each year of the life-cycle, the simulation generates a single random number for each unit. If a random number for a unit falls between zero and the risk of Component 1 (between zero and .01360 for the turbine of Unit 1), the unit performs unsatisfactorily due to mode or Component 1. If the random number falls between the risk of Component 1 and the sum of the risks of Components 1 and 2 (between .01360 and .01360+.01176), the unit performs unsatisfactorily due to mode or Component 2. If the random number falls between the sum of the risk of Components 1 and 2 and one (between .01360+.01176 and 1) the unit performs satisfactorily.

a. The initial risk, the degradation rates, and the risk after unsatisfactorily performance determine the risk of Component 1 and 2 in each period. The risk in any period depends on what happened to each component in all the previous periods. If a unit performs unsatisfactorily, the present value of the repair costs is calculated. A running total of this value for each component of each unit is calculated over the life-cycle. In addition, the total number of units out simultaneously in a period, regardless of cause, is used to determine system energy losses using a simple lookup table. A running total of the present worth of this value is also calculated over the life-cycle. The length of the life-cycle can be changed but is assumed to be 50 years in the macro.

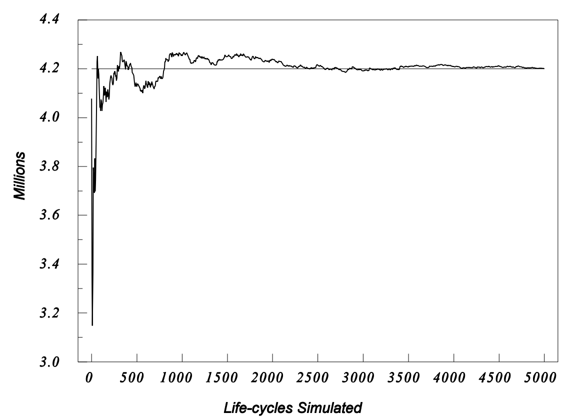

Figure F-4: Running Average Lifecycle Costs

[1] In this example, the joint occurrence of both components performing unsatisfactorily is ignored.

Table F-3: Base Condition Life-cycle Costs (Standard Errors in Parenthesis)

	Unit 1		Unit 2	
Reliability Cost	Turbine	Generator	Turbine	Generator
Expected Present value of Life-cycle Repair Costs	748,500 (16,119)	346,900 (7,241)	767,100 (15,876)	573,800 (8,728)
Expected Present value of Life-cycle Opportunity Costs	553,800 (17,180)			
Expected Present value of Life-cycle O&M Costs	1,210,156 (454)			
Total Life-cycle Costs	4,200,256 (30,590)			

Values in dollars.

b. As was noted above, the number of possible life-cycles is very large. To reasonably represent the distribution of possible life-cycle reliability costs, multiple life-cycles must be simulated. The number of life-cycles required depends on the complexity of the risks being modeled. The primary approach to deciding the required number of life-cycles to simulate is to increase the number of life-cycles until the statistic of interest (the mean of life-cycle costs), is stable. This statistic should asymptotically approach the "true" mean as the number life-cycles increase. Figure F-4 shows the running average of the base condition calculated total reliability costs. Table F-3 shows the results from 5000 life-cycles.

Table F-4: Immediate Rehabilitation Life-cycle Costs (Standard Errors in Parenthesis)

	Unit 1		Unit 2	
Reliability Cost	Turbine	Generator	Turbine	Generator
Expected Present value of Life-cycle Repair Costs	77,300 (3,700)	82,100 (2,600)	77,300 (3,700)	82,100 (2.600)
Expected Present value of Life-cycle Opportunity Costs	1,450,800 (30,400)			
Expected Present value of Life-cycle O&M Costs	179,000 (450)			
Total Life-cycle Costs	1,948,600 (31,069)			

Values in dollars.

F-4. Major Rehabilitation Strategy.

a. For the purposes of this example, only one rehabilitation strategy is considered, immediate rehabilitation of the turbines and generators in both units. In addition, construction activities are initiated immediately to rehabilitate Unit 1. After 2 years, Unit 1 construction and testing will be complete and Unit 2 will be rehabilitated. Both units will be available for service at the end of the fourth year. Table F-1 lists the revisions in risks and costs due to the rehabilitation. During the construction, only one unit is in operation so that the opportunity costs shown in Table F-2 are incurred. Additionally, no regular O&M expenditures take place for a unit that is out of service whether under repair or during rehabilitation construction. Table F-4 shows the reliability costs with this rehabilitation strategy. Note that the opportunity costs with rehabilitation, due to lost energy and capacity, exceed those that would have occurred without rehabilitation. This stems from the fact that during the rehabilitation construction (4 years), one of the units is out with certainty. Therefore, there is this certain loss plus the increased risk that both units will be out during the construction. After rehabilitation the risk of an outage is greatly reduced but the contribution to reducing the life-cycle present value is also less important due to discounting.

b. From the results from Tables F-3 and F-4, the expected present value of benefits from the proposed rehabilitation strategy are the difference in life-cycle costs. The summary statistics for life-cycle benefits are presented in Table F-5. Note that this analysis does not include additional benefits accruing from restoring lost generating efficiency nor from increasing efficiency beyond the original design. These benefits can be approximated by the deterministic amount of the present value of these efficiency gains over the 50-year time horizon. This would only be approximate since there is still a chance that unsatisfactory performance could occur after rehabilitation. Because of the efficiency improvement, any unsatisfactory performance after rehabilitation results in larger opportunity costs. Therefore, the risk-based opportunity costs after rehabilitation would be larger than that shown in Table F-4.

Table F-5: Summary Statistics of Rehabilitation Strategy

	Base Condition	Immediate Rehabilitation	Benefits	Standard Error of Benefits
Expected Present Value of Life-cycle Costs	4,200,300	1,948,600	2,251,700	43,602
Confidence Interval for Benefits				
5%			2,180,200	
95%			2,323,200	