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DATA COLLECTION AND ANALYSIS IN SUPPORT
OF RISK ASSESSMENT FOR HYDROELECTRIC
STATIONS

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DATA COLLECTION AND ANALYSIS IN SUPPORT OF RISK ASSESSMENT FOR HYDROELECTRIC STATIONS

ABSTRACT

This project is to provide the U. S. Army Corps of Engineers with a risk analysis that evaluates the non-routine closure of water flow through the turbines of powerhouses along the Columbia and Snake Rivers. The project is divided into four phases. Phase 1 efforts collected and analyzed relevant plant failure data for hydroelectric generating stations in the United States and Canada. Results from the Phase 1 efforts will be used to assess the risk (probability times consequences) associated with non-routine shut down of hydroelectric stations, which will be performed in the remaining phases of the project. Results of this project may be used to provide policy recommendations regarding operation and maintenance of hydroelectric stations.

The methodology used to complete the Phase 1 of the project is composed of data collection and analysis activities. Data collection included performing site visits, conducting a data survey of hydroelectric stations, conducting an expert panel workshop, and reviewing and tabulating failure data from generic sources. Data analysis included estimating failure rates obtained from the survey data, expert judgment elicitation process, generic data, and combining these failure rates to produce final failure rate parameters. This paper summarizes the data collection analysis, results and discussions for the Phase 1 efforts.

1.0 INTRODUCTION

The Pacific Northwest Laboratory (PNL) was requested by the U.S. Army Corps of Engineers (COE) to provide a risk analysis that evaluates the non-routine closure of water flow through the turbines of powerhouses along the Columbia and Snake Rivers. The purpose of the analysis is to evaluate the risks associated with events that would require a non-routine shutdown at hydroelectric stations and involve an inability to close the intake gates within the time normally allotted. The project is divided into four phases.

Phase 1 - Collects and analyzes relevant plant failure data regarding hydroelectric generating stations.

Phase 2 - Assesses the frequencies of significant failures and estimates the damages incurred.

Phase 3 - Considers and evaluates the consequences and costs of failures requiring an emergency intake closure.

Phase 4 - Develops input for policy recommendations based on results of previous phases.

This paper summarizes the collection and analysis of plant failure data, summarizes the results, and provides discussions for the Phase 1 efforts. Details of the analysis are provided in Blackburn et al. 1995.

2.0 PHASE 1 - DATA COLLECTION AND ANALYSIS

Phase 1 of the project consisted of two major activities: data collection and data analysis. Data collection included performing site visits, conducting a survey of hydroelectric stations, conducting an expert panel elicitation, and reviewing failure data from generic sources. Data analysis included estimating survey, expert, and generic failure rates and then combining these failure rates to produce the final failure data base to be used in the Phases 2, 3, and 4 efforts.

2.1 Data Collection

To initiate the data collection process, site visits with PNL and COE personnel were conducted at five hydroelectric stations. The site visits were performed to help familiarize analysis staff with hydroelectric station design and operation, and to gather the necessary information to prepare the survey and develop the preliminary risk assessment model. Using data obtained from the site visits, preliminary system analysis (using fault tree technique) and accident scenarios (using event tree technique) were developed to the degree necessary to identify the major components to be addressed in the survey and expert workshop. The preliminary event trees and fault trees from Phase 1 will be fully developed in Phase 2 of the project and used to perform the risk analysis regarding non-routine shut down of hydroelectric stations. (Risk is defined as the measure of the potential harm or loss [i.e., hazard] that reflects the likelihood [e.g., frequency] and severity of an adverse effect to health, property, or environment).

A survey was developed to gather historical design and operations data, maintenance data, and failure rate information on hydroelectric stations with Kaplan and Francis turbines that have ratings above 25 MWe. The survey was sent to hydroelectric power plants within the continental United States and Canada.

A formal expert judgement elicitation was conducted to validate the risk analysis model, and to supplement the estimates of failure data for various hydroelectric station components. A standard procedure that has evolved over the years was used to conduct the elicitation (Vo et al. 1991). Figure 1 shows the expert judgment elicitation process.

Figure 1. - Expert Elicitation Process Flow Diagram

2.2 Data Analysis

The data analysis consisted of tabulating the general survey data, and analyzing the failure rate information from the survey, generic sources, and expert elicitation. The general survey data were evaluated using basic descriptive statistics as applicable. Failure rate information was combined to yield a final failure rate (failures/unit-yr) for each system component of interest.

The survey and expert elicited component failure rate information was first tested to determine the most appropriate distribution function to describe the data. Normal, log-normal, and Weibull distributions were considered, and the data were found to be best represented by a log-normal distribution. In both data sets shape (α) and scale (β) parameters were computed for each component. In the survey data, a censored data approach was used to account for the high incidence of zero failure data (no failures during the reported period). For comparison purposes, the survey and expert elicited failure rates (λ) were calculated from the β values. Generic failure rate information was used to supplement the survey data when survey information was absent or statistically insufficient.

The log-normal distribution parameters (α and β) from each data source were then used in a Bayesian analysis to produce a combined failure rate estimate for each component. In the Bayesian analysis two distributions are used. The first distribution, called the *prior distribution*, used survey information supplemented by generic information. This distribution was then modified using the expert elicited information, called the *likelihood function*, to yield a final distribution called the *posterior distribution*. From the posterior distribution, the final component failure rates were calculated. Table 1 provides the survey/generic, expert, and combined (Bayesian) log-normal distribution parameters and failure rates for each component. Shaded boxes in Table 1 indicate generic data were used.

Table 1. Component Failure Rate Summary Data Table

System	Component	Survey/Generic			Expert			Bayesian		
		α	β	λ	α	β	λ	α	β	λ
Trash Rack	Protective Devices	2.80	20.66	4.84E-02	2.15	41.92	2.39E-02	2.25	38.03	2.63E-02
Trash Rack	Trash Rack Bars	2.46	473.95	2.11E-03	1.70	42.58	2.35E-02	1.77	51.33	1.95E-02
Trash Rack	Trash Rack Cleaning Device/Rake	2.80	2.52	3.97E-01	1.91	36.85	2.71E-02	1.99	51.33	1.95E-02
Trash Rack	Trash Rack Frame	3.35	7448.00	1.34E-04	3.37	454.42	2.20E-03	4.37	573.70	1.74E-03
Trash Rack	Trash Rack Supports	1.72	3927.00	2.55E-04	4.20	1857.65	5.38E-04	4.37	1977.00	5.06E-04
Intake Gate Gantry Crane Mechanism	Gantry Crane Controls	1.40	57.08	1.75E-02	1.38	56.64	1.77E-02	1.40	56.98	1.76E-02
Intake Gate Gantry Crane Mechanism	Gantry Crane Hoist	2.72	444.25	2.25E-03	1.93	148.07	6.75E-03	2.01	162.40	6.16E-03
Intake Gate Gantry Crane Mechanism	Gantry Crane Rigging	1.40	57.08	1.75E-02	2.36	160.93	6.21E-03	2.45	147.60	6.78E-03
Intake Gate Gantry Crane Mechanism	Gantry Crane Structures	1.40	57.08	1.75E-02	2.93	1390.27	7.19E-04	3.05	1065.00	9.39E-04
Intake Gate Gantry Crane Mechanism	Gantry Crane Travel	3.31	416.28	2.40E-03	2.93	342.06	2.92E-03	3.03	359.20	2.78E-03
Intake Gate Gantry Crane Mechanism	Gantry Crane Trolley and drive	3.92	2633.00	3.80E-04	2.77	216.91	4.61E-03	2.88	266.80	3.75E-03
Intake Gate Gate Mechanism	Cogs	1.40	57.08	1.75E-02	2.30	157.48	6.35E-03	2.44	138.70	7.21E-03
Intake Gate Gate Mechanism	Gate Locks/Pins/Dogging Beams	1.40	57.08	1.75E-02	3.23	142.37	7.02E-03	3.38	129.90	7.70E-03
Intake Gate Gate Mechanism	Gate Seals	1.95	360.97	2.77E-03	1.66	60.53	1.65E-02	1.72	85.75	1.17E-02
Intake Gate Gate Mechanism	Head Gate Guides	1.40	57.08	1.75E-02	4.39	1536.29	6.51E-04	4.57	1168.00	8.56E-04
Intake Gate Gate Mechanism	Head Gates	1.40	11.42	8.76E-02	3.67	727.04	1.38E-03	3.82	514.30	1.94E-03
Intake Gate Gate Mechanism	Rollers and Wheels	2.72	1202.00	8.32E-04	1.80	136.85	7.31E-03	1.87	158.00	6.33E-03
Intake Gate Hoist Mechanism	Sabotage	2.80	94.34	1.06E-02	3.60	242.98	4.12E-03	3.82	215.90	4.63E-03
Intake Gate Hoist Mechanism	Wire rope hoist controls	3.91	1322.00	7.56E-04	1.85	140.51	7.12E-03	1.94	149.70	6.68E-03
Intake Gate Hoist Mechanism	Wire rope hoist sheaves	1.40	57.08	1.75E-02	2.28	161.41	6.20E-03	2.23	319.00	3.13E-03
Intake Gate Hoist Mechanism	Wire rope hoist, brake or brake release	4.16	7643.00	1.31E-04	2.25	166.12	6.02E-03	2.39	189.20	5.29E-03
Intake Gate Hoist Mechanism	Wire rope hoist, hoist drum and cables	3.03	2416.00	4.14E-04	2.12	395.62	2.53E-03	2.35	222.90	4.49E-03
Intake Gate Hydraulic System	Emergency Lowering Circuit	3.63	726.28	1.38E-03	2.63	202.49	4.94E-03	2.74	227.40	4.40E-03
Intake Gate Hydraulic System	Failure During Handling	2.80	30.77	3.25E-02	2.14	95.02	1.05E-02	2.23	82.70	1.21E-02
Intake Gate Hydraulic System	Flow Control Valve	3.61	922.82	1.08E-03	3.30	225.07	4.44E-03	3.41	352.30	2.84E-03
Intake Gate Hydraulic System	Gate Latch Valve	1.40	11.42	8.76E-02	3.25	475.81	2.10E-03	3.41	327.70	3.05E-03
Intake Gate Hydraulic System	Hydraulic Cylinder	2.92	1158.00	8.64E-04	2.29	177.85	5.62E-03	2.37	225.10	4.44E-03
Intake Gate Hydraulic System	Hydraulic Cylinder Isolation Valve	1.40	11.42	8.76E-02	3.42	235.75	4.24E-03	3.56	183.20	5.46E-03
Intake Gate Hydraulic System	Hydraulic Drive Piping/Fluid	3.68	628.62	1.59E-03	2.55	182.54	5.48E-03	2.66	201.10	4.97E-03
Intake Gate Hydraulic System	Hydraulic Pumps	3.24	2716.00	3.68E-04	2.23	140.99	7.09E-03	2.32	176.40	5.67E-03
Intake Gate Hydraulic System	Lowering Valve	1.40	11.42	8.76E-02	2.22	190.37	5.25E-03	2.32	147.40	6.78E-03
Intake Valve	Air Bleed Valve	1.40	11.42	8.76E-02	1.94	233.41	4.28E-03	2.03	177.40	5.64E-03
Intake Valve	Equalization Line	2.00	1162.00	8.61E-04	2.71	378.28	2.64E-03	2.83	418.90	2.39E-03
Intake Valve	Valve Actuator	1.41	673.87	1.48E-03	1.96	165.05	6.06E-03	2.05	187.60	5.33E-03
Intake Valve	Valve Controls	1.40	57.08	1.75E-02	1.68	116.23	8.60E-03	1.76	109.00	9.17E-03
Intake Valve	Valve Flanges	1.40	57.08	1.75E-02	3.50	5011.87	2.00E-04	3.65	3337.00	3.00E-04
Intake Valve	Valve Linkage	1.14	594.88	1.68E-03	2.70	543.53	1.84E-03	2.82	548.00	1.82E-03
Intake Valve	Valve Seal	4.05	833.77	1.20E-03	2.05	150.60	6.64E-03	2.14	159.40	6.27E-03
Intake Valve	Valve Structure	3.62	7224.00	1.38E-04	3.27	1116.17	8.96E-04	3.38	1974.00	5.07E-04

α - standard deviation of a log-normal distribution
 β - mean of a log-normal distribution
 λ - failure rate (failures/unit-year)

Table 1. Component Failure Rate Summary Data Table

System	Component	Survey/Generic			Expert			Bayesian		
		α	β	λ	α	β	λ	α	β	λ
Penstock Scroll Case Draft Tube	Bypass valve	1.41	16.17	6.18E-02	1.97	430.21	2.32E-03	2.09	285.50	3.50E-03
Penstock Scroll Case Draft Tube	Draft tube equalizing vent	2.99	9114.00	1.10E-04	2.26	365.35	2.74E-03	2.36	533.40	1.87E-03
Penstock Scroll Case Draft Tube	Drain lines and valves	3.93	2987.00	3.35E-04	2.34	700.73	1.43E-03	2.44	750.70	1.33E-03
Penstock Scroll Case Draft Tube	Exposed penstock	2.80	48.66	2.06E-02	2.65	1472.88	6.79E-04	2.73	224.00	4.46E-03
Penstock Scroll Case Draft Tube	Exposed scrollcase	2.80	48.66	2.06E-02	2.03	3015.49	3.32E-04	2.17	1586.00	6.31E-04
Penstock Scroll Case Draft Tube	Flow Separators	0.96	982.25	1.02E-03	3.12	746.30	1.34E-03	3.24	763.60	1.31E-03
Penstock Scroll Case Draft Tube	Liners	3.99	4457.00	2.24E-04	3.40	373.96	2.67E-03	3.52	603.90	1.66E-03
Penstock Scroll Case Draft Tube	Penstock seals and joints	3.41	4074.00	2.45E-04	2.24	464.16	2.15E-03	2.35	549.40	1.82E-03
Penstock Scroll Case Draft Tube	Penstock surge tank	1.62	2030.00	4.93E-04	2.89	1289.53	7.75E-04	3.02	1344.00	7.44E-04
Penstock Scroll Case Draft Tube	Penstock valves	1.40	11.42	8.76E-02	1.89	247.07	4.05E-03	1.97	186.80	5.35E-03
Penstock Scroll Case Draft Tube	Personal access doors	1.65	1597.00	6.26E-04	1.36	251.49	3.98E-03	1.42	339.60	2.94E-03
Penstock Scroll Case Draft Tube	Scroll case equalizing vent	2.06	4619.00	2.16E-04	2.26	1313.03	7.62E-04	2.35	1458.00	6.86E-04
Penstock Scroll Case Draft Tube	Supporting structures	2.97	27390.00	3.65E-05	2.41	1148.70	8.71E-04	2.51	1920.00	5.21E-04
Wicket Gate	Automatic gate locks	3.78	1433.00	6.98E-04	2.39	128.85	7.76E-03	2.49	147.80	6.77E-03
Wicket Gate	Automatic wicket gate lubrication	3.15	73.65	1.36E-02	2.51	38.80	2.58E-02	2.61	42.33	2.36E-02
Wicket Gate	Emergency closure system	2.80	20.66	4.84E-02	1.91	495.93	2.02E-03	1.99	385.00	2.60E-03
Wicket Gate	Servomotors and piping	2.79	1278.00	7.82E-04	2.05	139.03	7.19E-03	2.14	172.20	5.81E-03
Wicket Gate	Shear pin detector	1.40	543.60	1.84E-03	3.00	160.05	6.25E-03	3.24	196.20	5.10E-03
Wicket Gate	Shear pins	2.29	10.67	9.37E-02	1.26	9.05	1.11E-01	1.31	9.11	1.10E-01
Wicket Gate	Shift ring	2.65	9402.00	1.06E-04	2.67	1076.51	9.29E-04	2.78	1290.00	7.75E-04
Wicket Gate	Stay Vanes	3.95	18280.00	5.47E-05	3.97	9977.01	1.00E-04	4.13	10490.00	9.53E-05
Wicket Gate	Wicket gate	2.66	810.64	1.23E-03	2.17	377.98	2.65E-03	2.25	424.20	2.36E-03
Wicket Gate	Wicket gate linkage	1.90	398.13	2.51E-03	2.41	58.97	1.70E-02	2.51	69.15	1.45E-02
Wicket Gate	Wicket gate packing or bushing	3.32	517.80	1.93E-03	2.85	153.63	6.51E-03	2.95	197.40	5.07E-03
Wicket Gate	Wicket gate seals	1.40	11.42	8.76E-02	2.38	79.46	1.26E-02	2.53	62.35	1.60E-02
Wicket Gate	Wicket gate thrust collar	1.40	5188.88	1.93E-04	0.00	1000.00	1.00E-03	0.00	1000.00	1.00E-03
Main Unit Turbine Runner	Blade bushings	2.80	81.30	1.23E-02	2.71	155.11	6.45E-03	2.76	107.40	9.31E-03
Main Unit Turbine Runner	Deflector	3.46	3089.00	3.24E-04	2.93	676.24	1.48E-03	3.05	920.30	1.09E-03
Main Unit Turbine Runner	Intermediate, inner or outer head	2.43	9052.00	1.10E-04	2.62	1423.81	7.02E-04	2.72	1661.00	6.02E-04
Main Unit Turbine Runner	Oil or oil leakage	3.44	3089.00	3.24E-04	2.02	35.11	2.85E-02	2.11	43.05	2.32E-02
Main Unit Turbine Runner	Runner clearance tolerances	3.13	9052.00	1.10E-04	1.92	163.20	6.13E-03	2.00	201.10	4.97E-03
Main Unit Turbine Runner	Turbine blade linkage or connections	2.80	81.30	1.23E-02	2.83	147.14	6.80E-03	2.95	140.00	7.14E-03
Main Unit Turbine Runner	Turbine guide bearing	1.83	158.24	6.32E-03	1.45	51.25	1.95E-02	1.51	59.48	1.68E-02
Main Unit Turbine Runner	Turbine Runner	2.73	466.10	2.15E-03	2.00	246.92	4.05E-03	2.08	262.20	3.81E-03
Main Unit Turbine Runner	Turbine vacuum breaker	2.78	308.60	3.24E-03	2.47	1007.30	9.93E-04	2.55	750.50	1.33E-03
Main Unit Turbine Shaft and Kaplan Mechanism	Bearings and lubrication	3.11	1575.00	6.35E-04	1.70	171.74	5.82E-03	1.79	189.90	5.27E-03
Main Unit Turbine Shaft and Kaplan Mechanism	Kaplan head	3.09	3235.00	3.09E-04	2.04	145.61	6.87E-03	2.13	178.60	5.60E-03
Main Unit Turbine Shaft and Kaplan Mechanism	Pipes and stuffing boxes	3.39	5250.00	1.90E-04	2.35	186.95	5.35E-03	2.45	242.10	4.13E-03
Main Unit Turbine Shaft and Kaplan Mechanism	Servomotor	2.83	3235.00	3.09E-04	1.89	177.35	5.64E-03	1.97	216.40	4.62E-03
Main Unit Turbine Shaft and Kaplan Mechanism	Shaft flanges	2.80	320.51	3.12E-03	2.32	2318.38	4.31E-04	2.41	1667.00	6.00E-04
Main Unit Turbine Shaft and Kaplan Mechanism	Shaft journal	2.80	320.51	3.12E-03	3.36	779.98	1.28E-03	3.50	724.30	1.38E-03
Main Unit Turbine Shaft and Kaplan Mechanism	Shaft packing	2.70	335.16	2.98E-03	2.33	54.26	1.84E-02	2.41	79.46	1.26E-02
Main Unit Turbine Shaft and Kaplan Mechanism	Turbine speed limiting device	1.40	38.05	2.63E-02	3.32	501.98	1.99E-03	3.55	347.20	2.88E-03

α - standard deviation of a log-normal distribution
 β - mean of a log-normal distribution
 λ - failure rate (failures/unit-year)

Table 1. Component Failure Rate Summary Data Table

System	Component	Survey/Generic			Expert			Bayesian		
		α	β	λ	α	β	λ	α	β	λ
Main Generator	Brakes	2.77	101.13	9.89E-03	1.84	89.43	1.12E-02	1.91	90.16	1.11E-02
Main Generator	Exciter	2.10	64.48	1.55E-02	1.20	159.01	6.29E-03	1.26	151.90	6.58E-03
Main Generator	Fire detection and suppression	2.66	2608.00	3.83E-04	2.12	514.51	1.94E-03	2.20	652.00	1.53E-03
Main Generator	Generator cooling	2.18	99.22	1.01E-02	2.30	382.98	2.61E-03	2.40	342.20	2.92E-03
Main Generator	Grounding	2.34	711.44	1.41E-03	1.48	824.94	1.21E-03	1.57	814.50	1.23E-03
Main Generator	Guide Bearings	2.65	441.51	2.26E-03	1.25	143.22	6.98E-03	1.30	147.40	6.78E-03
Main Generator	Rotor	1.49	227.95	4.39E-03	2.02	315.84	3.17E-03	2.10	307.40	3.25E-03
Main Generator	Shaft or shaft couplings	2.80	160.26	6.24E-03	2.67	2133.09	4.69E-04	2.73	621.00	1.61E-03
Main Generator	Stator	1.28	42.03	2.38E-02	1.77	93.00	1.08E-02	1.84	87.04	1.15E-02
Main Generator	Thrust Bearings	2.16	158.38	6.31E-03	1.67	113.17	8.84E-03	1.74	117.80	8.49E-03
Main Unit Governor Wicket Gates and Blades	Accumulator tanks and components	1.58	371.25	2.69E-03	2.88	246.62	4.05E-03	3.02	256.90	3.89E-03
Main Unit Governor Wicket Gates and Blades	Actuator pilot valve	4.05	3041.00	3.29E-04	2.00	41.92	2.39E-02	2.11	48.65	2.06E-02
Main Unit Governor Wicket Gates and Blades	Blade distributing valve	1.40	11.42	8.76E-02	1.62	119.62	8.36E-03	1.69	96.62	1.03E-02
Main Unit Governor Wicket Gates and Blades	Blade positioning mechanism	3.34	8535.00	1.17E-04	1.44	132.98	7.52E-03	1.52	147.30	6.79E-03
Main Unit Governor Wicket Gates and Blades	Compensating dashpots	2.65	1574.00	6.35E-04	1.94	57.31	1.74E-02	2.03	83.21	1.20E-02
Main Unit Governor Wicket Gates and Blades	Gate distributing valve	1.40	11.42	8.76E-02	1.99	136.08	7.35E-03	2.09	106.20	9.42E-03
Main Unit Governor Wicket Gates and Blades	Governor flyball motor	2.80	13.04	7.67E-02	2.07	74.99	1.33E-02	2.17	60.88	1.64E-02
Main Unit Governor Wicket Gates and Blades	Governor hydraulic fluid	2.80	18.94	5.28E-02	2.23	142.68	7.01E-03	2.33	105.50	9.48E-03
Main Unit Governor Wicket Gates and Blades	Governor hydraulic fluid valves	1.40	11.42	8.76E-02	1.61	92.92	1.08E-02	1.68	76.80	1.30E-02
Main Unit Governor Wicket Gates and Blades	Governor oil piping	2.68	14680.00	6.81E-05	2.36	744.68	1.34E-03	2.44	1584.00	6.31E-04
Main Unit Governor Wicket Gates and Blades	Governor oil pumps/motors	2.14	66.77	1.50E-02	1.76	66.40	1.51E-02	1.83	66.46	1.50E-02
Main Unit Governor Wicket Gates and Blades	Governor oil tank	4.10	48590.00	2.06E-05	2.56	1573.09	6.36E-04	2.70	2026.00	4.94E-04
Main Unit Governor Wicket Gates and Blades	Hydraulic connections	3.76	96260.00	1.04E-05	2.50	225.37	4.44E-03	2.62	367.90	2.72E-03
Main Unit Governor Wicket Gates and Blades	Mechanical connections	2.80	18.94	5.28E-02	1.95	45.28	2.21E-02	2.05	41.66	2.40E-02
Main Unit Governor Wicket Gates and Blades	Permanent magnet generator	2.53	1137.00	8.80E-04	2.88	190.69	5.24E-03	3.02	228.00	4.39E-03
Main Unit Governor Wicket Gates and Blades	Restoring cables or mechanism	2.06	591.27	1.69E-03	1.42	110.72	9.03E-03	1.49	129.10	7.75E-03
Main Unit Governor Wicket Gates and Blades	Restoring devices	1.43	765.02	1.31E-03	1.38	105.36	9.49E-03	1.41	382.50	2.61E-03
Main Unit Governor Wicket Gates and Blades	Speed signal generator	3.49	2642.00	3.79E-04	2.34	135.11	7.40E-03	2.45	173.00	5.78E-03
Main Unit Governor Wicket Gates and Blades	Sump tanks	1.40	228.31	4.38E-03	2.66	1130.48	8.85E-04	2.78	977.50	1.02E-03
AC and DC Systems	120 VAC Distribution	1.40	4.17	2.40E-01	2.40	95.52	1.05E-02	2.51	71.85	1.39E-02
AC and DC Systems	2400 VAC Distribution	2.00	1449.00	6.90E-04	2.34	114.86	8.71E-03	2.47	152.20	6.57E-03
AC and DC Systems	4160 VAC Distribution	2.44	557.94	1.79E-03	3.03	129.15	7.74E-03	3.18	149.50	6.69E-03
AC and DC Systems	480 VAC Distribution	3.34	190.80	5.24E-03	2.50	86.19	1.16E-02	2.61	94.25	1.06E-02
AC and DC Systems	Annunciation system	4.12	173.16	5.78E-03	1.99	35.52	2.82E-02	2.08	37.08	2.70E-02
AC and DC Systems	Battery switchboard bus/breakers	4.11	1900.00	5.26E-04	2.60	110.83	9.02E-03	2.72	132.40	7.55E-03
AC and DC Systems	Control room equipment	2.80	51.81	1.93E-02	2.24	46.27	2.16E-02	2.33	47.07	2.12E-02
AC and DC Systems	Emergency diesel generator	4.04	1155.00	8.66E-04	2.48	119.07	8.40E-03	2.59	134.10	7.46E-03
AC and DC Systems	Governor electrical supply and control system	3.68	327.82	3.05E-03	2.64	130.17	7.68E-03	2.74	141.10	7.09E-03
AC and DC Systems	Intake gate electrical controls	3.26	215.82	4.63E-03	1.92	81.37	1.23E-02	2.01	85.49	1.17E-02
AC and DC Systems	Main unit control switchboard	2.80	8.70	1.15E-01	2.73	140.58	7.11E-03	2.77	24.46	4.09E-02
AC and DC Systems	Station battery	2.59	289.13	3.46E-03	2.83	315.00	3.17E-03	2.95	312.80	3.20E-03
AC and DC Systems	Transfer switch	1.40	114.16	8.76E-03	2.62	147.55	6.78E-03	2.83	141.40	7.07E-03

α - standard deviation of a log-normal distribution

β - mean of a log-normal distribution

λ - failure rate (failures/unit-year)

Table 1. Component Failure Rate Summary Data Table

System	Component	Survey/Generic			Expert			Bayesian		
		α	β	λ	α	β	λ	α	β	λ
Protection	86 relays	1.40	38.05	2.63E-02	4.12	249.53	4.01E-03	4.32	206.70	4.84E-03
Protection	Generator differential relay	1.92	915.20	1.09E-03	3.55	200.62	4.98E-03	3.70	227.70	4.39E-03
Protection	Generator ground relay	1.03	1042.00	9.60E-04	3.85	305.12	3.28E-03	4.02	341.20	2.93E-03
Protection	Generator loss of field relays	2.86	18800.00	5.32E-05	3.70	200.62	4.98E-03	3.85	292.90	3.41E-03
Protection	Generator overcurrent relay	2.93	7441.00	1.34E-04	3.72	247.34	4.04E-03	3.87	328.50	3.04E-03
Protection	Generator overvoltage relay	2.90	3540.00	2.82E-04	3.72	247.34	4.04E-03	3.87	308.70	3.24E-03
Protection	Generator phase unbalance relay	3.96	99750.00	1.00E-05	3.81	373.03	2.68E-03	3.89	8281.00	1.21E-04
Protection	Line directional ground relay	1.40	38.05	2.63E-02	3.84	242.36	4.13E-03	4.01	204.80	4.88E-03
Protection	Line phase relays	3.47	3562.00	2.81E-04	3.85	305.12	3.28E-03	4.02	381.50	2.62E-03
Protection	Line residual relays	3.69	56170.00	1.78E-05	3.85	305.12	3.28E-03	4.02	490.20	2.04E-03
Protection	Main transformer differential relay	1.37	1658.00	6.03E-04	3.72	247.34	4.04E-03	3.87	289.80	3.45E-03
Protection	Main unit relaying	1.40	38.05	2.63E-02	2.85	91.55	1.09E-02	2.97	85.09	1.18E-02
Protection	Station service system relaying	1.40	38.05	2.63E-02	3.57	247.34	4.04E-03	3.72	211.60	4.73E-03
Protection	Station service transformers differential relays	1.40	38.05	2.63E-02	3.91	206.33	4.85E-03	4.09	176.90	5.65E-03
Protection	Transformer neutral ground relay	1.40	38.05	2.63E-02	3.74	238.17	4.20E-03	3.90	204.40	4.89E-03
Protection	Under/over voltage relay for station battery	1.40	38.05	2.63E-02	3.85	305.12	3.28E-03	4.02	252.50	3.96E-03
Fish Screen and Vertical Barrier Screen	Brush drive assembly	1.40	1.14	8.76E-01	2.02	23.57	4.24E-02	2.10	18.32	5.46E-02
Fish Screen and Vertical Barrier Screen	Fish screen controls	3.78	954.63	1.05E-03	2.54	56.84	1.76E-02	2.65	69.25	1.44E-02
Fish Screen and Vertical Barrier Screen	Perforated plates	1.40	3.81	2.63E-01	2.71	89.63	1.12E-02	2.83	68.89	1.45E-02
Fish Screen and Vertical Barrier Screen	Screen drive system assembly	3.79	1364.00	7.33E-04	1.75	16.19	6.18E-02	1.82	18.00	5.56E-02
Fish Screen and Vertical Barrier Screen	Stainless steel bar screen	1.40	3.81	2.63E-01	2.83	76.16	1.31E-02	2.95	59.33	1.69E-02
Fish Screen and Vertical Barrier Screen	Structural frame/extension mechanism	3.95	2252.00	4.44E-04	2.27	58.00	1.72E-02	2.37	67.90	1.47E-02
Fish Screen and Vertical Barrier Screen	Traveling mesh	3.94	77.45	1.29E-02	2.29	13.13	7.62E-02	2.39	14.21	7.04E-02
Fish Screen and Vertical Barrier Screen	Vertical barrier screen frame	1.40	3.81	2.63E-01	2.48	100.00	1.00E-02	2.58	76.15	1.31E-02
Fish Screen and Vertical Barrier Screen	Vertical barrier screen mesh	1.40	3.81	2.63E-01	2.53	51.99	1.92E-02	2.63	41.81	2.39E-02
Fish Screen and Vertical Barrier Screen	Vertical barrier screen perforated plate	1.40	3.81	2.63E-01	2.57	117.00	8.55E-03	2.68	87.94	1.14E-02
Fish Screen and Vertical Barrier Screen	Wire rope/handling controls	0.97	6.14	1.63E-01	1.79	30.84	3.24E-02	1.86	26.96	3.71E-02

α - standard deviation of a log-normal distribution
 β - mean of a log-normal distribution
 λ - failure rate (failures/unit-year)

2.3 Discussion

Of the 337 surveys distributed, 150 were returned. This overall return rate of 45% is considered excellent. The 150 respondents have a total of 680 units with an average operation time of 34.9 years for a total of 23,732 unit-years of operation. It should be noted that every plant responding to the survey did not necessarily provide complete component failure rate information. On the average, only 32 plants (9.5% of the distributed surveys) responded for any given component. Generally, the number of respondents was sufficient to generate a statistically valid failure rate estimate. However, in some cases the reported numbers of failures were either too few or too widely varied to be usable in this analysis. In these cases generic information was compiled from a number of sources and was used to supplement the survey information (NUREG/CR-4550 1987, NUREG/CR-2815 1985, IEEE 1983, Curley 1994).

Several insights can be drawn from the survey general information and from the comments provided with the survey component failure rates. First, the initiating events identified in the model have in fact occurred. Twenty-nine of the respondents indicated events have occurred where intake gate closure was required to control a running unit. In one case damage from an overspeed condition was reported. A second insight from the survey is that failures of systems required to mitigate overspeed conditions (e.g., wicket gates, governor, intake gate, etc.) can be expected to occur in the future.

For components with adequate survey data, the component failure rates (failures/unit-yr) ranged from $1.0\text{E-}05$ (generator phase unbalance relay) to $1.6\text{E-}01$ (fish screen wire rope handling controls) failures per unit-year. NOTE: A failure rate of $1.0\text{E-}01$ failures per unit-year correlates to one failure every 10 years for each unit. Overall, the data are considered very reasonable. In general, the components with moving parts and others such as shear pins and shaft packing had the higher failure rates. Large structural components such as the trash rack frame and supports, gantry crane structures, and head gates tended to have lower failure rates.

For components where generic data were used to supplement the survey information, failure rates ranged from $1.9\text{E-}04$ (wicket gate thrust collar) to $8.8\text{E-}01$ (fish screen brush drive assembly) failures per unit-year. The generic failure rate values tend to be conservatively higher than the survey data failure rates.

The conduct of the expert elicitation went extremely well, and exceptional cooperation was achieved from both expert participants and observers alike. The experts carefully deliberated about their failure rate estimates during the workshop, and a number of carefully thought out revisions were made after the workshop. Excellent rationale was provided by the experts to justify their estimates. In general, the data were tightly grouped indicating good agreement among the experts. A general trend was noted. The failure rate derived from the expert estimates tends to be larger than the one derived from the survey data. It is expected that the

survey data will tend to underestimate the failure rates because the respondent is being asked to recall specific failures. Some failures are frequently forgotten or simply not reported. Experts were asked to give a best estimate of the failure rate based on their experience. This type of elicitation tends to produce an estimate that overestimates the actual value.

The expert rationale and comments provided insights on several issues. Specifically, proper maintenance can be instrumental in reducing component and system failure rates. The experts indicated that systems which were easily accessible and routinely inspected were much more reliable than systems receiving little or no preventive maintenance. In addition, the experts noted that failure rates would be higher early and late in component life (bathtub curve), and higher in newly designed systems. Newly designed systems were considered to be especially susceptible to the commonly experienced failure modes of cavitation and flow induced vibrations.

For all plant components studied, expert elicited failure rate estimates ranged from $1.0\text{E-}04$ (wicket gate stay vanes) to $1.1\text{E-}01$ (wicket gate shear pin) failures per unit-year. In general, the data seem to be very reasonable. The components with moving parts had the higher failure rates, and large structural components tended to have lower failure rates.

Figure 2 shows the expert elicited and survey failure rates plotted for the 13 components of the

Figure 2. - Wicket Gate System Expert and Survey Failure Rate Plot

wicket gate system. Gaps in the plot correlate to components that were added at the expert workshop (no survey data exists). When the expert elicited failure rates are compared to the survey failure rates, the failure rate trends match exceptionally well. Although the expert elicited failure rate is generally higher than the survey failure rate, it is obvious that there is significant agreement about the relative failure rates between components. This trending improves the confidence in both the survey and expert data. The same general trends are apparent throughout the remainder of the data.

As expected the Bayesian updated failure rates lie between the expert elicited and survey/generic failure rates. Figure 3 shows the medians and uncertainties for the first three applicable components of the wicket gate system. It is obvious from this plot that the final Bayesian failure rates are closer to the expert elicited failure rate. This is due in part to the fact that the Bayesian process naturally weights the results toward the data which have lower statistical uncertainties. The survey data have larger uncertainties than the expert data by one or two orders of magnitude. The Bayesian process weights the expert data accordingly.

The Bayesian technique used also naturally weights the final result toward the likelihood data. The analyst must determine which data set is the most reliable and then use this data set as the likelihood function. In this study, the expert elicitation process was a more focused data collection technique than the survey distribution so the expert data were judged to be more reliable than the survey data. They provided improved knowledge based on operational experience. The expert data were therefore used as the likelihood function in the Bayesian analysis. The Bayesian process then weighted the results accordingly. The same general trends shown in Figure 3 are apparent throughout the data.

Figure 3. - Failure Rate Median and Uncertainty Comparison Plot

For all systems studied, the final combined component failure rates ranged from 9.5E-05 (wicket gate stay vanes) to 1.1E-01 (wicket gate shear pin) failures per unit-year. A listing of the ten components with the highest failure rates are provided in Table 2. These component failure rate values do not reflect the associated system reliability. Overall, the data are considered very reasonable and will provide an excellent input into the Phase 2 and Phase 3 analyses.

Phase 2 and Phase 3 of the project will evaluate the overall plant risk including component importance factors. While specific system reliability predications cannot be made at this time, it is expected that the fish screen system will be important. Experience has shown that new designs tend to have a higher failure rate compared to proven designs. The fish screen system is an example of a new design that the experts believe to have a higher failure rate than most other hydroelectric station systems. The survey results support this opinion. Fish screen system final combined failure rates occupied three of the top ten calculated failure rates. Its components have some of the highest failure rates, and certain failures of the fish screen could result in debris being carried into the turbine.

It should be noted that systems with low reliability components are not necessarily the most risk significant. Risk significance is a combination of the component reliability and severity of the component failure consequences. If a system has high reliability, but a failure results in serious consequences, it could be very risk significant. Conversely, a system with low reliability could prove to be risk insignificant if a failure of the system results in minor consequences. The fish screen and vertical barrier screen have low reliability compared to other components but their failure consequences have not yet been determined. Component failure consequences and risk significance will be assessed in Phase 2 and Phase 3 analyses.

Table 2. - Ten Components With Highest Failure Rates

System	Component	Failure Rate (failure/unit-year)
Wicket Gate	Shear pins	1.10E-01
Fish Screen and Vertical Barrier Screen	Traveling mesh	7.04E-02
Fish Screen and Vertical Barrier Screen	Screen drive system assembly	5.56E-02
Fish Screen and Vertical Barrier Screen	Wire rope/handling controls	3.71E-02
AC and DC Systems	Annunciation system	2.70E-02
Wicket Gate	Automatic wicket gate lubrication	2.36E-02
Main Unit Turbine Runner	Oil or oil leakage	2.32E-02
Main Unit Governor Wicket Gates and Blades	Actuator pilot valve	2.06E-02
Trash Rack	Trash Rack Bars	1.95E-02
Main Unit Turbine Runner	Turbine guide bearing	1.68E-02

3.0 PHASE 2, 3, AND 4 EFFORTS

Phase 2 of the project (which is currently being performed) evaluates the probability per year that emergency or non-routine shut down of a unit will be required due to occurrence of an event. The analysis includes qualitative and quantitative risk assessments using approaches outlined in the ASME Risk-Based Inspection Guidelines (ASME 1991). Analysis considers the hydroelectric plant's component functional interactions and the probability of their failures initiating events and/or contributing to events that require emergency closure of turbine intake gates.

Phase 3 will evaluate the economic consequences involved in a failure requiring an emergency intake gate closure. The analysis will consider adverse effects, direct and indirect effects, and losses as described in the ASME Guidelines. The analysis will determine the probable and foreseeable maximum losses for closure times ranging from 5 minutes to infinity. Results from Phase 2 and Phase 3 analyses will be used in the Phase 4 effort, which will focus on policy recommendations regarding operation and maintenance of hydroelectric stations.

4.0 CONCLUSIONS

Based on the results of the Phase 1 study, the following observations and insights were gained.

The survey data return rate was excellent, and the surveys provided a substantial amount of very useful information regarding design and operation of hydroelectric stations.

The expert elicitation workshop went very well. The experts carefully deliberated about their failure rate estimates during the workshop, and a number of carefully thought out revisions were made after the workshop. The rationale provided by the experts to justify their estimates were also excellent. The expert rationale and comments provided insights on several issues. Specifically, proper maintenance can be instrumental in reducing component and system failure rates. Information obtained from expert panel indicated that the systems which were easily accessible and routinely inspected were much more reliable.

The final Bayesian analysis combined failure rates are between the expert elicited failure rates and the survey/generic failure rates. The combined estimates tended to be closer to the expert elicited data. As expected, the final combined data appear reasonable and reflect plant operational practices.

The final combined data will be useful in the Phase 2 and Phase 3 analyses for estimating frequencies and consequences of non-routine shutdown/closure of hydroelectric generating

stations. Results of this project may be used to provide policy recommendations regarding operation and maintenance of hydroelectric stations, which will be performed in Phase 4 efforts.

Specifically, information obtained from this project can be used to estimate the service life of components and probability of hydroelectric station failures. This information may also be used to assist the Corps in establishing scheduled replacement policies, and better decision making for costly investments for major rehabilitation and major maintenance and inspections.

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