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Common-Cause Failure Parameter Estimations

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Prepared by
F. M. Marshall/INEEL
D. M. Rasmuson/NRC
A. Mosleh/Univ. of MD

Idaho National Engineering and Environmental Laboratory
Lockheed Martin Idaho Technologies Company
Idaho Falls, ID 83415

Subcontractor:
Department of Materials and Nuclear Engineering
University of Maryland
College Park, MD 20742-2115

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Safety Programs Division
Office for Analysis and Evaluation of Operational Data
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ABSTRACT

This report documents the quantitative results of the common cause failure (CCF) data collection effort described in Volumes 1 - 4 of the Common Cause Failure System Database and Analysis System (References 2-5), as well as some qualitative insights about the data. These results are for use in Probabilistic Risk Assessment (PRA) studies of commercial nuclear power plants in the U.S. It summarizes the results of the parameter estimation quantification process, performed on the CCF data, as described in Volume 2 of that series of reports.

Equipment failures that contribute to CCF events are identified during searches of Licensee Event Reports and Nuclear Plant Reliability Data System failure reports. Once CCF events are identified by screening reports of equipment failures, they are coded for entry into a personal computer storage system. Once all data for a specific system and component data set have been entered, parameter estimations are performed, producing the results. The results of the database analysis are presented here as a summary of the entire database, and as individual reports for individual system/component combinations describe the system and component boundaries, along with the guidelines for identifying CCF events that may be unique to the data set.

The quantitative results are presented as both alpha factors and multiple Greek letter parameter estimations. The alpha factor uncertainty distributions are also presented.

CONTENTS

EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission's (NRC's) Office for Analysis and Evaluation of Operational Data (AEOD) has developed and maintained a common cause failure (CCF) database for the U.S. commercial nuclear power industry. Previous studies documented methods for identifying and quantifying CCFs. This report contains the CCF parameter estimates for the majority of the risk important safety systems and components in commercial nuclear power plants. The methods used to quantify these parameters are described in Volumes 1 - 4 of the Common Cause Failure Database and Analysis System.(2-5)

A CCF event consists of component failures that meet four criteria: (1) two or more individual components fail or are degraded, including failures during demand, in-service testing, or deficiencies that would have resulted in a failure if a demand signal had been received; (2) components fail within a selected period of time such that success of the PRA mission would be uncertain; (3) component failures result from a single common cause and coupling mechanism; and (4) a component failure occurs within the established component boundary.

Two data sources are used to select equipment failures to be reviewed for CCF events: The Nuclear Plant Reliability Data System and the Sequence Coding and Search System. These sources served as the developmental basis for the CCF data collection and analysis system. The CCF data collection and analysis system consists of (1) CCF event identification methodology, (2) event coding guidance, and (3) a software system to estimate CCF parameters.

A software system stores CCF and independent failure data, and automates the PRA parameter estimation process. The system employs two quantification models: alpha factor and the multiple Greek letter. These models are used throughout the nuclear industry. The individual summary reports for each system/component combination provide the parameter estimations for that set of data. These results can be used in PRA studies throughout the industry in place of the current CCF parameter estimates, giving a more accurate treatment of CCFs in risk modeling.

In addition to the individual results provided in this report, there are some general insights about the CCF events that are contained in the database.

ACRONYMS

ADS	automatic depressurization system
AEOD	Nuclear Regulatory Commission's Office for the Analysis and Evaluation of Operational Data
AFP	auxiliary feedwater pump
AFW	auxiliary feedwater
AOV	air operated valve (AOV)
BWR	boiling water reactor
CCCG	common cause component group
CCF	common cause failure
CCP	centrifugal charging pump
CSR	containment spray recirculation
CSS	containment spray system
CST	condensate storage tank
ECCS	emergency core cooling system
EDG	emergency diesel generator
ESFAS	engineered safety features actuation system
ESW	emergency service water
HPCI	high pressure coolant injection
HPSI	high pressure safety injection
HX	heat exchanger
IC	isolation condenser
INEEL	Idaho National Engineering and Environmental Laboratory
LER	Licensee Event Report
LOCA	loss of coolant accident
LOSP	loss of offsite power
LPCI	low pressure coolant injection
LPSI	low pressure safety injection
MCC	motor control centers
MFP	main feedwater pump
MGL	multiple Greek letter
MLE	maximum likelihood estimates
MOV	motor operated valve
MS	main steam
MSIV	main steam isolation valve
NPRDS	Nuclear Plant Reliability Data System
NRC	Nuclear Regulatory Commission
PORV	power operated relief valve
PRA	probabilistic risk assessment
PRT	pressurizer relief tank
PWR	pressurized water reactor
RCIC	reactor core isolation cooling
RCS	reactor coolant system
RHR	residual heat removal
RPV	reactor pressure vessel
RTB	reactor trip breaker

RV	relief valve
RWST	refueling water storage tank
SI	safety injection
SLC	standby liquid control
SV	safety valve
TS	technical specifications
VAC	volts alternating current
VDC	volts direct current

1. INTRODUCTION

Purpose of the Database

The U.S. Nuclear Regulatory Commission's (NRC's) Office for Analysis and Evaluation of Operational Data (AEOD) has developed and maintained a common cause failure (CCF) database for the U.S. commercial nuclear power industry. Previous studies documented methods for identifying and quantifying CCF events.[1] This document contains the summaries of common cause failure event analyses based upon event data contained in the CCF event database, using the CCF database software. The purpose of these summaries is to provide estimates of common cause parameters for use in agency reliability and risk studies. An overview of this CCF project and coding process is contained in Reference 2. The CCF data collection and analysis system consists of (1) CCF event identification methodology, (2) event coding guidance, and (3) a software system to estimate CCF parameters.

Data Sources

The data sources used are Licensee Event Reports (LERs) and failure records contained in the Nuclear Plant Reliability Data System (NPRDS). Data from 1980 through 1995 were analyzed. Because of the differences in the two data sources (LERs discuss plant and system events, while NPRDS contains component failure information), there is little duplication of data, and a check for duplicated events is performed. Data from other sources were used in special cases (e.g., "Special Reports" for emergency diesel generators).

Event Classification

A CCF event consists of component failures that meet four criteria: (1) two or more individual components fail or are degraded, including failures during demand, in-service testing, or deficiencies that would have resulted in a failure if a demand signal had been received; (2) components fail within a selected period of time such that success of the PRA mission would be uncertain; (3) component failures result from a single common cause and coupling mechanism; and (4) a component failure occurs within the established component boundary. Each event is coded following rules that are found in References 3 and 4. These rules were developed to help reduce the variability that exists between different analysts when they code the events.

Database Content and Use

The table of contents contains a list of the components for which CCF events have been collected and analyzed. Component definitions follow probabilistic risk assessment (PRA) component boundaries and are described in the individual summary report for each system/component combination set of data. Reference 5 contains guidance for performing database searches and CCF parameter estimations. Section 2 of this document presents a summary of the data contained within the database, along with some general insights about the complete set of CCF data.

Use of Parameter Estimates

The recommended parametric model to use in quantifying CCFs is the alpha factor model. It is preferred to the multiple Greek letter (MGL) method for several reasons. First, it has a firm statistical sampling basis. Secondly, reasonable and defensible uncertainty distributions can be defined and estimated for the alpha factor CCF parameters. It is recommended that mean values be used instead of the maximum likelihood estimates. Table 1 contains formulas for using the alpha factor method in CCF analyses (assuming staggered testing). Table 2 contains formulas related to nonstaggered testing. Note that $Q_T = A_1/\alpha_1$ where Q_T is the total failure probability, Q_1 is the independent failure probability of the component, and

$$\alpha_t = \sum_{i=1} i\alpha_i \ .$$

Section 4 of this document contains summary reports for each set of data for which CCF events are in the CCF database. These reports contain the alpha factor parameter estimates with the uncertainty distributions for each set of data. MGL model estimates for each set of data are also displayed in the summary reports. Additional information about the quantification of CCF parameters in reliability and risk studies are found in References 3 and 6.

Quality Assurance

The data classification, loading, and parameter estimation have several levels of quality control built into the process. First, all events are reviewed by two data analysts to make sure that the events are classified as CCF events and coded correctly. Subsequently, a PRA analyst reviews the CCF events and results for consistency and comparison with PRA experience. A final review is performed by an independent CCF expert, outside the Idaho National Engineering and Environmental Laboratory (INEEL).

Sources of Uncertainty

Several sources of uncertainty exists in the parameter estimates. One source is the inherent variability of the data itself. Additional uncertainty results from the analysts' interpretation of the events from the written event description, usually due to the lack of information in the source data. To reduce the effect of this uncertainty on the final results, event identification and coding guidelines were developed. Other sources of uncertainty include plant-to-plant variation, etc. Future efforts will address and quantify these uncertainties. Prior to using the estimates provided in this report, it is recommended that the user evaluate the individual event data from the database to ensure that the events included in the parameter estimations are relevant to the individual study being performed.

Special CCF Data Analysis

Special CCF event analyses can be performed using the database. The summary reports contain generic or average CCF parameter estimates that can be used in most studies at the NRC. When an application requires plant-specific values, the CCF database can be used to obtain specific CCF parameter estimates for these specialized cases.

Additional Information

Additional information about CCFs, how the data were classified, and how to use the data in reliability and risk studies can be found in the references.

Proprietary Information

Because the CCF event database contains proprietary information from NPRDS, the database itself is proprietary. However, the results presented here in the individual summary reports can be used and published as needed.

Contacts

For more information about the database, please contact:

Dr. Dale M. Rasmuson
Telephone: (301) 415-7571

<u>Organization and Mailing Address</u>
Reliability and Risk Assessment Branch
Safety Programs Division
Office for Analysis and Evaluation of
Operational Data
U.S. Nuclear Regulatory Commission
Mail Stop: T4A9
Washington, D.C. 20555-0001

Table 1. Common cause quantification using alpha factor model (*staggered testing*).

CCCG Size	Configuration	Common Cause Failure Probability
2	1 of 2	$\alpha_2 Q_T$
	2 of 2	
3	1 of 3	$\alpha_3 Q_T$
	2 of 3	$\left\| \frac{3\alpha_2}{2} + \alpha_3 \right\| Q_T$
	3 of 3	
4	1 of 4	$\alpha_4 Q_T$
	2 of 4	$\left\| \frac{6\alpha_2}{3} + \frac{4\alpha_3}{3} + \alpha 4 \right\| Q_T$
	3 of 4	$\left\| \frac{4\alpha_3}{3} + \alpha_4 \right\| Q_T$
	4 of 4	
5	1 of 5	$\alpha_5 Q_T$
	2 of 5	$\left\| \frac{5\alpha_4}{4} + \alpha_5 \right\| Q_T$
	3 of 5	$\left\| \frac{10\alpha_3}{6} + \frac{5\alpha_4}{4} + \alpha_5 \right\| Q_T$
	4 of 5	$\left\| \frac{10\alpha_2}{4} + \frac{10\alpha_3}{6} + \frac{5\alpha 4}{4} + \alpha_5 \right\| Q_T$
	5 of 5	
6	1 of 6	$\alpha_6 Q_T$
	2 of 6	$\left\| \frac{6\alpha_5}{5} + \alpha_6 \right\| Q_T$
	3 of 6	$\left\| \frac{15\alpha_4}{10} + \frac{6\alpha_5}{5} + \alpha_6 \right\| Q_T$
	4 of 6	$\left\| \frac{20\alpha_3}{10} + \frac{15\alpha_4}{10} + \frac{6\alpha_5}{5} + \alpha_6 \right\| Q_T$
	5 of 6	$\left\| \frac{15\alpha_2}{5} + \frac{20\alpha_3}{10} + \frac{15\alpha_4}{10} + \frac{6\alpha_5}{5} + \alpha_6 \right\| Q_T$
	6 of 6	

Table 2. Common cause quantification using alpha factor model (*nonstaggered testing*).

CCCG Size	Configuration	Common Cause Failure Probability
2	1 of 2	$\frac{2\alpha_2}{\alpha_t}Q_T$
	2 of 2	
3	1 of 3	$\frac{3\alpha_3}{\alpha_t}Q_T$
	2 of 3	$\frac{3(\alpha_2 + \alpha_3)}{\alpha_t}Q_T$
	3 of 3	
4	1 of 4	$\frac{4\alpha_4}{\alpha_t}Q_T$
	2 of 4	$\frac{4(\alpha_2 + \alpha_3 + \alpha_4)}{\alpha_t}Q_T$
	3 of 4	$\frac{4(\alpha_3 + \alpha_4)}{\alpha_t}Q_T$
	4 of 4	
5	1 of 5	$\frac{5\alpha_5}{\alpha_t}Q_T$
	2 of 5	$\frac{5(\alpha_4 + \alpha_5)}{\alpha_t}Q_T$
	3 of 5	$\frac{5(\alpha_3 + \alpha_4 + \alpha_5)}{\alpha_t}Q_T$
	4 of 5	$\frac{5(\alpha_2 + \alpha_3 + \alpha_4 + \alpha_5)}{\alpha_t}Q_T$
	5 of 5	
6	1 of 6	$\frac{6\alpha_6}{\alpha_t}Q_T$
	2 of 6	$\frac{6(\alpha_5 + \alpha_6)}{\alpha_t}Q_T$
	3 of 6	$\frac{6(\alpha_4 + \alpha_5 + \alpha_6)}{\alpha_t}Q_T$
	4 of 6	$\frac{6(\alpha_3 + \alpha_4 + \alpha_5 + \alpha_6)}{\alpha_t}Q_T$
	5 of 6	$\frac{6(\alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6)}{\alpha_t}Q_T$
	6 of 6	

2. GENERAL INSIGHTS FROM ANALYSIS OF CCF DATA

The CCF database developed in this project is a rich source of information on various aspects of common cause failure. Exploring the full potential of the database merits a dedicated activity and is outside the scope of the current effort, which has focused on building the infrastructure for such analyses. Nevertheless, some general observations have been made about the character of CCF events, including their causes and coupling factors, and frequency of occurrence. Some of these insights are summarized in this section.

Table 3 lists the systems, component types, and failure modes for which CCF events have been collected and entered into the database. It also contains the number of CCF events for each system and component combination and the number of associated independent failure events. Table 3 only displays the event counts for failure modes that are relevant to PRA studies. Other failure modes, such as failure to close for reactor trip breakers, were found in the source data; these events were coded and entered into the CCF database, even though they are not likely to be used in PRA studies.

Basic information about the nature of CCF events is displayed in Figures 1 and 2, which illustrate the distribution of CCF event proximate causes and coupling factors, respectively. This information provides a general picture of the types of CCF events that may be expected to occur, and what design features might be most susceptible to CCF events. These figures also illustrate the different characteristics of partial CCF events and complete CCF events (events with timing factor, shared cause factor, and component degradation values for each component in the CCCG =1.0). Figures 3, 4, and 5 display the number of CCF events by year of occurrence.

A general review of the actual events and the distributions provided in Figures 1and 2, reveals the following insights regarding CCF events:

- A major contributor to CCF events is programmatic maintenance practices. The frequency of scheduling has been a factor in the numerous wear out-caused and aging-caused events. Additionally, the quality of the maintenance, both in the procedures and in performance of the maintenance activities, is a key factor. Similar events have occurred at different plants—lubrication of circuit breakers (too much, too little, or too long between lubrications), improperly set torque and limit switches on motor operated valves (MOV) that are reported as misadjustments and not setpoint drift. This indicates that there are maintenance practices that need to be reviewed to reduce common cause failure potential.

- Another contributor is design problems. Many of the design-related events resulted from a design modification, indicating that perhaps the modification review processes were not rigorous and resulted in CCF susceptibilities. This theory was not investigated as part of the project, but can be considered in CCF event reduction efforts.

- Human errors related to procedures caused a small percentage of the total events, but the impact of the individual events is usually greater, since human errors have overridden the programmatic controls. This is illustrated by comparing Figure 1b with Figure 1a, which shows that human error causes a larger portion of complete CCF events than partial CCF events. Examples of events caused by human error are all emergency diesel generator (EDG) day tanks simultaneously drained for a chemistry surveillance, two pump breakers racked out as the plant changed modes from shutdown to power.

- A vast majority of the CCF events are not due to multiple failures in response to an operational demand, but result from a "condition of equipment." The most common is inspection or surveillance test of one component revealing a deficiency that prompts the licensee to inspect/test the redundant component, resulting in the discovery that the same defective condition exists on both components. This demonstrates that detection of failures during the testing and surveillance program prevents CCF events from occurring during demand situations.

- The CCF database contains several examples where both CCF and independent events recur at some, but not all, plants, perhaps indicating ineffective root cause analysis and corrective action. Examples of repeated events are water in compressed air systems, pump seal wear out, and turbine governor misadjustment. Additionally, not all plants experience the same type of recurring event. This indicates that plant-to-plant variability exists in the CCF parameters that might cause the CCF parameter estimates for some plants to be higher than the industry average for certain component and system combinations. Thus, it is very important to perform plant-specific CCF parameter estimations for plant-specific PRAs and reliability studies.

With respect to quantification of common cause failures, the overall conclusion is that, based on the evaluation of over 15 years of operating experience data, CCF parameters for similar components vary among systems and failure modes. Table 4 displays maximum likelihood estimates (MLE) for both EDG failure modes, fail to start and fail to run. Tables 5 and 6 display the MLEs for both the alpha factors (α_2) and beta factors for several component and system combinations. These results illustrate that the parameter estimates vary for different failure modes within the same component group, and that they also vary between different systems for the same component.

Another useful observation is that common cause failure parameters of different components are available. Figure 6 shows the component-to-component variability of the mean α_2 for various system and component combinations. It also shows a beta distribution fit to these data. The equation for this beta distribution is:

$$\pi(\alpha) \propto \frac{\Gamma(A+B)}{\Gamma(A)(B)} \alpha^{A-1} (1-\alpha)^{B-1}$$

where $A = 2.0291$, $B = 45.707$.

$$\alpha_{5\%} = 0.0079$$
$$\alpha_{95\%} = 0.0984$$
$$\alpha_{mean} = 0.0425$$

Table 3. Component types and systems analyzed for CCF events (1980-1995).

Component Type	PRA-relevant Failure Modes	Systems Analyzed for the Component Type	No. of CCF Events for System and Component Type	No. of Independent Failures for System & Component Type	Total No. of CCF Events for Component Type	Total Number of Independent Failures for Component Type
Air-Operated Valves	Fail to Open	Auxiliary Feedwater (PWR)	46 ✓	197	127	431
	Fail to Close	High Pressure Injection (BWR)	2 ✗	28		
	Fail to Remain Closed	Isolation Condenser (BWR)	1 ✗	9		
		Main Steam Isolation (BWR & PWR)	78 ✓	197		
Batteries/Chargers	No, High Output	DC Power (BWR & PWR)	60 ✓	1,260	60	1,260
Check Valves	Fail to Open	Auxiliary Feedwater (PWR)	59 ✓	202	139	557
	Fail to Close	High Pressure Injection (BWR/PWR)	15/21 21	84/145		
	Fail to Remain Closed	Low Pressure Injection (BWR/PWR)	23/21 21	88/38		
Circuit Breakers	Fail to Open	DC Power (BWR & PWR)	8 ✓	112	116	977
	Fail to Close	AC Power (BWR & PWR)	82 ✓	755		
	Fail to Remain Closed	Reactor Trip Breakers (fail to open only) (PWR)	26 ✓	110		
Emergency Diesel Generators	Fail to Start, Run	Emergency Power (BWR & PWR)	131 ✓	1,361	131	1,361
Heat Exchangers	Fail to Transfer Heat	Containment Spray (PWR)	10 ✓	14	19	32
		Residual Heat Removal (BWR/PWR)	8 ✓	15		
		Isolation Condensers (BWR)	1 ✗	2		
Motor-Operated Valves	Fail to Open	Auxiliary Feedwater (PWR)	30 ✓	422	195	2,577
	Fail to Close	Containment Spray (PWR)	15 ✓	250		
	Fail to Remain Closed	High Pressure Injection (BWR/PWR)	11/40 40	372/292		
		Isolation Condenser (BWR)	2 ✗	44		
		Low Pressure Injection/RHR (BWR/PWR)	61/23 23	498/470		
		Pressurizer (PWR)	7 ✓	155		
		Refueling Water Storage Tank (PWR)	6 ✓	74		
Pumps	Fail to Start	Auxiliary Feedwater (PWR)	51 ✓	919	281	3,519
		Emergency Service Water (BWR & PWR)	141 ✓	1,184		
		High Pressure Injection (BWR/PWR)	2/42 42	343/492		
		Low Pressure Injection (BWR/PWR)	9/26 26	149/362		
		Standby Liquid Control (BWR)	10 ✗	70		
Relief Valves	Fail to Open	BWR Primary System	38 ✗	271	121	1,047
	Fail to Close	Pressurizer (PWR)	22 ✓	337		
	Fail to Remain Closed	Steam Generator (PWR)	61 ✓	439		
Safety Valves	Fail to Open	Pressurizer (PWR)	6 ✓	119	38	280
	Fail to Close Fail to Remain Closed	Steam Generator (PWR)	32 ✓	161		
Strainers	Fail to Allow Flow	Containment Sump (PWR)	1 ✓	3	37	170
		Emergency Service Water (BWR & PWR)	34 ✓	162		
		Suppression Pool (BWR)	2 ✗	5		

1,264 12,211

PWRs related → 1,087

- CCW PUMPS
- CHILLERS
- DAMPERS
- TA CONTROLS

Table 4. Emergency diesel generator CCF parameter estimations.

	Fail to Start			**Fail to Run**		
	CCCG=2	**CCCG=3**	**CCCG=4**	**CCCG=2**	**CCCG=3**	**CCCG=4**
Alpha Factor	**Alpha Factor Parameter Estimations**					
α_1	0.968323	0.9630082	0.9636932	0.9599057	0.950802	0.949033
α_2	3.12E-02	2.04E-02	1.35E-02	4.01E-02	2.89E-02	2.19E-02
α_3	—	1.66E-02	1.14E-02	—	2.11E-02	1.46E-02
α_4	—	—	1.14E-02	—	—	1.45E-02
MGL Parameter	**MGL Parameter Estimations**					
1-Beta	9.69E-01	9.63E-01	9.64E-01	9.60E-01	9.50E-01	9.49E-01
Beta	3.12E-02	3.70E-02	3.63E-02	4.01E-02	4.99E-02	5.10E-02
Gamma	—	4.50E-01	6.27E-01	—	4.22E-01	5.72E-01
Delta	—	—	5.01E-01	—	—	4.99E-01
Adj. Independent Events	544.37	816.55	1,088.73	461.18	691.77	922.35

Fail to Start
Number of Independent Failure Events: 773
Number of Common Cause Failure Events: 55

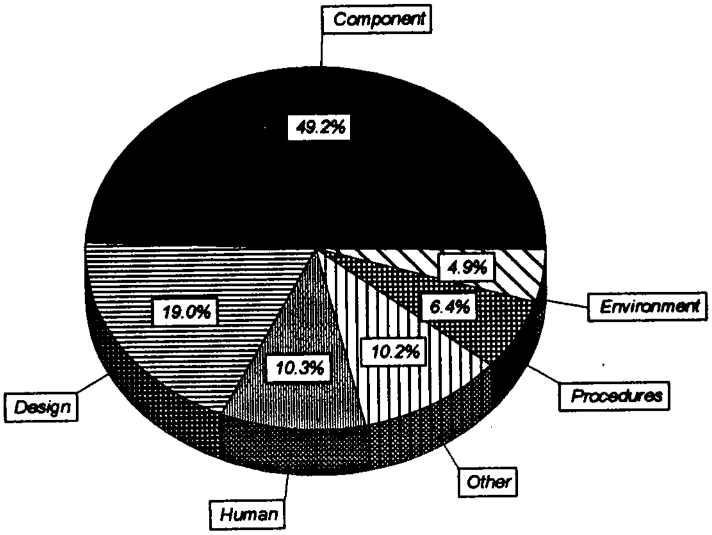
Fail to Run
Number of Independent Failure Events: 588
Number of Common Cause Failure Events: 76

Table 5. Alpha and beta factors for motor operated valves (CCCG=6).

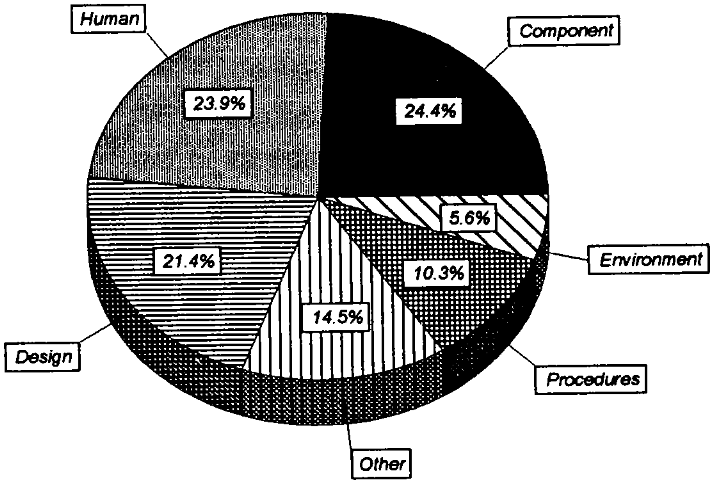
System	**Alpha Factor (α_2)**		**Beta Factor (β)**	
	Fail to Open	**Fail to Close**	**Fail to Open**	**Fail to Close**
Auxiliary Feedwater - PWR	1.31E-2	2.20E-2	3.47E-2	5.41E-2
High Pressure Safety Injection - PWR	2.22E-2	2.66E-2	5.69E-2	3.53E-2
Low Pressure Safety Injection - PWR	1.17E-2	9.33E-3	1.74E-2	1.54E-2
Low Pressure Coolant Injection - BWR	1.53E-2	2.06E-2	3.44E-2	4.37E-2

Table 6. Alpha and beta factors for pumps.

System	**CCCG**	**Alpha Factor (α_2)**		**Beta Factor (β)**	
		Fail to Start	**Fail to Run**	**Fail to Start**	**Fail to Run**
Emergency Service Water- BWR & PWR	6	4.03E-2	1.28E-2	9.70E-2	3.94E-2
Auxiliary Feedwater - PWR	4	4.52E-2	2.42E-2	1.33E-2	3.88E-2
High Pressure Safety Injection - PWR	3	2.58E-2	1.96E-2	5.53E-2	2.80E-2
Low Pressure Safety Injection - PWR	2	6.32E-2	5.35E-2	6.32E-2	5.35E-2
Low Pressure Coolant Injection - BWR	4	3.15E-2	6.49E-3	3.17E-2	6.49E-3
Standby Liquid Control - BWR	2	9.80E-2	3.24E-2	9.80E-2	3.24E-2

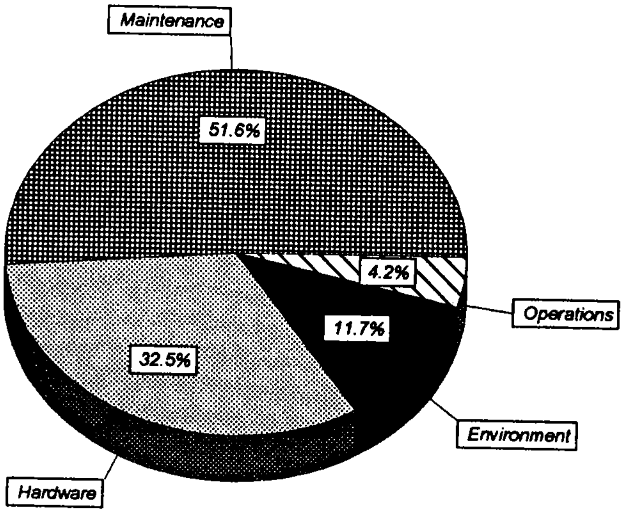


a. Distribution of causes of complete and partial CCF events.

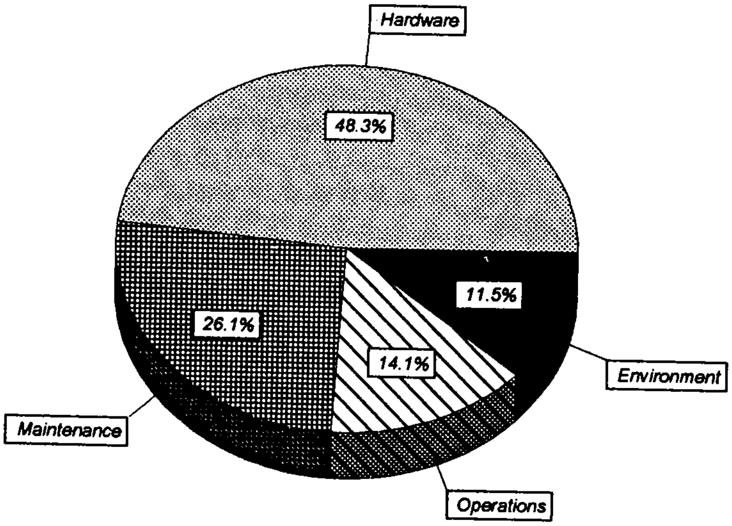


b. Distribution of causes of only the complete CCF events.

Figure 1. Distribution of CCF events by cause.



a. Distribution of coupling factors for both complete and partial CCF events.



b. Distribution of coupling factors for only the complete CCF events.

Figure 2. Distribution of CCF events by coupling factor.

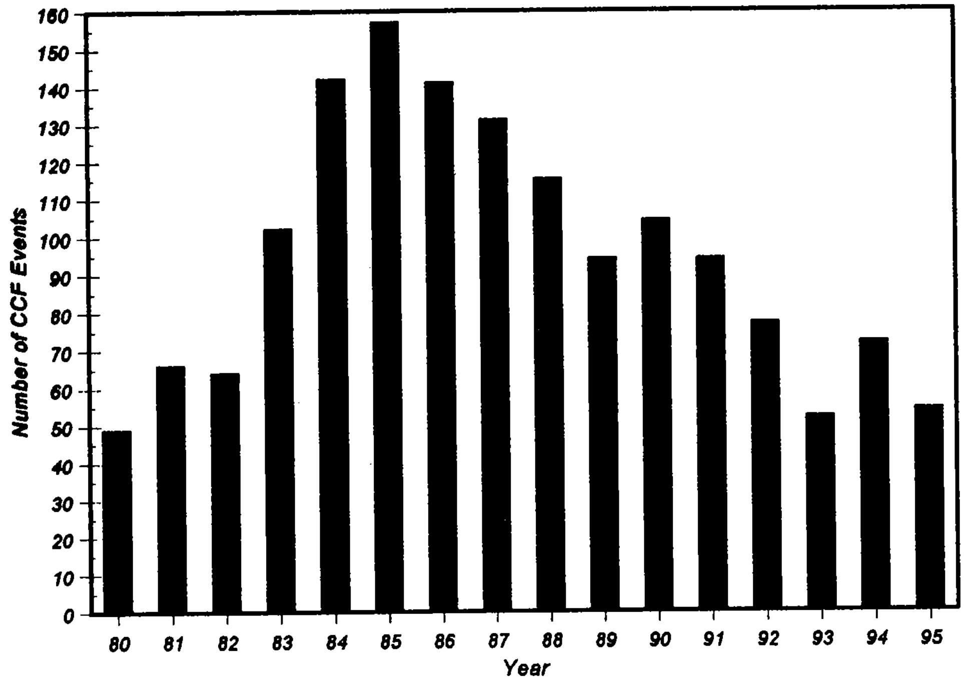


Figure 3. Distribution of all CCF events in database by year.

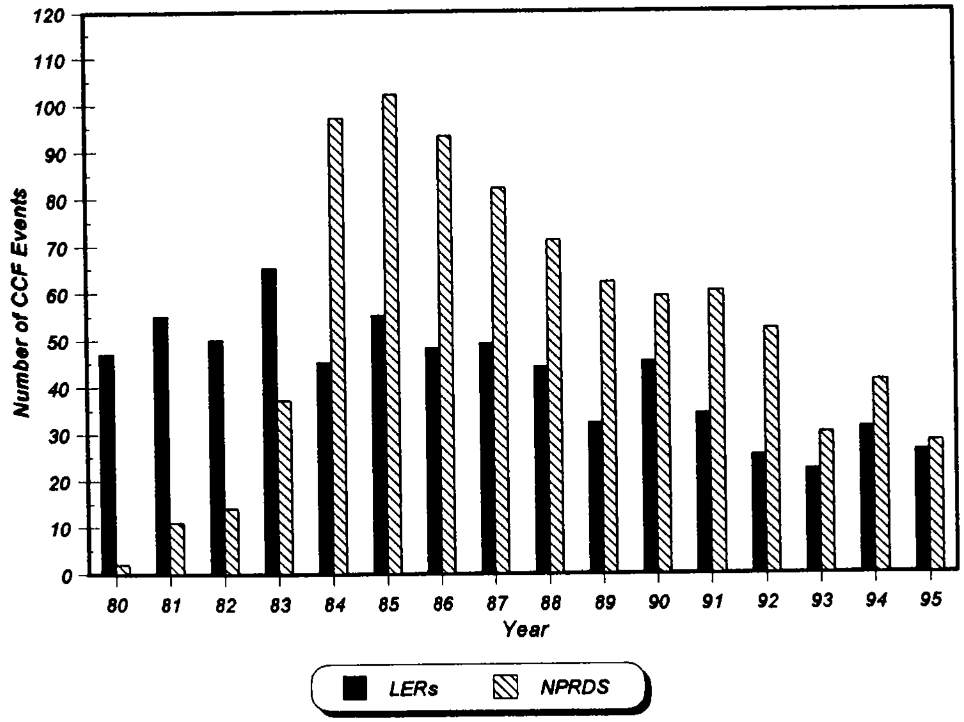


Figure 4. Distribution of CCF events by year and source.

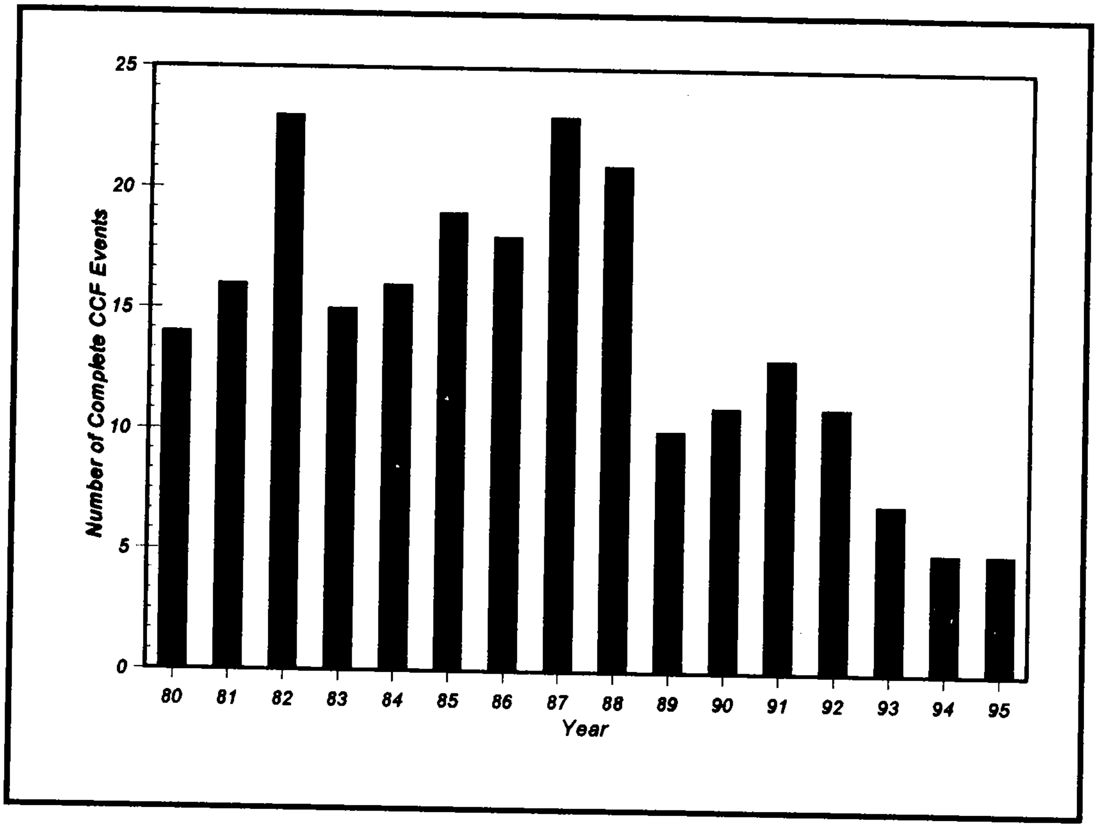


Figure 5. Distribution of complete CCF events by year.

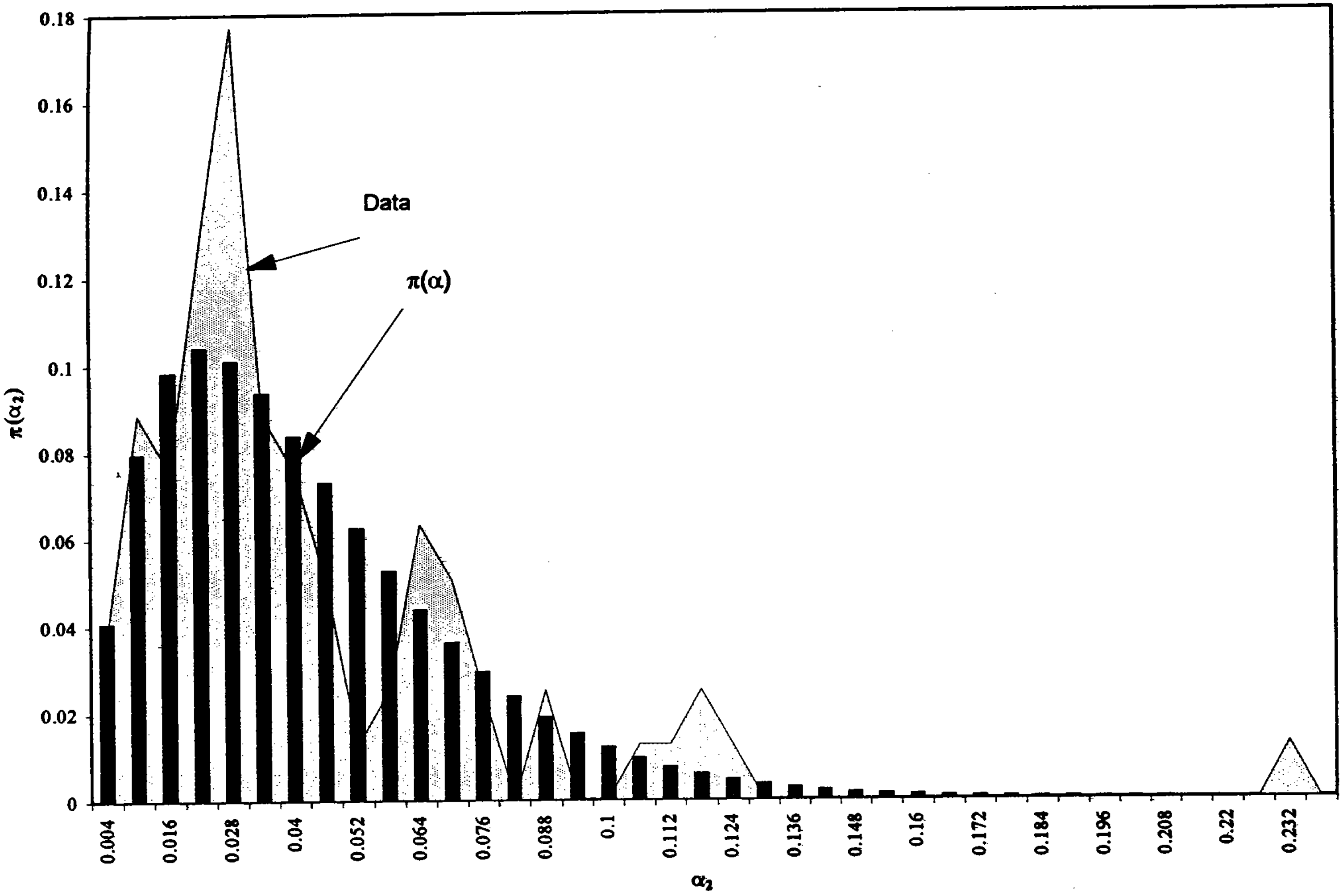


Figure 6. Component-to-component variability of alpha factors.

3. REFERENCES

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2. U.S Nulcear Regulatory Commission, *Common Cause Failure Database and Analysis System Volume 1—Overview*, NUREG/CR-6268, June 1998, INEEL/EXT-97-00696.

3. U.S Nulcear Regulatory Commission, *Common Cause Failure Database and Analysis System Volume 2—Event Definition and Classification*, NUREG/CR-6268, June 1998, INEEL/EXT-97-00696.

4. U.S Nulcear Regulatory Commission, *Common Cause Failure Database and Analysis System Volume 3—Data Collection and Event Coding*, NUREG/CR-6268, June 1998, INEEL/EXT-97-00696.

5. K. J. Kvarfordt, et al., *Common Cause Failure Database and Analysis System Volume 4—CCF Software Reference Manual*, INEEL/EXT-97-00696, July 1997.

6. A. Mosleh, et. al., *Guidelines on Modeling Common Cause Failures in Probabilistic Risk Assessments*, INEEL/EXT-97-01327, November, 1997.

4. SUMMARY REPORTS

The following sections of this document summarize the information about each set of data for which CCF events were collected and are contained in the CCF database. They are listed by the system/component combination that is of interest from a risk perspective. The full listing of the data sets and the order in which they appear in this section of the document is in the Table of Contents. These summary reports are all in the same format, and contain the same information, individualized for each specific set of data.

Each report briefly describes the system, with discussion of the specific components within the system that are risk significant. There is also discussion of the failure mode of interest, typically only for those failure modes that are risk important. The CCF parameter estimates displayed in the summary report tables, for both the alpha factor and multiple Greek letter methods, were obtained directly from the CCF database software, along with the uncertainty distributions for the alpha factor estimates.

1. DC Power System - Batteries and Chargers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving batteries and battery charger at both boiling water reactor (BWR) power plants and pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to provide voltage/amperage output and providing high voltage/amperage output. The data cover the time period from 1980 through 1995.

The data review identified 12 common-cause failure to provide voltage/amperage events for batteries, 42 common-cause failure to provide voltage/amperage output events for battery chargers, and six common-cause high voltage/ amperage output events for battery chargers. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for battery failure to provide voltage/amperage are shown in Tables 1-1 and 1-2, respectively. Table 1-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode. Tables 1-4 through 1-9 contain the corresponding information for the battery charger failure to provide output and battery charger high output failure modes. The size of the affected population of batteries and chargers is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 1-10 through 1-24.

2. SYSTEM DESCRIPTION

The Class 1E DC power system consists of batteries and their respective output breaker, battery chargers and their associated input/output breakers supplying 250 VDC, 125 VDC and a few lower voltages to essential equipment. Two Boiling Water Reactors, Nine Mile Point 1 and Oyster Creek, have motor-generator sets suppling DC power in place of battery chargers, but were considered within this report. Components of the DC power system are arranged in trains, or divisions, which are electrically independent and physically separated.

A DC power train or division normally consists of one battery, one or two battery chargers, and associated distribution panels. Four trains of DC power are typical but the number can be as few as one train for older plants (e.g., Big Rock Point). Some sites have shared DC power systems between the units. For example, at Browns Ferry, a multi-unit site, one DC power system provides power to all three units. Each DC power train receives power from the Class 1E 480 VAC electrical busses via the battery charger and supplies the normal source of DC power to the various loads while maintaining the batteries in a fully charged condition. A battery charger's electrical capacity is usually sufficient to supply all DC loads and concurrently charge the associated battery. In the event of a loss of AC power, the station batteries supply an emergency source of DC power to the essential DC loads. The capacity of the storage battery is sufficient to power all required loads on a DC power train for a specific length of time. A schematic of a single train of the DC power system is shown in Figure 1-1.

ALPHA FACTOR AND MGL PARAMETERS
DC Power Batteries

Table 1-1: Summary of Alpha Factor Parameter Estimations - Batteries No Voltage/Amperage Output

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9901388	0.9873122	0.9868140	0.9872159	0.9875319
α_2	9.86E-03	7.81E-03	6.77E-03	5.17E-03	3.89E-03
α_3		4.88E-03	3.05E-03	3.69E-03	3.36E-03
α_4			3.37E-03	1.30E-03	2.22E-03
α_5				2.62E-03	7.83E-04
α_6					2.22E-03

Table 1-2: Summary of MGL Parameter Estimations - Batteries No Voltage/Amperage Output

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.90E-01	9.87E-01	9.87E-01	9.87E-01	9.88E-01
Beta	9.86E-03	1.27E-02	1.32E-02	1.28E-02	1.25E-02
Gamma		3.85E-01	4.87E-01	5.96E-01	6.88E-01
Delta			5.25E-01	5.15E-01	6.08E-01
Epsilon				6.68E-01	5.75E-01
Mu					7.39E-01

Table 1-3: Summary of Average Impact Vectors - Batteries No Voltage/Amperage Output

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	154.35	231.53	308.71	385.89	463.06
N_1	3.8827	3.6533	3.3410	3.0925	2.9390
N_2	1.5759	1.8593	2.1391	2.0365	1.8337
N_3		1.1630	0.9650	1.4548	1.5866
N_4			1.0656	0.5129	1.0458
N_5				1.0330	0.3696
N_6					1.0478

Total Number of Independent Failure Events: 257

Total Number of Common-Cause Failure Events: 12

ALPHA FACTOR AND MGL PARAMETERS
DC Power Chargers

Table 1-4: Summary of Alpha Factor Parameter Estimations - Chargers No Voltage/Amperage

Alpha Factor	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
α_1	0.9873822	0.9795111	0.9766041	0.9749025	0.9716802
α_2	1.26E-02	1.80E-02	1.49E-02	1.33E-02	1.23E-02
α_3		2.51E-03	6.81E-03	6.83E-03	6.53E-03
α_4			1.67E-03	3.76E-03	4.16E-03
α_5				1.27E-03	3.12E-03
α_6					2.25E-03

Table 1-5: Summary of MGL Parameter Estimations - Chargers No Voltage/Amperage

MGL Parameter	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
1-Beta	9.87E-01	9.80E-01	9.77E-01	9.75E-01	9.72E-01
Beta	1.26E-02	2.05E-02	2.34E-02	2.51E-02	2.83E-02
Gamma		1.22E-01	3.62E-01	4.72E-01	5.67E-01
Delta			1.97E-01	4.24E-01	5.93E-01
Epsilon				2.52E-01	5.63E-01
Mu					4.19E-01

Table 1-6: Summary of Average Impact Vectors - Chargers No Voltage/Amperage

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
Adj. Ind. Events	344.77	517.16	689.55	861.93	1034.32
N_1	23.2786	24.9458	25.5530	24.8060	22.6062
N_2	4.7033	9.9522	10.9280	12.0477	13.3289
N_3		1.3873	4.9832	6.2092	7.1050
N_4			1.2201	3.4184	4.5295
N_5				1.1525	3.3963
N_6					2.4446

Total Number of Independent Failure Events: 874
Total Number of Common-Cause Failure Events: 42

ALPHA FACTOR AND MGL PARAMETERS
DC Power Chargers

Table 1-7: Summary of Alpha Factor Parameter Estimations - Chargers High Voltage/Amperage

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9950344	0.9900374	0.9849809	0.9844117	0.9818690
α_2	4.97E-03	9.96E-03	1.50E-02	1.19E-02	1.11E-02
α_3		0.00E+00	0.00E+00	3.65E-03	5.57E-03
α_4			0.00E+00	0.00E+00	1.44E-03
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 1-8: Summary of MGL Parameter Estimations - Chargers High Voltage/Amperage

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.95E-01	9.90E-01	9.85E-01	9.84E-01	9.82E-01
Beta	4.97E-03	9.96E-03	1.50E-02	1.56E-02	1.81E-02
Gamma		0.00E+00	0.00E+00	2.34E-01	3.87E-01
Delta			0.00E+00	0.00E+00	2.06E-01
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 1-9: Summary of Average Impact Vectors - Chargers High Voltage/Amperage

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	59.58	89.38	119.17	148.96	178.75
N_1	2.6802	3.0890	2.8780	2.9177	2.3736
N_2	0.3107	0.9305	1.8610	1.8419	2.0520
N_3		0.0000	0.0000	0.5631	1.0270
N_4			0.0000	0.0000	0.2656
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 129
Total Number of common-Cause Failure Events: 6

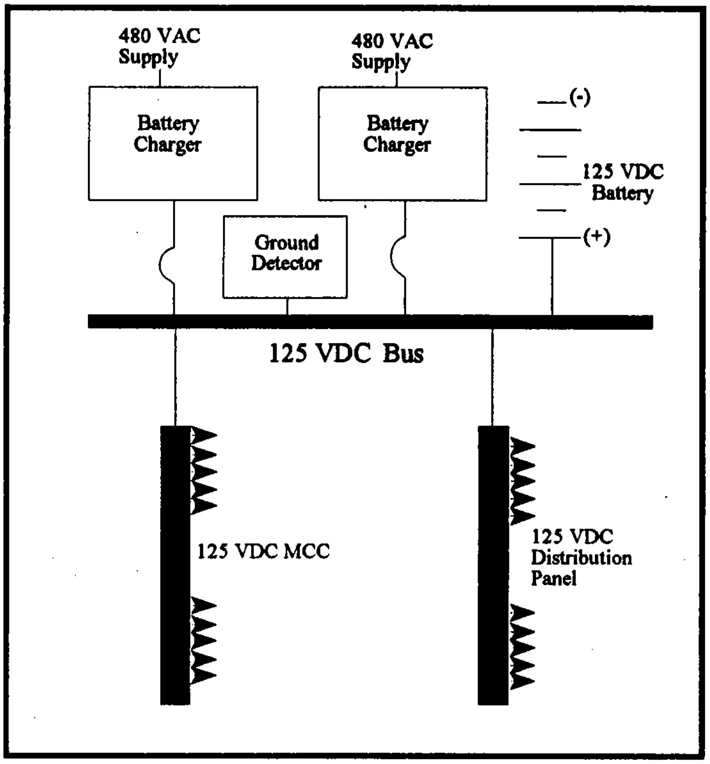

Figure 1-1. Generic DC power train.

3. COMPONENT BOUNDARIES

The super component of this analysis was the DC Power train consisting of several sub-components (e.g., battery charger, battery, and connecting bus work). Individual load breakers in the distribution panels were not included. Each battery charger's piece-parts included the AC input breaker as well as the DC output breaker. The battery output breaker and associated fuses were considered integral parts of the battery.

4. FAILURE EVENT DEFINITION

Successful operation of a DC power system is defined as each train maintaining DC power from either the battery charger or the battery to the essential loads. The respective failure modes used for evaluating the battery and battery charger data were:

NO No Voltage/Amperage Output. Examples are:

- battery charger input/output circuit breaker fails open,
- battery output circuit breaker fails open,
- circuit breakers fails to close,
- battery charger fails to produce output,
- battery electrolyte level or specific gravity low, and
- battery fuses blown.

HI High Voltage/Amperage Output. Examples are:

- battery charger setpoint drift, and
- battery charger output phase imbalance.

DC power malfunctions are considered to be failures to provide adequate DC power on demand. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the DC power system.

Battery chargers and battery failures are evaluated to determine the effect on the DC power system. In general, if the failure causes the component to fail to operate, it will be considered a failure of a DC power train. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered DC power system failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of DC power system demand. The exception to this is if a licensee reported that the DC power system component "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications for individual components (i.e., battery chargers or batteries) in the proper configuration is not considered a failure, unless the improper configuration would have prevented the DC power system or individual train from operating as designed.

Some LERs reported only one actual failure, but the report information indicated that a second component would have failed. If the cause of the actual failure would have clearly caused failure of another battery charger, then the event was identified as a CCF. If, however, the report did not clearly identify that another battery charger would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 1-10 through 1-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of DC power. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
DC Power Batteries

Table 1-10: Alpha Factor Distribution Summary - Battery No Voltage/Amperage Output, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9717763	0.9879515	0.9898062	0.9977822	0.9901388	1.6776E+02	2.0459E+00
α_2	2.22E-03	1.21E-02	1.02E-02	2.82E-02	9.86E-03	2.0459E+00	1.6776E+02

Table 1-11: Alpha Factor Distribution Summary - Battery No Voltage/Amperage Output, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9706556	0.9849635	0.9862149	0.9949938	0.9873122	2.5038E+02	3.8223E+00
α_2	1.81E-03	8.84E-03	7.59E-03	2.01E-02	7.81E-03	2.2465E+00	2.5196E+02
α_3	7.91E-04	6.20E-03	4.96E-03	1.58E-02	4.88E-03	1.5758E+00	2.5263E+02

Table 1-12: Alpha Factor Distribution Summary - Battery No Voltage/Amperage Output, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9715154	0.9840170	0.9849484	0.9933295	0.9868140	3.3675E+02	5.4697E+00
α_2	1.95E-03	7.87E-03	6.93E-03	1.70E-02	6.77E-03	2.6929E+00	3.3953E+02
α_3	2.93E-04	3.59E-03	2.68E-03	9.99E-03	3.05E-03	1.2276E+00	3.4099E+02
α_4	5.62E-04	4.53E-03	3.61E-03	1.16E-02	3.37E-03	1.5492E+00	3.4067E+02

Table 1-13: Alpha Factor Distribution Summary - Battery No Voltage/Amperage Output, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9728488	0.9838839	0.9846190	0.9923949	0.9872159	4.2703E+02	6.9948E+00
α_2	1.62E-03	6.37E-03	5.63E-03	1.37E-02	5.17E-03	2.7645E+00	4.3126E+02
α_3	7.01E-04	4.30E-03	3.57E-03	1.04E-02	3.69E-03	1.8668E+00	4.3216E+02
α_4	3.76E-05	1.72E-03	1.04E-03	5.72E-03	1.30E-03	7.4650E-01	4.3328E+02
α_5	4.94E-04	3.73E-03	3.00E-03	9.45E-03	2.62E-03	1.6170E+00	4.3241E+02

Table 1-14: Alpha Factor Distribution Summary - Battery No Voltage/Amperage Output, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9740430	0.9839752	0.9845835	0.9918218	0.9875319	5.1647E+02	8.4111E+00
α_2	1.20E-03	4.98E-03	4.37E-03	1.09E-02	3.89E-03	2.6128E+00	5.2227E+02
α_3	7.79E-04	4.05E-03	3.44E-03	9.41E-03	3.36E-03	2.1272E+00	5.2275E+02
α_4	2.56E-04	2.59E-03	1.99E-03	6.96E-03	2.22E-03	1.3585E+00	5.2352E+02
α_5	1.21E-05	1.17E-03	6.25E-04	4.17E-03	7.83E-04	6.1290E-01	5.2427E+02
α_6	4.62E-04	3.24E-03	2.63E-03	8.08E-03	2.22E-03	1.6997E+00	5.2318E+02

ALPHA FACTOR DISTRIBUTIONS
DC Power Battery Chargers

Table 1-15: Alpha Factor Distribution Summary - Charger No Voltage/Amperage Output, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9755644	0.9864840	0.9873253	0.9945362	0.9873822	3.7758E+02	5.1733E+00
α_2	5.46E-03	1.35E-02	1.27E-02	2.44E-02	1.26E-02	5.1733E+00	3.7758E+02

Table 1-16: Alpha Factor Distribution Summary - Charger No Voltage/Amperage Output, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9678705	0.9786828	0.9792392	0.9875901	0.9795111	5.5731E+02	1.2139E+01
α_2	1.00E-02	1.82E-02	1.76E-02	2.82E-02	1.80E-02	1.0339E+01	5.5911E+02
α_3	4.90E-04	3.16E-03	2.60E-03	7.74E-03	2.51E-03	1.8010E+00	5.6765E+02

Table 1-17: Alpha Factor Distribution Summary - Charger No Voltage/Amperage Output, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9658384	0.9756914	0.9761114	0.9841213	0.9766041	7.3980E+02	1.8432E+01
α_2	8.65E-03	1.51E-02	1.47E-02	2.31E-02	1.49E-02	1.1482E+01	7.4675E+02
α_3	2.81E-03	6.92E-03	6.49E-03	1.25E-02	6.81E-03	5.2458E+00	7.5299E+02
α_4	3.22E-04	2.25E-03	1.83E-03	5.61E-03	1.67E-03	1.7037E+00	7.5653E+02

Table 1-18: Alpha Factor Distribution Summary - Charger No Voltage/Amperage Output, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9648649	0.9738979	0.9742318	0.9817981	0.9749025	9.2478E+02	2.4786E+01
α_2	7.94E-03	1.35E-02	1.31E-02	2.01E-02	1.33E-02	1.2776E+01	9.3679E+02
α_3	3.20E-03	6.97E-03	6.63E-03	1.19E-02	6.83E-03	6.6212E+00	9.4295E+02
α_4	1.23E-03	3.85E-03	3.50E-03	7.63E-03	3.76E-03	3.6520E+00	9.4591E+02
α_5	2.69E-04	1.83E-03	1.49E-03	4.54E-03	1.27E-03	1.7365E+00	9.4783E+02

Table 1-19: Alpha Factor Distribution Summary - Charger No Voltage/Amperage Output, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9621408	0.9707803	0.9710582	0.9784809	0.9716802	1.1074E+03	3.3332E+01
α_2	7.52E-03	1.24E-02	1.21E-02	1.82E-02	1.23E-02	1.4108E+01	1.1266E+03
α_3	3.28E-03	6.70E-03	6.42E-03	1.11E-02	6.53E-03	7.6456E+00	1.1331E+03
α_4	1.64E-03	4.25E-03	3.96E-03	7.82E-03	4.16E-03	4.8422E+00	1.1359E+03
α_5	1.02E-03	3.19E-03	2.91E-03	6.34E-03	3.12E-03	3.6396E+00	1.1371E+03
α_6	7.62E-04	2.71E-03	2.43E-03	5.64E-03	2.25E-03	3.0965E+00	1.1376E+03

DC Power Battery Chargers

Table 1-20: Alpha Factor Distribution Summary - Charger High Voltage/Amperage Output, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9649838	0.9892422	0.9932855	0.9997226	0.9950344	7.1790E+01	7.8070E-01
α_2	2.76E-04	1.08E-02	6.72E-03	3.50E-02	4.97E-03	7.8070E-01	7.1790E+01

Table 1-21: Alpha Factor Distribution Summary - Charger High Voltage/Amperage Output, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9609826	0.9841820	0.9870264	0.9976626	0.9900374	1.0767E+02	1.7305E+00
α_2	1.14E-03	1.20E-02	9.23E-03	3.26E-02	9.96E-03	1.3177E+00	1.0808E+02
α_3	4.85E-06	3.77E-03	1.43E-03	1.55E-02	0.00E+00	4.1280E-01	1.0899E+02

Table 1-22: Alpha Factor Distribution Summary - Charger High Voltage/Amperage Output, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9567497	0.9789141	0.9810055	0.9939244	0.9849809	1.4675E+02	3.1610E+00
α_2	3.59E-03	1.61E-02	1.40E-02	3.58E-02	1.50E-02	2.4148E+00	1.4750E+02
α_3	5.06E-08	1.75E-03	3.39E-04	8.36E-03	0.00E+00	2.6260E-01	1.4965E+02
α_4	1.07E-05	3.23E-03	1.43E-03	1.25E-02	0.00E+00	4.8360E-01	1.4943E+02

Table 1-23: Alpha Factor Distribution Summary - Charger High Voltage/Amperage Output, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9577666	0.9775451	0.9791626	0.9917905	0.9844117	1.8992E+02	4.3626E+00
α_2	3.14E-03	1.32E-02	1.16E-02	2.89E-02	1.19E-02	2.5699E+00	1.9171E+02
α_3	2.43E-04	5.02E-03	3.46E-03	1.51E-02	3.65E-03	9.7510E-01	1.9331E+02
α_4	9.29E-09	1.20E-03	1.83E-04	5.94E-03	0.00E+00	2.3360E-01	1.9405E+02
α_5	2.52E-05	3.01E-03	1.56E-03	1.09E-02	0.00E+00	5.8400E-01	1.9370E+02

Table 1-24: Alpha Factor Distribution Summary - Charger High Voltage/Amperage Output, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9567749	0.9752721	0.9765979	0.9892538	0.9818690	2.3160E+02	5.8722E+00
α_2	3.10E-03	1.19E-02	1.06E-02	2.53E-02	1.11E-02	2.8311E+00	2.3464E+02
α_3	8.36E-04	6.60E-03	5.28E-03	1.69E-02	5.57E-03	1.5676E+00	2.3591E+02
α_4	1.95E-05	2.44E-03	1.25E-03	8.87E-03	1.44E-03	5.7830E-01	2.3689E+02
α_5	1.28E-08	1.03E-03	1.70E-04	5.00E-03	0.00E+00	2.4330E-01	2.3723E+02
α_6	3.65E-05	2.75E-03	1.53E-03	9.57E-03	0.00E+00	6.5190E-01	2.3682E+02

2. DC Power Distribution Circuit Breakers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving DC power distribution circuit breakers at both pressurized water reactor (PWR) and boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure event reports from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify CCF events. Failure modes analyzed are failure to close and failure to remain closed (spurious open). The data cover the time period from 1980 through 1995.

The data review identified four common-cause failure to close events, and two common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to close are shown in Tables 2-1 and 2-2, respectively. Table 2-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 2-4 through 2-6 contain the corresponding information for the failure to remain closed failure mode. The size of the affected population of circuit breakers is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 2-7 through 2-16.

2. SYSTEM DESCRIPTION

The DC distribution circuit breakers are part of the class 1E DC electrical power distribution system providing reliable power to various safety related components and instrumentation necessary for safe shutdown of the reactor plant. Most DC loads are supplied from 125 volt DC (VDC) panels through individual distribution breakers, though some plants may have 250 VDC distribution systems to support DC-powered motor-operated valves or other relatively large DC-powered loads. In general, each DC distribution circuit breaker configuration ensures that adequate instrumentation and safety related components are available for postulated accidents in the Final Safety Analysis.

Multiple trains or divisions are available to ensure DC power is supplied to redundant components. These DC distribution divisions typically number from as few as two to as many as eight depending on the design of the plant. The DC power is normally distributed to the loads from a battery charger in parallel with a battery. The battery charger is usually powered from a class 1E 480 VAC bus, supplied from off-site power or the emergency diesel generators. In the event power is not available from the normal source, dedicated station batteries supply DC power to the distribution system. A simplified schematic for a typical train or division of DC-power distribution is presented in Figure 2-1.

The DC distribution breakers are normally in the closed position regardless of whether the plant is at power or shutdown. Most of the DC distribution breakers are manipulated locally with only instrumentation available to the control room operator .

ALPHA FACTOR AND MGL PARAMETERS
DC Power Distribution Circuit Breakers

Table 2-1: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9473154	0.9571841	0.9559739	0.9512818	0.9482570
α_2	5.27E-02	1.04E-02	1.76E-02	2.21E-02	2.04E-02
α_3		3.24E-02	1.90E-03	6.19E-03	9.91E-03
α_4			2.45E-02	6.64E-04	3.94E-03
α_5				1.98E-02	8.03E-04
α_6					1.67E-02

Table 2-2: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.47E-01	9.57E-01	9.56E-01	9.51E-01	9.48E-01
Beta	5.27E-02	4.28E-02	4.40E-02	4.87E-02	5.17E-02
Gamma		7.57E-01	6.00E-01	5.47E-01	6.05E-01
Delta			9.28E-01	7.68E-01	6.84E-01
Epsilon				9.68E-01	8.16E-01
Mu					9.54E-01

Table 2-3: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	18.13	27.20	36.27	45.33	54.40
N_1	1.9798	2.6450	2.9017	2.8001	2.7358
N_2	1.1184	0.3250	0.7220	1.1163	1.2304
N_3		1.0100	0.0780	0.3134	0.5969
N_4			1.0040	0.0336	0.2374
N_5				1.0016	0.0484
N_6					1.0046

Total Number of Independent Failure Events: 34
Total Number of Common-Cause Failure Events: 4

ALPHA FACTOR AND MGL PARAMETERS
DC Power Distribution Circuit Breakers

Table 2-4: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9933168	0.9865754	0.9797273	0.9835007	0.9859907
α_2	6.68E-03	1.34E-02	2.03E-02	8.52E-03	4.00E-03
α_3		0.00E+00	0.00E+00	7.98E-03	6.67E-03
α_4			0.00E+00	0.00E+00	3.34E-03
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 2-5: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.93E-01	9.87E-01	9.80E-01	9.84E-01	9.86E-01
Beta	6.68E-03	1.34E-02	2.03E-02	1.65E-02	1.40E-02
Gamma		0.00E+00	0.00E+00	4.84E-01	7.14E-01
Delta			0.00E+00	0.00E+00	3.33E-01
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 2-6: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	24.00	36.00	48.00	60.00	72.00
N_1	1.3264	1.4800	1.2940	1.5994	1.9000
N_2	0.1704	0.5100	1.0200	0.5334	0.3000
N_3		0.0000	0.0000	0.5000	0.5000
N_4			0.0000	0.0000	0.2500
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 60
Total Number of Common-Cause Failure Events: 2

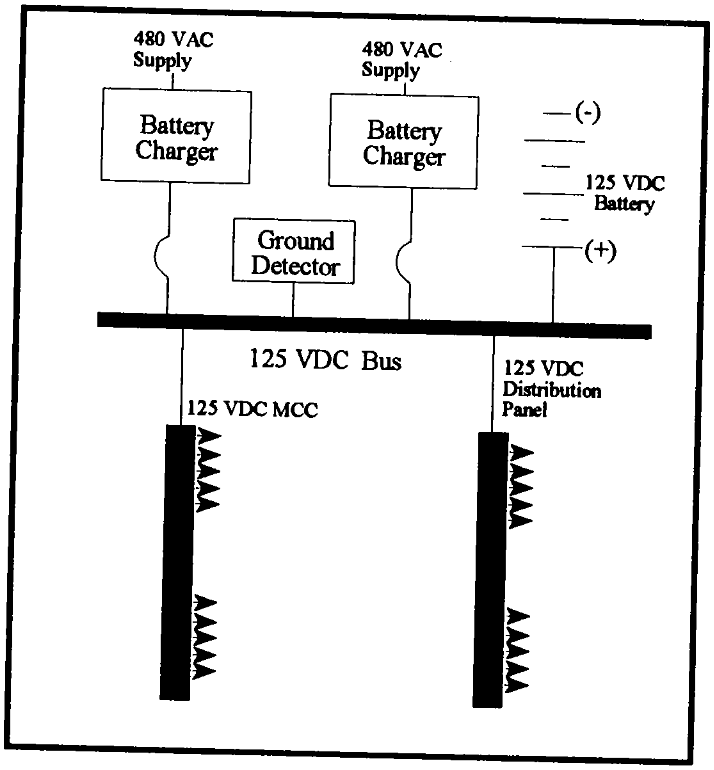

Figure 2-1. Generic DC distribution system.

3. COMPONENT BOUNDARIES

The safety function of a DC circuit breaker is to connect a power source to a load, monitor the current flow through the breaker, and isolate the load from the source if the current demand exceeds the design current flow or when an external trip signal is initiated. This action protects both the source and the load from equipment damage and executes the design function of the breaker.

DC circuit breakers have overcurrent protection that is a built in part of breaker unit. Most circuit breakers, especially for safety related equipment applications, provide additional protection by monitoring such parameters as under voltage, ground faults, and other protection schemes as required for breaker/system protection or the specific safety application. This additional application hardware is generally located exterior to the circuit breaker and merely utilizes the remote operating features of the breaker. This hardware as well as the remote operating hardware is considered integral to the function of the circuit breaker and part of the breaker for failure analysis. It includes all sensing devices, cabling, and components necessary to process the signals and provide control signals to the individual breaker.

4. FAILURE EVENT DEFINITION

Successful DC distribution breakers system response to a demand requires that DC electrical power be available to the required safety related loads for the duration of the mission time. The failure modes used in evaluating the DC distribution breakers data were:

OO Failure to Close: The breaker did not close or would not have been able to close if a close signal had been generated. A failure reported as a miscalibration with no indication of high or low will be coded as "CC."

SA Failure to Remain Closed (Spurious Operation): The breaker opened when it should have stayed closed, as a result of a breaker fault. (There were no events of a spurious closing breaker found in the data review.) Some reports state that the breaker was found in the tripped condition; these are considered SA. Also included are spurious operation of the breaker due to bumping the cabinet or radio interference.

A breaker found open when it should have been closed, with no indication that it had ever been closed, and incapable of actuating due to physical block (e.g. locked or actually out of the cabinet) was considered a CC.

Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of breaker demand. The exception to this is if a licensee reported that the breaker "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the breaker from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that a second circuit breaker would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another circuit breaker, then the event was identified as a CCF. If, however, the report did not clearly identify that another circuit breaker would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to a circuit breaker demand (e.g. the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 2-7 through 2-16 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of DC distribution breakers. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
DC Power Distribution Circuit Breakers

Table 2-7: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8731594	0.9491360	0.9584446	0.9931974	0.9473154	2.9640E+01	1.5884E+00
α_2	6.80E-03	5.09E-02	4.16E-02	1.27E-01	5.27E-02	1.5884E+00	2.9640E+01

Table 2-8: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8969182	0.9547478	0.9610404	0.9910350	0.9571841	4.5045E+01	2.1350E+00
α_2	2.84E-04	1.51E-02	9.00E-03	5.07E-02	1.04E-02	7.1220E-01	4.6468E+01
α_3	3.31E-03	3.02E-02	2.38E-02	7.88E-02	3.24E-02	1.4228E+00	4.5757E+01

Table 2-9: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9053988	0.9536551	0.9581134	0.9866630	0.9559739	6.3872E+01	3.1040E+00
α_2	1.70E-03	1.91E-02	1.45E-02	5.19E-02	1.76E-02	1.2758E+00	6.5700E+01
α_3	1.63E-06	5.09E-03	1.52E-03	2.23E-02	1.90E-03	3.4060E-01	6.6635E+01
α_4	2.62E-03	2.22E-02	1.77E-02	5.74E-02	2.45E-02	1.4876E+00	6.5488E+01

Table 2-10: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9093273	0.9511836	0.9544780	0.9817768	0.9512818	8.6172E+01	4.4225E+00
α_2	3.30E-03	2.04E-02	1.69E-02	4.91E-02	2.21E-02	1.8443E+00	8.8750E+01
α_3	1.60E-04	8.01E-03	4.79E-03	2.68E-02	6.19E-03	7.2540E-01	8.9869E+01
α_4	1.03E-07	2.95E-03	5.91E-04	1.40E-02	6.64E-04	2.6720E-01	9.0327E+01
α_5	2.27E-03	1.75E-02	1.41E-02	4.44E-02	1.98E-02	1.5856E+00	8.9090E+01

Table 2-11: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9127378	0.9501542	0.9527894	0.9785713	0.9482570	1.0761E+02	5.6453E+00
α_2	3.21E-03	1.77E-02	1.50E-02	4.17E-02	2.04E-02	2.0950E+00	1.1125E+02
α_3	7.02E-04	1.00E-02	7.34E-03	2.86E-02	9.91E-03	1.1375E+00	1.1212E+02
α_4	3.10E-05	4.86E-03	2.41E-03	1.80E-02	3.94E-03	5.5010E-01	1.1271E+02
α_5	2.14E-07	2.58E-03	6.03E-04	1.19E-02	8.03E-04	2.9170E-01	1.1296E+02
α_6	2.03E-03	1.46E-02	1.19E-02	3.66E-02	1.67E-02	1.6565E+00	1.1160E+02

ALPHA FACTOR DISTRIBUTIONS
DC Power Distribution Circuit Breakers

Table 2-12: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9371516	0.9819588	0.9898860	0.9997741	0.9933168	3.4856E+01	6.4040E-01
α_2	2.28E-04	1.80E-02	1.01E-02	6.29E-02	6.68E-03	6.4040E-01	3.4856E+01

Table 2-13: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9346175	0.9757363	0.9813307	0.9977106	0.9865754	5.2680E+01	1.310E+00
α_2	6.51E-04	1.66E-02	1.11E-02	5.13E-02	1.34E-02	8.9720E-01	5.3093E+01
α_3	9.89E-06	7.65E-03	2.91E-03	3.13E-02	0.00E+00	4.1280E-01	5.3577E+01

Table 2-14: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9320285	0.9695993	0.9736112	0.9934481	0.9797273	7.3994E+01	2.3200E+00
α_2	2.66E-03	2.06E-02	1.66E-02	5.24E-02	2.03E-02	1.5738E+00	7.4740E+01
α_3	9.99E-08	3.44E-03	6.68E-04	1.64E-02	0.00E+00	2.6260E-01	7.6051E+01
α_4	2.10E-05	6.34E-03	2.82E-03	2.46E-02	0.00E+00	4.8360E-01	7.5830E+01

Table 2-15: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9394756	0.9708570	0.9738659	0.9919555	0.9835007	9.9641E+01	2.9910E+00
α_2	1.07E-03	1.23E-02	9.30E-03	3.38E-02	8.52E-03	1.2614E+00	1.0137E+02
α_3	3.61E-04	8.89E-03	5.97E-03	2.74E-02	7.98E-03	9.1200E-01	1.0172E+02
α_4	1.76E-08	2.28E-03	3.46E-04	1.12E-02	0.00E+00	2.3360E-01	1.0240E+02
α_5	4.79E-05	5.69E-03	2.95E-03	2.06E-02	0.00E+00	5.8400E-01	1.0205E+02

Table 2-16: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9447094	0.9720386	0.9744660	0.9910729	0.9859907	1.2437E+02	3.5776E+00
α_2	5.23E-04	8.43E-03	6.05E-03	2.45E-02	4.00E-03	1.0791E+00	1.2687E+02
α_3	4.63E-04	8.13E-03	5.75E-03	2.39E-02	6.67E-03	1.0406E+00	1.2691E+02
α_4	3.12E-05	4.40E-03	2.22E-03	1.62E-02	3.34E-03	5.6270E-01	1.2739E+02
α_5	2.37E-08	1.90E-03	3.16E-04	9.28E-03	0.00E+00	2.4330E-01	1.2770E+02
α_6	6.80E-05	5.10E-03	2.85E-03	1.78E-02	0.00E+00	6.5190E-01	1.2730E+02

3. 4160 Volt AC Power Distribution Circuit Breakers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving 4160 volt AC (VAC) circuit breakers at both pressurized water reactors (PWR) and boiling water reactors (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to close and failure to remain closed (spurious open). The data cover the time period from 1980 through 1995.

The data review identified 21 common-cause failure to close events and 7 common cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to close are shown in Tables 3-1 and 3-2, respectively. Table 3-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 3-4 through 3-6 contain the corresponding information for the failure to remain closed failure mode. The size of the affected population of circuit breakers is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 3-7 through 3-16.

2. SYSTEM DESCRIPTION

The 4160 VAC circuit breakers are part of the AC electrical power distribution system that supply power to safety related and non-safety related large loads. For the purpose of this study, only those breakers supplying safety related loads will be considered. These breakers are normally remotely operated but may also be locally operated in most cases.

The 4160 VAC breakers considered here are feeder breakers to smaller electrical distribution centers (480 VAC motor control center), breakers between two 4160 busses, and the supply feeder breakers from off-site power. Breakers which supply power to 4160 volt busses, as well as breakers supplying loads from the 4160 busses, were considered. Circuit breakers that supply individual components (e.g. safety injection pumps) are not included in this study, but are included in the component studies as a part of the individual component. Breakers used to supply power from an emergency diesel generator (EDG) to a 4160 volt bus will be specifically excluded and will be considered under a separate study of EDGs. Figure 3-1 shows a typical AC power distribution system. The circuit breakers considered in this study are enclosed in boxes.

ALPHA FACTOR AND MGL PARAMETERS
4160 Volt AC Power Distribution Breakers

Table 3-1: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9615087	0.9467144	0.9483494	0.9486893	0.9486355
α_2	3.85E-02	3.21E-02	2.05E-02	2.36E-02	2.46E-02
α_3		2.12E-02	1.55E-02	4.19E-03	6.87E-03
α_4			1.56E-02	1.09E-02	1.28E-04
α_5				1.27E-02	9.12E-03
α_6					1.06E-02

Table 3-2: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.62E-01	9.47E-01	9.48E-01	9.49E-01	9.49E-01
Beta	3.85E-02	5.33E-02	5.17E-02	5.13E-02	5.14E-02
Gamma		3.98E-01	6.02E-01	5.40E-01	5.21E-01
Delta			5.02E-01	8.49E-01	7.43E-01
Epsilon				5.37E-01	9.94E-01
Mu					5.38E-01

Table 3-3: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	57.53	86.30	115.07	143.84	172.60
N_1	10.0880	10.8399	12.6096	13.6983	14.6228
N_2	2.7069	3.2941	2.7657	3.9164	4.8554
N_3		2.1734	2.0850	0.6952	1.3559
N_4			2.1032	1.8089	0.0252
N_5				2.1001	1.8008
N_6					2.1000

Total Number of Independent Failure Events: 189
Total Number of Common-Cause Failure Events: 21

ALPHA FACTOR AND MGL PARAMETERS
4160 Volt AC Power Distribution Breakers

Table 3-4: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9508714	0.9514366	0.9566398	0.9578107	0.9600692
α_2	4.91E-02	2.25E-02	1.62E-02	1.23E-02	9.82E-03
α_3		2.61E-02	1.04E-02	1.08E-02	7.86E-03
α_4			1.68E-02	7.06E-03	8.44E-03
α_5				1.21E-02	4.43E-03
α_6					9.38E-03

Table 3-5: Summary of MGL Parameter Estimations- Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.51E-01	9.51E-01	9.57E-01	9.58E-01	9.60E-01
Beta	4.91E-02	4.86E-02	4.34E-02	4.22E-02	3.99E-02
Gamma		5.37E-01	6.26E-01	7.09E-01	7.54E-01
Delta			6.17E-01	6.38E-01	7.39E-01
Epsilon				6.31E-01	6.21E-01
Mu					6.79E-01

Table 3-6: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	35.00	52.50	70.00	87.50	105.00
N_1	2.1611	1.9040	1.8248	1.5196	1.2858
N_2	1.9200	1.2858	1.2163	1.1393	1.0870
N_3		1.4911	0.7810	1.0065	0.8705
N_4			1.2582	0.6558	0.9348
N_5				1.1195	0.4904
N_6					1.0379

Total Number of Independent Failure Events: 140
Total Number of Common-Cause Failure Events: 7

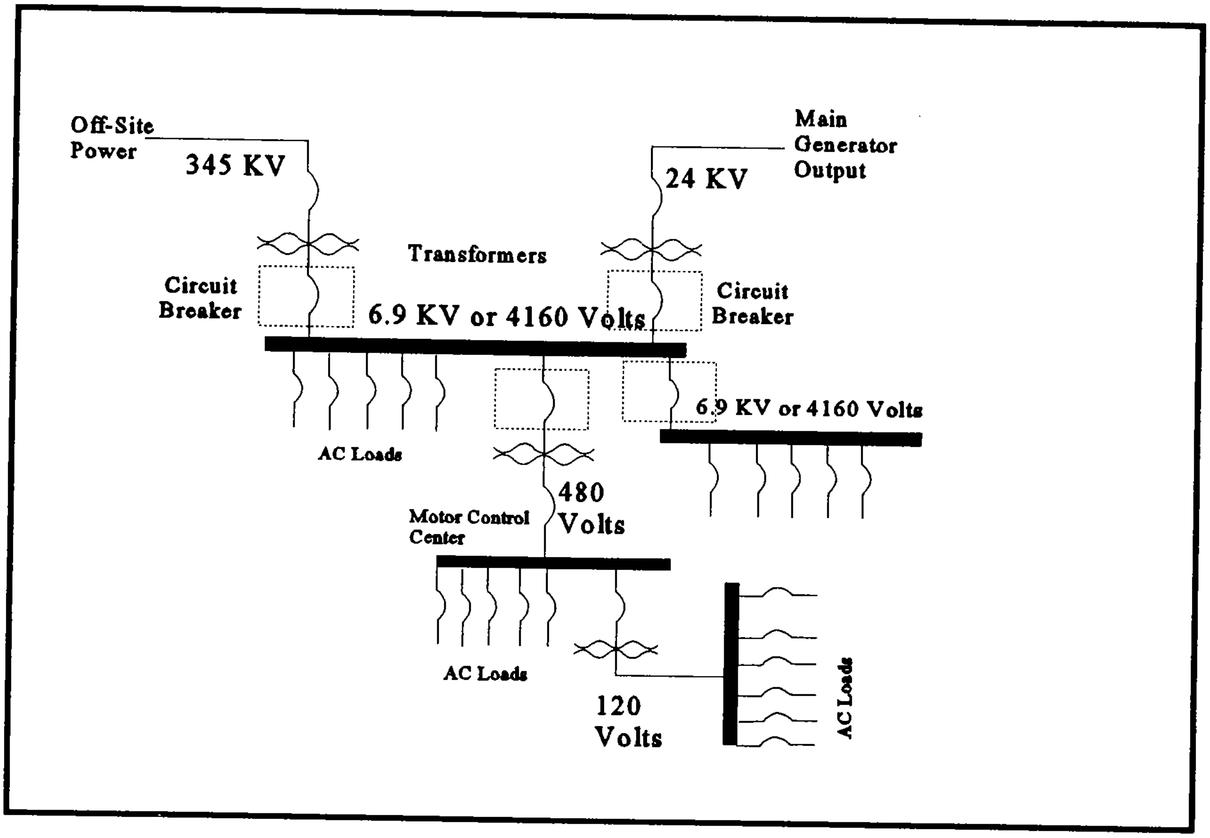

Figure 3-1. Generic AC power distribution system.

3. COMPONENT BOUNDARIES

The super component, the 4160 VAC circuit breaker, is defined as the breaker itself and the equipment contained in the breaker cubicle. External equipment used to monitor under voltage, ground faults, differential faults, and other protection schemes for individual breakers are also considered part of the breaker.

AC circuit breakers have overcurrent protection that is integral to the breaker unit. Most circuit breakers, especially for safety related equipment applications, provide additional protection by monitoring such parameters as under voltage, differential faults, ground faults, and other protection schemes as required for breaker/system protection or the specific safety application. This additional application hardware is generally located external to the circuit breaker and merely utilizes the remote operating features of the breaker. This hardware, as well as the remote operating hardware, is considered integral to the function of the circuit breaker for failure analysis. It includes all sensing devices, cabling, and components necessary to process the signals and provide control signals to the individual breaker.

4. FAILURE EVENT DEFINITION

Successful 4160 VAC circuit breaker response to a demand requires that the 4160 VAC circuit breaker provide electrical power to the bus or load for the duration of the mission time. The failure modes used in evaluating the 4160 VAC circuit breaker data are:

OO Failure to Close: The breaker did not close or would not have been able to close if a close signal had been generated. A failure reported as a miscalibration with no indication of high or low will be coded as "CC".

SA Failure to Remain Closed (Spurious Operation): The breaker opened when it should have stayed closed, as a result of a breaker fault. Some reports indicate that the breaker was found in the tripped condition; these are considered CX. Also included are spurious operation of the breaker due to bumping the cabinet or radio interference.

A breaker found open when it should have been closed, with no indication that it had ever been closed, and incapable of actuating due to physical block (e.g. locked or actually out of the cabinet) was considered a CC.

Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of breaker demand. The exception to this is if a licensee reported that the breaker "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the breaker from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that a second circuit breaker would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another circuit breaker, then the event was identified as a CCF. If, however, the report did not clearly identify that another circuit breaker would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to an circuit breaker actuation demand (e.g. the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 3-7 through 3-16 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of 4160 volt breakers. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
4160 Volt AC Power Distribution Breakers

Table 3-7: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9195659	0.9604494	0.9642149	0.9884371	0.9615087	7.7148E+01	3.1769E+00
α_2	1.16E-02	3.96E-02	3.58E-02	8.04E-02	3.85E-02	3.1769E+00	7.7148E+01

Table 3-8: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9097540	0.9471576	0.9496600	0.9760211	0.9467144	1.1234E+02	6.2675E+00
α_2	1.01E-02	3.10E-02	2.84E-02	6.08E-02	3.21E-02	3.6813E+00	1.1493E+02
α_3	5.24E-03	2.18E-02	1.92E-02	4.74E-02	2.12E-02	2.5862E+00	1.1602E+02

Table 3-9: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9172217	0.9486167	0.9504691	0.9736767	0.9483494	1.5238E+02	8.2539E+00
α_2	6.20E-03	2.07E-02	1.87E-02	4.18E-02	2.05E-02	3.3195E+00	1.5731E+02
α_3	3.16E-03	1.46E-02	1.27E-02	3.28E-02	1.55E-02	2.3476E+00	1.5829E+02
α_4	3.86E-03	1.61E-02	1.41E-02	3.51E-02	1.56E-02	2.5868E+00	1.5805E+02

Table 3-10: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9217985	0.9491493	0.9505953	0.9715542	0.9486893	1.9558E+02	1.0478E+01
α_2	8.58E-03	2.25E-02	2.10E-02	4.17E-02	2.36E-02 .	4.6444E+00	2.0141E+02
α_3	3.53E-04	5.37E-03	3.88E-03	1.55E-02	4.19E-03	1.1072E+00	2.0495E+02
α_4	1.82E-03	9.91E-03	8.38E-03	2.33E-02	1.09E-02	2.0425E+00	2.0402E+02
α_5	3.23E-03	1.30E-02	1.15E-02	2.81E-02	1.27E-02	2.6841E+00	2.0337E+02

Table 3-11: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9248135	0.9494143	0.9506095	0.9699408	0.9486355	2.3770E+02	1.2665E+01
α_2	9.57E-03	2.25E-02	2.13E-02	3.98E-02	2.46E-02	5.6345E+00	2.4473E+02
α_3	1.26E-03	7.58E-03	6.31E-03	1.82E-02	6.87E-03	1.8965E+00	2.4847E+02
α_4	4.04E-07	1.35E-03	3.95E-04	5.94E-03	1.28E-04	3.3790E-01	2.5030E+02
α_5	1.50E-03	8.16E-03	6.90E-03	1.92E-02	9.12E-03	2.0441E+00	2.4832E+02
α_6	2.79E-03	1.10E-02	9.72E-03	2.36E-02	1.06E-02	2.7519E+00	2.4761E+02

ALPHA FACTOR DISTRIBUTIONS

4160 Volt AC Power Distribution Breakers

Table 3-12: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8929497	0.9513050	0.9573305	0.9890407	0.9508714	4.6691E+01	2.390E+00
α_2	1.10E-02	4.87E-02	4.27E-02	1.07E-01	4.91E-02	2.390E+00	4.6691E+01

Table 3-13: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9041008	0.9511225	0.9551858	0.9842352	0.9514366	6.9604E+01	3.5769E+00
α_2	3.24E-03	2.29E-02	1.87E-02	5.68E-02	2.25E-02	1.6730E+00	7.1508E+01
α_3	4.42E-03	2.60E-02	2.18E-02	6.20E-02	2.61E-02	1.9039E+00	7.1277E+01

Table 3-14: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9167994	0.9549320	0.9579085	0.9828894	0.9566398	9.6525E+01	4.5555E+00
α_2	2.68E-03	1.75E-02	1.44E-02	4.29E-02	1.62E-02	1.7701E+00	9.9310E+01
α_3	5.94E-04	1.03E-02	7.32E-03	3.03E-02	1.04E-02	1.0436E+00	1.0040E+02
α_4	2.58E-03	1.72E-02	1.42E-02	4.24E-02	1.68E-02	1.7418E+00	9.9339E+01

Table 3-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9231756	0.9557788	0.9580466	0.9806273	0.9578107	1.2706E+02	5.8787E+00
α_2	2.31E-03	1.41E-02	1.17E-02	3.38E-02	1.23E-02	1.8673E+00	1.3107E+02
α_3	1.15E-03	1.07E-02	8.34E-03	2.82E-02	1.08E-02	1.4185E+00	1.3152E+02
α_4	2.53E-04	6.69E-03	4.43E-03	2.08E-02	7.06E-03	8.8940E-01	1.3205E+02
α_5	1.85E-03	1.28E-02	1.05E-02	3.18E-02	1.21E-02	1.7035E+00	1.3124E+02

Table 3-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9289252	0.9575574	0.9594123	0.9798560	0.9600692	1.5676E+02	6.9482E+00
α_2	1.87E-03	1.14E-02	9.48E-03	2.75E-02	9.82E-03	1.8661E+00	1.6184E+02
α_3	9.17E-04	8.62E-03	6.72E-03	2.28E-02	7.86E-03	1.4111E+00	1.6230E+02
α_4	6.44E-04	7.62E-03	5.73E-03	2.11E-02	8.44E-03	1.2475E+00	1.6246E+02
α_5	9.26E-05	4.48E-03	2.69E-03	1.50E-02	4.43E-03	7.3370E-01	1.6298E+02
α_6	1.47E-03	1.03E-02	8.41E-03	2.57E-02	9.38E-03	1.6898E+00	1.6202E+02

4. Reactor Trip Circuit Breakers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving reactor trip circuit breakers (RTB) at pressurized water reactor (PWR) power plants. Due to the difference in the control rod drive systems between the boiling water reactors (BWRs) and the PWRs, data for the BWR reactor trip system were not included here. Licensee Event Reports (LERs) and failure reports from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify CCF events. The only failure mode analyzed is failure to open. The data cover the time period from 1980 through 1995.

The data review identified 26 common-cause failure to open events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 4-1 and 4-2, respectively. Table 3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events. The size of the affected population of RTBs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 4-4 through 4-8.

2. SYSTEM DESCRIPTION

The RTBs are part of the reactor protection system, and supply power to the control rod drive mechanisms. Both AC and DC breakers are used for the RTBs. On a reactor trip signal, the breakers will open, removing power from the control rod drive mechanisms. The control rods will then unlatch and drop into the reactor core due to gravity. Figure 4-1 shows the RTB arrangement for a 4-RTB plant.

ALPHA FACTOR AND MGL PARAMETERS
Reactor Trip Breakers

Table 4-1: Summary of Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9345364	0.9080446	0.9127947	0.9031512	0.9060815
α_2	6.55E-02	5.67E-02	2.69E-02	3.91E-02	2.85E-02
α_3		3.52E-02	3.70E-02	1.45E-02	2.45E-02
α_4			2.34E-02	2.47E-02	6.73E-03
α_5				1.86E-02	1.86E-02
α_6					1.55E-02

Table 4-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.35E-01	9.08E-01	9.13E-01	9.03E-01	9.06E-01
Beta	6.55E-02	9.20E-02	8.72E-02	9.69E-02	9.39E-02
Gamma		3.83E-01	6.92E-01	5.96E-01	6.96E-01
Delta			3.87E-01	7.49E-01	6.25E-01
Epsilon				4.30E-01	8.35E-01
Mu					4.55E-01

Table 4-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	35.77	53.66	71.55	89.43	107.32
N_1	9.8793	9.5893	11.1638	10.1976	10.7098
N_2	3.1977	3.9513	2.4333	4.3167	3.7172
N_3		2.4538	3.3525	1.6001	3.1938
N_4			2.1164	2.7196	0.8772
N_5				2.0471	2.4226
N_6					2.0234

Total Number of Independent Failure Events: 110
Total Number of Common-Cause Failure Events: 26

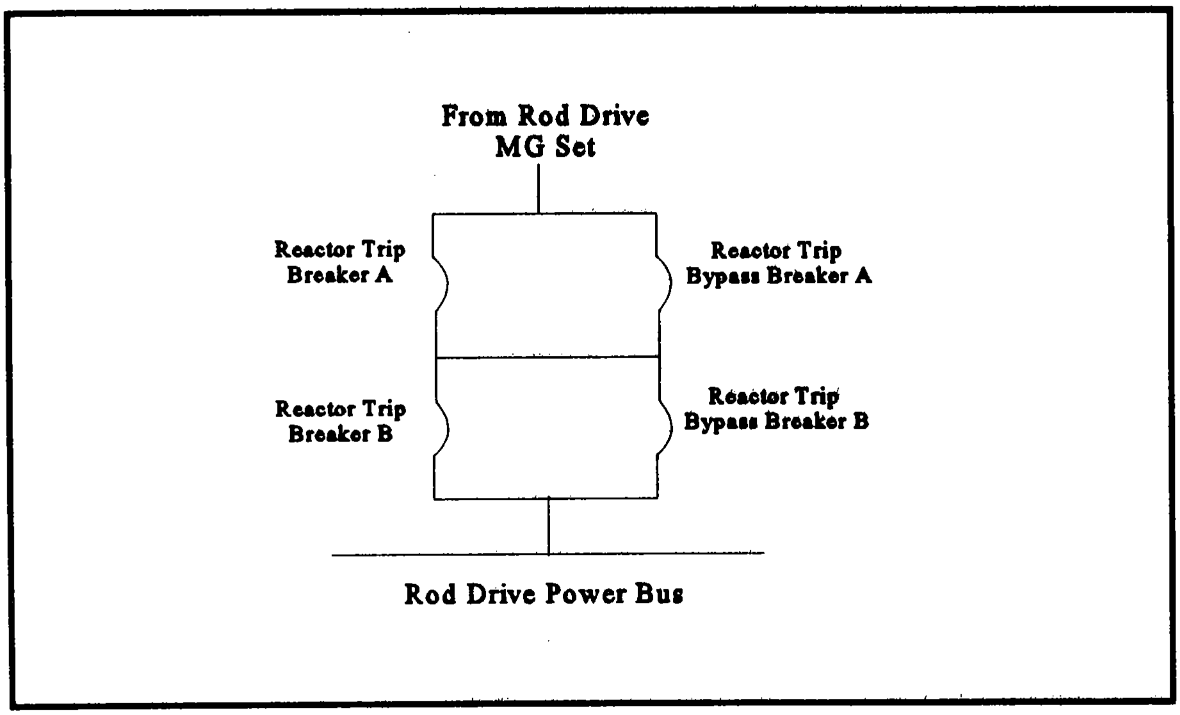

Figure 4-1. Reactor trip breaker configuration.

3. COMPONENT BOUNDARIES

The component, RTB, is defined as the breaker itself as well the components that control the individual breakers. The component would include those circuit breakers that supply the power which causes the breaker to remain closed. The circuitry that provides input power to the breakers is not viewed as part of the breaker.

4. FAILURE EVENT DEFINITION

Successful RTB response to a demand requires that the control rods are released and the reactor trips. The only failure mode used in evaluating the RTB data is:

CC Failure to Open: The breaker did not open or would not have been able to open if an open signal had been generated. Slow opening times are considered to be failures.

For purposes of this CCF study, a personnel error resulting in more than one functionally inoperable RTBs (even without any component malfunction) was considered a CCF failure.

Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of breaker demand. The exception to this is if a licensee reported that the breaker "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the breaker from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second RTB would have occurred from the same cause if a scram signal was present. If the cause of the actual failure would have clearly caused failure of another RTB, then the event was identified as a CCF. If, however, the report did not clearly identify that another RTB would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to a RTB demand (e.g. the condition was found during inspection, and no actual demand failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 4-4 through 4-8 present the alpha factor uncertainty distribution summaries for each configuration of RTBs. Westinghouse plants typically have four RTBs; Combustion Engineering and Babcock & Wilcox plants can have up to nine RTBs. Due to the limitations of the CCF software in analyzing large redundancy components, the CCCG of 6 is used to represent the CE and B&W plants. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Reactor Trip Breakers

Table 4-4: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8791355	0.9376736	0.9425879	0.9793896	0.9345364	5.5179E+01	3.6677E+00
α_2	2.06E-02	6.23E-02	5.74E-02	1.21E-01	6.55E-02	3.6677E+00	5.5179E+01

Table 4-5: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8618842	0.9158815	0.9191093	0.9588360	0.9080446	7.8449E+01	7.2051E+00
α_2	1.87E-02	5.07E-02	4.72E-02	9.45E-02	5.67E-02	4.3385E+00	8.1316E+01
α_3	8.92E-03	3.35E-02	2.99E-02	7.02E-02	3.52E-02	2.8666E+00	8.2788E+01

Table 4-6: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8764690	0.9210872	0.9234878	0.9574900	0.9127947	1.0741E+02	9.2022E+00
α_2	7.05E-03	2.56E-02	2.30E-02	5.33E-02	2.69E-02	2.9871E+00	1.1363E+02
α_3	9.99E-03	3.10E-02	2.84E-02	6.11E-02	3.70E-02	3.6151E+00	1.1300E+02
α_4	5.38E-03	2.23E-02	1.96E-02	4.84E-02	2.34E-02	2.6000E+00	1.1401E+02

Table 4-7: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8758854	0.9159004	0.9177401	0.9496183	0.9031512	1.3767E+02	1.2641E+01
α_2	1.35E-02	3.36E-02	3.15E-02	6.07E-02	3.91E-02	5.0447E+00	1.4527E+02
α_3	2.42E-03	1.34E-02	1.13E-02	3.15E-02	1.45E-02	2.0121E+00	1.4830E+02
α_4	5.34E-03	1.97E-02	1.76E-02	4.11E-02	2.47E-02	2.9532E+00	1.4736E+02
α_5	4.27E-03	1.75E-02	1.54E-02	3.79E-02	1.86E-02	2.6311E+00	1.4768E+02

Table 4-8: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8840584	0.9194497	0.9209712	0.9496321	0.9060815	1.6850E+02	1.4762E+01
α_2	9.16E-03	2.45E-02	2.28E-02	4.58E-02	2.85E-02	4.4963E+00	1.7877E+02
α_3	6.69E-03	2.04E-02	1.87E-02	3.99E-02	2.45E-02	3.7344E+00	1.7953E+02
α_4	4.98E-04	6.49E-03	4.81E-03	1.82E-02	6.73E-03	1.1899E+00	1.8207E+02
α_5	3.58E-03	1.46E-02	1.28E-02	3.14E-02	1.86E-02	2.6659E+00	1.8060E+02
α_6	3.61E-03	1.46E-02	1.29E-02	3.15E-02	1.55E-02	2.6753E+00	1.8059E+02

5. Emergency Diesel Generators

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common cause failure (CCF) parameters of various models using operational data involving emergency diesel generators (EDGs) at both pressurized water reactor (PWR) and boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and special reports retrieved from NUDOCS have been screened to identify common cause failure events. Failure modes analyzed are failure to start and failure to run. The data cover the time period from 1980 through 1995.

The data review identified 55 common cause failure-to-start events and 76 common cause failure-to-run events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to start are shown in Tables 5-1 and 5-2, respectively. Table 5-3 contains the average impact vectors (N_1-N_5) and the number of adjusted independent events for this failure mode. Tables 5-4 through 5-6 contain the corresponding information for the failure to run failure mode. The size of the affected population of EDGs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), delta (δ), epsilon (ϵ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 5-7 through 5-14.

Important events identified during the data review include two events in which the failure of a single component, (rather than multiple components) resulted in the failure of more than one EDG. In one case, the fuel oil storage tank isolation valve was locked closed instead of locked open, which limited the fuel supply for each EDG to the contents of the day tank. The other event was caused by a mispositioned service water valve that resulted in three EDGs overheating.

2. SYSTEM DESCRIPTION

The emergency diesel generators (EDGs) are part of the class 1E AC electrical power distribution system providing reliable emergency power to electrical buses that supply the emergency core cooling system (ECCS) and various other equipment necessary for safe shutdown of the reactor plant. In general, each EDG configuration ensures that adequate electrical power is available in a postulated loss-of-offsite power (LOSP), with or without a concurrent large break loss of coolant accident (LOCA). Gas turbine generators and hydroelectric generators (used at some locations for emergency power) are not part of this study. High pressure core spray diesels are considered (for this study) to be a separate train of the emergency AC power system. Diesel engines used for fire pumps, Appendix R purposes, or non-class 1E backup generators are not included.

The EDGs are normally in standby, whether the plant is at power or shutdown. At least one EDG is required by Technical Specifications to be aligned to provide emergency power to safety related electrical buses in case of a LOSP to the plant. In some cases a "swing" EDG is used that can supply power to more than one power plant (but not simultaneously) such that two power plants will have a total of only three EDGs: one EDG dedicated to each specific power plant, and the third, a swing EDG, capable of powering either plant. Electrical load shedding (intentional load removal) of the safety bus and subsequent sequencing of required loads after closure of the EDG output breaker, is considered part of the EDG function. The EDG system is automatically actuated by signals that sense either a loss of coolant accident or a loss of, or degraded, electrical power to its safety bus. Manual initiation of the EDG system is accomplished by the control room operator if necessary.

ALPHA FACTOR AND MGL PARAMETERS
Emergency Diesel Generators

Table 5-1: Summary of Alpha Factor Parameter Estimations - Fail to Start

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5
α_1	0.9688323	0.9630082	0.9636932	0.9635193
α_2	3.12E-02	2.04E-02	1.35E-02	1.22E-02
α_3		1.66E-02	1.14E-02	8.34E-03
α_4			1.14E-02	6.99E-03
α_5				8.92E-03

Table 5-2: Summary of MGL Parameter Estimations - Fail to Start

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5
1-Beta	9.69E-01	9.63E-01	9.64E-01	9.64E-01
Beta	3.12E-02	3.70E-02	3.63E-02	3.65E-02
Gamma		4.50E-01	6.27E-01	6.65E-01
Delta			5.01E-01	6.56E-01
Epsilon				5.61E-01

Table 5-3: Summary of Average Impact Vectors - Fail to Start

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5
Adj.Ind.Events	544.37	816.55	1088.73	1360.92
N_1	30.0085	24.2744	19.7472	11.9150
N_2	18.4780	17.7723	15.5719	17.4351
N_3		14.5261	13.0616	11.8825
N_4			13.1280	9.9522
N_5				12.7084

Total Number of Independent Failure Events: 773
Total Number of Common Cause Failure Events: 55

ALPHA FACTOR AND MGL PARAMETERS
Emergency Diesel Generators

Table 5-4: Summary of Alpha Factor Parameter Estimations - Fail to Run

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5
α_1	0.9599057	0.950802	0.949033	0.9522332
α_2	4.01E-02	2.89E-02	2.19E-02	1.47E-02
α_3		2.11E-02	1.46E-02	1.39E-02
α_4			1.45E-02	8.01E-03
α_5				1.11E-02

Table 5-5: Summary of MGL Parameter Estimations - Fail to Run

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5
1-Beta	9.60E-01	9.50E-01	9.49E-01	9.52E-01
Beta	4.01E-02	4.99E-02	5.10E-02	4.78E-02
Gamma		4.22E-01	5.72E-01	6.92E-01
Delta			4.99E-01	5.79E-01
Epsilon				5.81E-01

Table 5-6: Summary of Average Impact Vectors - Fail to Run

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5
Adj.Ind.Events	461.18	691.77	922.35	1152.94
N_1	36.3009	28.8207	21.2966	16.6702
N_2	20.7793	21.8777	21.7294	18.0603
N_3		15.9841	14.5212	17.1180
N_4			14.4583	9.8346
N_5				13.6582

Total Number of Independent Failure Events: 588
Total Number of Common Cause Failure Events: 76

3. COMPONENT BOUNDARIES

The super component, EDG, is defined as the combination of the diesel engine(s) with all components in the exhaust path, electrical generator, generator exciter, output breaker, combustion air, lube oil systems(including the device that physically controls the cooling medium), cooling system (including the device that physically controls the cooling medium), fuel oil system (including all storage tanks permanently connected to the engine supply), and the starting compressed air system. All pumps, valves and valve operators with their power supply breakers, and associated piping for the above systems are included. The only portions of the EDG cooling systems included were the specific devices that control cooling medium flow to the individual EDG auxiliary heat exchangers, including the control instruments. The service water system (cooling medium) outside the control valves was excluded. The EDG room ventilation was included if the licensee reported ventilation failures that affected EDG functional operability. Figure 5-1 shows the component boundary as defined for this study.

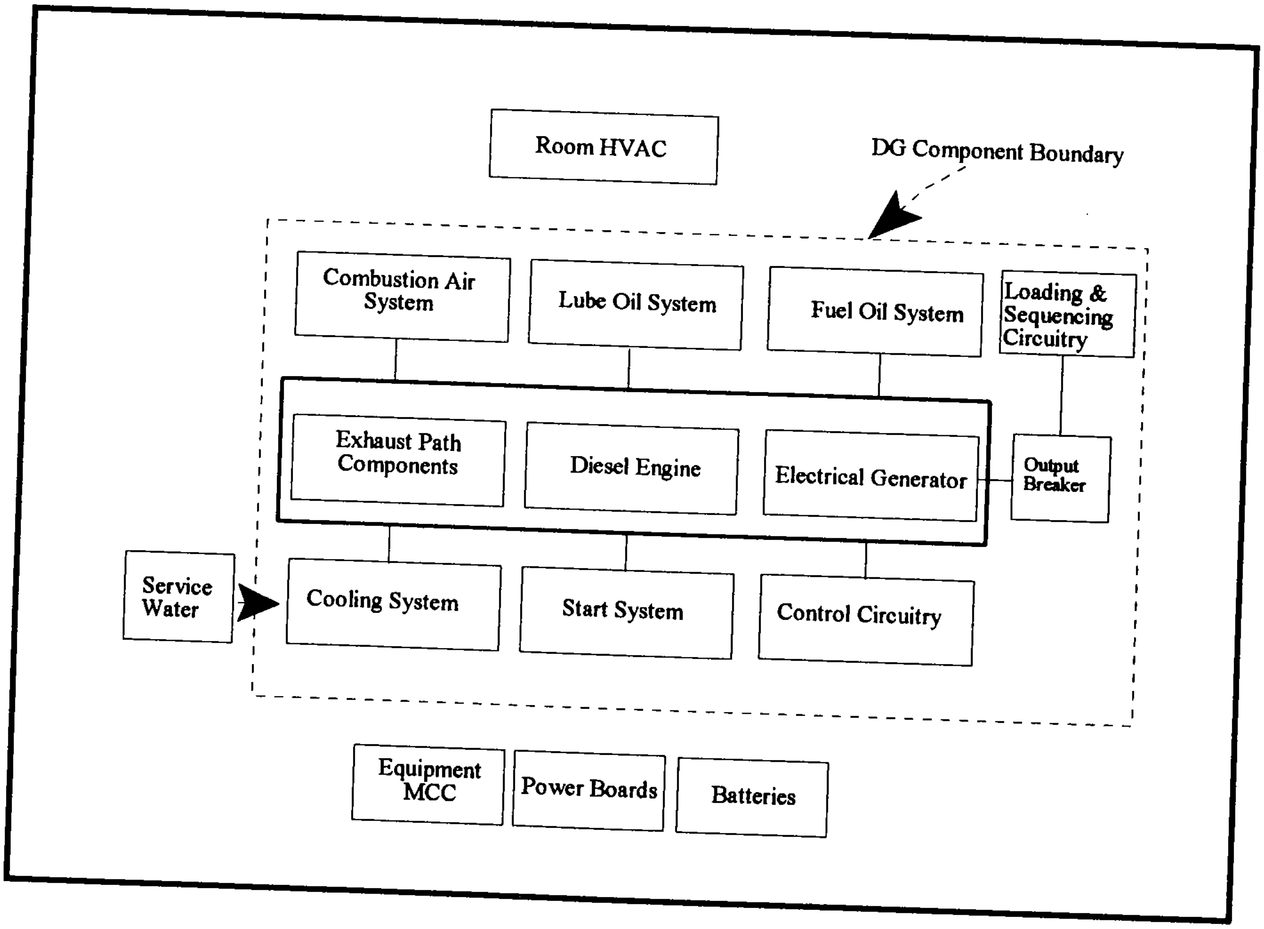

Figure 5-1. EDG boundaries.

Included within the EDG system are the circuit breakers that are located at the motor control centers (MCC) and the associated power boards, that supply power specifically to any of the EDG equipment. The MCCs and the power boards are not included except the load shedding and load sequencing circuitry/devices that are, in some cases, physically located within the MCCs. Load shedding of the safety bus and subsequent load sequencing onto the bus of vital electrical loads is considered integral to the EDG function and is therefore considered within the bounds of this study. All instrumentation, control logic, and the attendant process detectors for system initiations, trips, and operational control are included. Batteries were included if failures impacted EDG functional operability.

4. FAILURE EVENT DEFINITION

Successful EDG system response to a demand requires that the EDGs provide electrical power to the safety bus with all required loads energized (sequenced onto the bus) for the duration of the mission time. The failure modes used in evaluating the EDG data are:

FS Fail to Start: A successful start will be the EDG start through output breaker closing and loading to the requirement for the current configuration. For example, if the start is in response to an actual loss of power, the full sequence of loading must be completed in order for the start to be considered successful. If only partial loading occurs before the failure, the failure mode will be fail to start. If the start requires no loading (e.g. a test or on a SI signal), the success criteria will be only the EDG start.

FR Fail to Run: In order for the failure to be a failure to run, the EDG must be loaded (required for the current conditions) and stable before the failure. This failure mode implies a successful start, but a subsequent failure to run for the duration of the mission time.

The EDG failures represent malfunctions that hindered or prevented successful operation of the EDG system. Slow EDG starting times during testing, were considered successful provided the start took less than 20 seconds and the EDG was otherwise fully capable. Most licensees reporting a slow start time provided additional analysis to indicate that the slow start time did not adversely affect the ability of the plant to respond to a design basis accident. Conditions related to potential failure due to seismic design, environmental qualification, or other similar concerns were not considered. Any EDG inoperabilities declared strictly for administrative reasons were not considered failures (e.g. a surveillance test not performed within the required time frame). Failures during troubleshooting or when the EDG would not reasonably be considered fully capable, such as after major maintenance, were also not considered failures. If a failure occurred on equipment other than what had been repaired during an operational surveillance test following maintenance, another failure was counted.

For purposes of this CCF study, a personnel error resulting in more than one functionally inoperable EDG (even without any component malfunction) was considered a CCF failure. Examples are improper prestart lineup and significant setting errors in the governor or voltage regulator controls. These types of errors would have prevented fulfillment of the EDG system design function. On the other hand, operator error in such things as paralleling to the grid or improper adjustment of voltage or speed controls were not considered failures because these do not normally apply to an actual EDG demand.

Some CCF events affected the second unit of a multiple-unit site; if the report indicated that EDGs at the other unit(s) would have also failed for the same reason one CCF event was coded, with the CCCG value assigned as the total number of EDGs at the site. When a licensee modified the design or replaced parts on multiple EDGs (at a site) in response to the failure of a single component, the replaced components were considered to have failed. These events were coded as CCFs.

Many LERs and special reports reported only one actual failure, but the report information indicated that failure of a second EDG would have occurred from the same cause if a start and run had been attempted. When the cause of the actual failure would have clearly caused failure of another EDG, the event was identified as a CCF. If, however, the report did not clearly identify that another EDG would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an EDG start demand (e.g. the condition was found during inspection, and no actual start or run failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 5-7 through 5-14 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of EDGs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Emergency Diesel Generators

Table 5-7: Alpha Factor Distribution Summary - Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9560716	0.9685697	0.9690884	0.9792986	0.9688323	5.8391E+02	1.8948E+01
α_2	2.07E-02	3.14E-02	3.09E-02	4.39E-02	3.12E-02	1.8948E+01	5.8391E+02

Table 5-8: Alpha Factor Distribution Summary - Fail to Start, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9517748	0.9627733	0.9631228	0.9725894	0.9630082	8.5602E+02	3.3099E+01
α_2	1.33E-02	2.04E-02	2.01E-02	2.88E-02	2.04E-02	1.8160E+01	8.7096E+02
α_3	1.04E-02	1.68E-02	1.64E-02	2.45E-02	1.66E-02	1.4939E+01	8.7418E+02

Table 5-9: Alpha Factor Distribution Summary - Fail to Start, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9539635	0.9633908	0.9636560	0.9719226	0.9636932	1.1332E+03	4.3062E+01
α_2	8.64E-03	1.37E-02	1.34E-02	1.97E-02	1.35E-02	1.6126E+01	1.1601E+03
α_3	6.77E-03	1.13E-02	1.11E-02	1.68E-02	1.14E-02	1.3324E+01	1.1629E+03
α_4	6.96E-03	1.16E-02	1.13E-02	1.71E-02	1.14E-02	1.3612E+01	1.1627E+03

Table 5-10: Alpha Factor Distribution Summary - Fail to Start, CCCG =5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9547430	0.9631795	0.9633931	0.9708936	0.9635193	1.4109E+03	5.3936E+01
α_2	8.05E-03	1.24E-02	1.22E-02	1.75E-02	1.22E-02	1.8163E+01	1.4467E+03
α_3	4.89E-03	8.39E-03	8.17E-03	1.27E-02	8.34E-03	1.2295E+01	1.4525E+03
α_4	3.81E-03	6.95E-03	6.73E-03	1.09E-02	6.99E-03	1.0186E+01	1.4547E+03
α_5	5.42E-03	9.07E-03	8.85E-03	1.35E-02	8.92E-03	1.3292E+01	1.4515E+03

ALPHA FACTOR DISTRIBUTIONS
Emergency Diesel Generators

Table 5-11: Alpha Factor Distribution Summary - Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9448042	0.9597754	0.9603523	0.9727656	0.9599057	5.0701E+02	2.1249E+01
α_2	2.72E-02	4.02E-02	3.97E-02	5.52E-02	4.01E-02	2.1249E+01	5.0701E+02

Table 5-12: Alpha Factor Distribution Summary - Fail to Run, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9365886	0.9500783	0.9504684	0.9622466	0.9500802	7.3579E+02	3.8662E+01
α_2	1.96E-02	2.88E-02	2.83E-02	3.93E-02	2.89E-02	2.2265E+01	7.5219E+02
α_3	1.34E-02	2.12E-02	2.08E-02	3.03E-02	2.11E-02	1.6397E+01	7.5806E+02

Table 5-13: Alpha Factor Distribution Summary - Fail to Run, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9372270	0.9490287	0.9493250	0.9598252	0.9490033	9.6835E+02	5.209E+01
α_2	1.49E-02	2.18E-02	2.15E-02	2.99E-02	2.19E-02	2.2283E+01	9.9808E+02
α_3	8.93E-03	1.45E-02	1.42E-02	2.11E-02	1.46E-02	1.4784E+01	1.056E+03
α_4	9.05E-03	1.46E-02	1.43E-02	2.13E-02	1.45E-02	1.4942E+01	1.054E+03

Table 5-14: Alpha Factor Distribution Summary - Fail to Run, CCCG =5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9419575	0.9521985	0.9524344	0.9616241	0.9522332	1.2077E+03	6.0628E+01
α_2	9.70E-03	1.48E-02	1.46E-02	2.08E-02	1.47E-02	1.8788E+01	1.2495E+03
α_3	8.90E-03	1.38E-02	1.36E-02	1.96E-02	1.39E-02	1.7530E+01	1.2508E+03
α_4	4.33E-03	7.94E-03	7.68E-03	1.24E-02	8.01E-03	1.0680E+01	1.2583E+03
α_5	6.84E-03	1.12E-02	1.10E-02	1.65E-02	1.11E-02	1.4242E+01	1.2541E+03

6. Containment Spray Heat Exchangers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common cause failure (CCF) parameters of various models using operational data involving heat exchangers (HX) in the containment spray and recirculation (CSR) system at both pressurized water reactors (PWRs) and boiling water reactors (BWRs). Only two BWR plants have a containment spray system separate from the residual heat removal or low pressure coolant injection system. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common cause failure events. The only failure modes analyzed is failure to transfer heat. The data cover the time period from 1980 through 1995.

The data review identified 10 common-cause failure-to-transfer heat events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to transfer heat are shown in Tables 6-1 and 6-2, respectively. Table 6-3 contains the average impact vectors (N_1-N_2) and the number of adjusted independent events for this failure mode. The alpha factor model parameters are denoted by α_1-α_4 Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. The size of the affected population of condensers is denoted as CCCG. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Table 6-4 through 6-6.

2. SYSTEM DESCRIPTION

The containment spray system is a subsystem of the emergency core cooling system (ECCS) that provides for the removal of heat and containment pressure control following a loss of coolant accident (LOCA) or a steamline break inside containment. Following the initial post-accident injection phase, primary coolant from the containment sump or suppression pool is pumped through spray headers in the top of the containment building. The containment spray system typically consists of two separate and complete trains, each with a vertically mounted centrifugal pump, heat exchangers, and piping that allows pump suction from either an initial injection coolant source (on PWRs) or the containment recirculation coolant source. Power to the containment spray pumps is provided from the 1E electrical system, backed up by the 1E emergency diesels generators. Not all plant designs include a heat exchanger for cooling, and these plants are not included in the study. Some plant designs include a sodium hydroxide chemical addition to the containment spray system to improve the removal of iodine from the containment atmosphere, and some plants have both heat exchangers and chemical addition systems.

The containment spray system is normally in standby and is automatically started by the engineered safety features actuation system (ESFAS) on high containment pressure. The containment spray system can be manually actuated from the main control panel. Figure 6-1 provides an illustration of a typical flow path for the containment spray system.

ALPHA FACTOR AND MGL PARAMETERS
Containment Spray Heat Exchangers

Table 6-1: Summary of Alpha Factor Parameter Estimations - Fail to Transfer Heat

CCCG	**2**	**3**	**4**
α_1	0.7010040	0.6995701	0.6733120
α_2	2.99E-01	1.07E-01	1.54E-01
α_3		1.94E-01	1.53E-02
α_4			1.58E-01

Table 6-2: Summary of MGL Parameter Estimations - Fail to Transfer Heat

CCCG	**2**	**3**	**4**
1-Beta	7.01E-01	7.00E-01	6.73E-01
Beta	2.99E-01	3.00E-01	3.27E-01
Gamma		6.45E-01	5.30E-01
Delta			9.12E-01

Table 6-3: Summary of Average Impact Vectors - Fail to Transfer Heat

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**
Adj. Ind. Events	8.00	12.00	16.00
N_1	3.5414	3.0183	1.3800
N_2	4.9227	2.2918	3.9663
N_3		4.1578	0.3937
N_4			4.0727

Total Number of Independent Failure Events: 14
Total Number of Common Cause Failure Events: 10

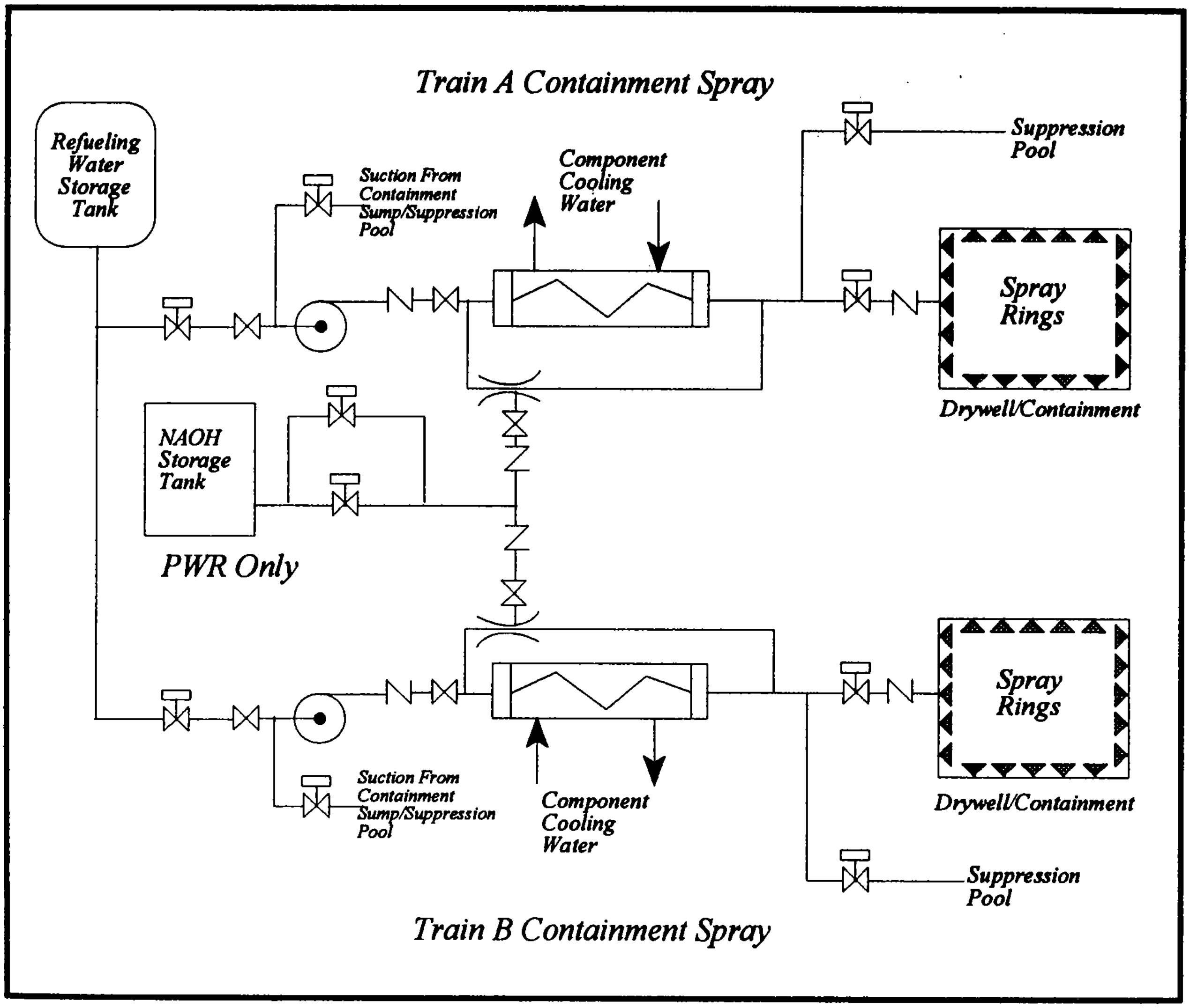

Figure 6-1. Typical PWR containment spray system.

3. COMPONENT BOUNDARIES

The main component of a CSR heat exchanger is the heat exchanger itself. It consists of the main tank (shell), internal cooling water tubes, temperature sensors, and a temperature control valve. The cooling water system on the heat exchanger side of the isolation valves in included; the remainder of the cooling water system is not.

4. FAILURE EVENT DEFINITION

Successful operation of a containment spray heat exchanger is defined as heat transfer above the minimum design basis requirements. The only failure mode used in evaluating CSR heat exchanger data is:

PG Plugged or Failure to Transfer Heat. Examples are:

- Reduction in flow affecting heat transfer rate, and
- Temperature switch failure.

Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the CSR heat exchangers.

Administrative inoperability, such as seismic qualification, were not considered failures because they are conditional upon the circumstances existing at the time of CSR system demand. The exception to this is if a licensee reported that the heat exchanger "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the heat exchanger from operating properly on a safety demand.

Some LERs reported only one actual failure, but the report information indicated that failure of a second CSR heat exchanger would have occurred from the same cause if system operation had been attempted. When the cause of the actual failure would have clearly caused failure of another CSR heat exchanger, the event was identified as a CCF. If, however, the report did not clearly identify that another CSR heat exchanger would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another CSR heat exchanger operation demand (e.g. the condition was found during inspection, and no actual heat exchanger operation was required), only those cases for which a second failure could be certain was identified as a CCF.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 6-4 through 6-6 present the alpha factor uncertainty distribution summaries for containment spray heat exchangers. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Containment Spray Heat Exchangers

Table 6-4: Alpha Factor Distribution Summary - Fail to Transfer Heat, CCCG = 2

Name	5th%	Mean	Median	95%	MLE	a	b
α_1	0.6578248	0.7962228	0.8037526	0.9087970	0.7010040	2.1071E+01	5.3927E+00
α_2	9.12E-02	2.04E-01	1.96E-01	3.42E-01	2.99E-01	5.3927E+00	2.1071E+01

Table 6-5: Alpha Factor Distribution Summary - Fail to Transfer Heat, CCCG = 3

Name	5th%	Mean	Median	95%	MLE	a	b
α_1	0.6929708	0.8065102	0.8120006	0.9012601	0.6995701	3.0218E+01	7.2496E+00
α_2	1.83E-02	7.15E-02	6.40E-02	1.51E-01	1.07E-01	2.6790E+00	3.4789E+01
α_3	4.80E-02	1.22E-01	1.15E-01	2.19E-01	1.94E-01	4.5706E+00	3.2897E+01

Table 6-6: Alpha Factor Distribution Summary - Fail to Transfer Heat, CCCG = 4

Name	5th%	Mean	Median	95%	MLE	a	b
α_1	0.7172539	0.8121561	0.8161921	0.8932539	0.6733120	4.2080E+01	9.7327E+00
α_2	3.36E-02	8.72E-02	8.20E-02	1.59E-01	1.54E-01	4.5201E+00	4.7293E+01
α_3	1.75E-04	1.27E-02	7.17E-03	4.39E-02	1.53E-02	6.5630E-01	5.1156E+01
α_4	3.40E-02	8.79E-02	8.27E-02	1.60E-01	1.58E-01	4.5563E+00	4.7256E+01

7. Residual Heat Removal Heat Exchangers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common cause failure (CCF) parameters of various models using operational data involving heat exchangers (HX) in the residual heat removal (RHR) system [including BWR low pressure coolant injection (LPCI) heat exchanger] at both pressurized water reactor (PWR) and boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common cause failure events. The only failure mode analyzed is failure to transfer heat. The data cover the time period from 1980 through 1995.

The data review identified eight common cause failure-to-transfer heat events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to transfer heat are shown in Tables 7-1 and 7-2, respectively. Table 7-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode. The size of the affected population of heat exchangers is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 7-4 through 7-6.

2. SYSTEM DESCRIPTION

The RHR system, including the BWR LPCI system, is a subsystem of the emergency core cooling system (ECCS) that functions to provide decay heat removal/shutdown cooling to maintain reactor coolant inventory and provide adequate long term decay heat removal following an emergency plant shutdown. This is the general design of both a PWR and a BWR power plant. The RHR function is performed over a relatively long time interval after shutdown. The RHR system injects directly into the primary system through the heat exchangers. Figure 7-1 illustrates the typical flow path for the RHR system, and it is general enough to apply to either a BWR or a PWR power plant. The system is typically comprised of two separate trains, each train with one or two high capacity centrifugal pumps, heat exchangers, connecting piping, and valves to control flow, etc. The pumps receive power from the 1E emergency power system which is backed up by the emergency diesel generators.

The system is normally aligned and in the standby mode. The RHR pumps are started by the engineered safety features actuation system (ESFAS) or may be manually actuated from the main control room.

ALPHA FACTOR AND MGL PARAMETERS
Residual Heat Removal Heat Exchangers

Table 7-1: Summary of Alpha Factor Parameter Estimations - Fail to Transfer Heat

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.6613589	0.7321429	0.7692530
α_2	3.39E-01	1.79E-02	2.88E-02
α_3		2.50E-01	0.00E+00
α_4			2.02E-01

Table 7-2: Summary of MGL Parameter Estimations - Fail to Transfer Heat

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	6.61E-01	7.32E-01	7.69E-01
Beta	3.39E-01	2.68E-01	2.31E-01
Gamma		9.33E-01	8.75E-01
Delta			1.00E+00

Table 7-3: Summary of Average Impact Vectors - Fail to Transfer Heat

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj.Ind.Events	13.33	20.00	26.67
N_1	0.6670	0.5000	0.0000
N_2	7.1670	0.5000	1.0000
N_3		7.0000	0.0000
N_4			7.0000

Total Number of Independent Failure Events: 15
Total Number of Common Cause Failure Events: 8

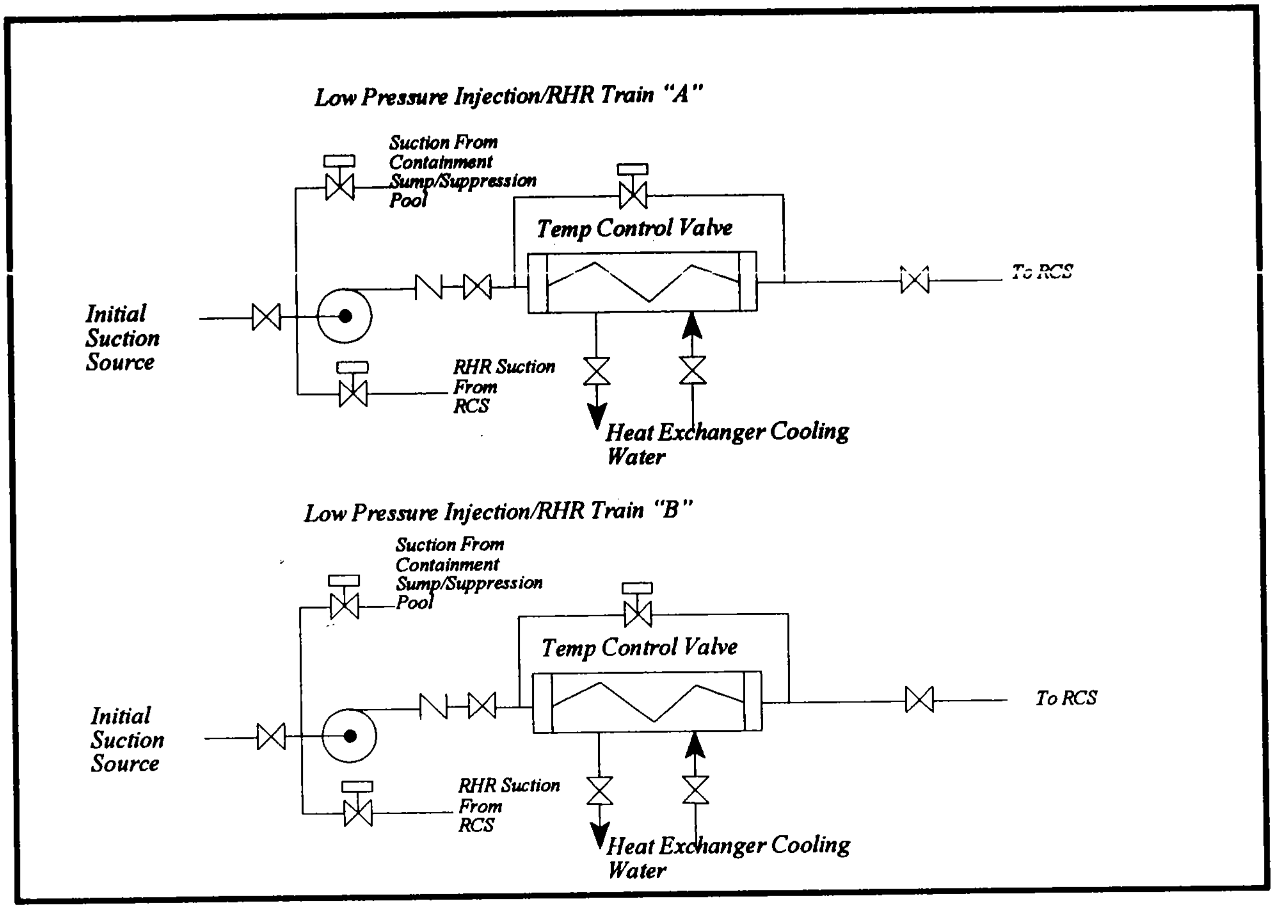

Figure 7-1. Residual heat removal system.

3. COMPONENT BOUNDARIES

The main component of an RHR heat exchanger is the heat exchanger itself. It consists of the main tank (shell), internal cooling water tubes, temperature sensors, and a temperature control valve. The cooling water on the heat exchanger side of the isolation valves is included; the remainder of the cooling water system is not.

4. FAILURE EVENT DEFINITION

Successful operation of an RHR heat exchanger is defined as heat transfer above the minimum design basis requirements. The only failure mode used in evaluating RHR heat exchanger data is:

PG Plugged or Failure to Transfer Heat. Examples are:
- Reduction in flow affecting heat transfer rate,
- Temperature switch failure, and
- Biofouling.

Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the RHR heat exchangers. Administrative inoperabilities, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of RHR system demand. The exception to this is if a licensee reported that the heat exchanger "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the heat exchanger from operating properly on a safety demand.

Some LERs reported only one actual failure, but the report information indicated that failure of a second RHR heat exchanger would have occurred from the same cause if system operation had been attempted. When the cause of the actual failure would have clearly caused failure of another RHR heat exchanger, the event was identified as a CCF. If, however, the report did not clearly identify that another RHR heat exchanger would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another RHR heat exchanger operation demand (e.g. the condition was found during inspection, and no actual heat exchanger operation was required), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 7-4 through 7-6 present the alpha factor uncertainty distribution summaries for the RHR heat exchangers. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Residual Heat Removal Heat Exchangers

Table 7-4: Alpha Factor Distribution Summary - Fail to Transfer Heat, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.6211913	0.7549416	0.7604498	0.8698278	0.6613589	2.3527E+01	7.6370E+00
α_2	1.30E-01	2.45E-01	2.40E-01	3.79E-01	3.39E-01	7.6370E+00	2.3527E+01

Table 7-5: Alpha Factor Distribution Summary - Fail to Transfer Heat, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7078387	0.8113636	0.8161079	0.8986601	0.7321429	3.570E+01	8.300E+00
α_2	7.69E-04	2.02E-02	1.35E-02	6.24E-02	1.79E-02	8.8720E-01	4.3113E+01
α_3	8.60E-02	1.69E-01	1.63E-01	2.68E-01	2.50E-01	7.4128E+00	3.6587E+01

Table 7-6: Alpha Factor Distribution Summary - Fail to Transfer Heat, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7651855	0.8467117	0.8505293	0.9151798	0.7692530	5.1370E+01	9.300E+00
α_2	3.24E-03	2.56E-02	2.06E-02	6.51E-02	2.88E-02	1.5538E+00	5.9116E+01
α_3	1.26E-07	4.33E-03	8.42E-04	2.06E-02	0.00E+00	2.6260E-01	6.0407E+01
α_4	6.22E-02	1.23E-01	1.19E-01	1.99E-01	2.02E-01	7.4836E+00	5.3186E+01

8. BWR Isolation Condensers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving the isolation condenser (IC) system at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. The only failure mode analyzed is failure to transfer heat. The data cover the time period from 1980 through 1995.

The data review identified one common-cause failure-to-transfer heat event. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to transfer heat are shown in Tables 8-1 and 8-2, respectively. Table 8-3 contains the average impact vectors (N_1-N_2) and the number of adjusted independent events for this failure mode. The size of the affected population of condensers is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_2. Beta (β) is the multiple Greek letter model parameter. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Table 8-4.

2. SYSTEM DESCRIPTION

The isolation condenser is part of the BWR emergency core cooling system (ECCS) that transfers residual and decay heat from the reactor coolant system to the atmosphere in the event that the main condenser is not available, or when a high reactor pressure condition exists. The IC system may be placed into service either manually or automatically. The IC system operates using natural circulation as the driving head through the isolation condenser tubes, and is available for operation when there is no electrical power. The primary side of the isolation condenser system is a closed loop from the reactor pressure vessel steam space through the tubes in the isolation condenser, with the condensate returning back to the recirculation loops. During normal plant operations, the secondary (shell) side of the isolation condenser contains sufficient water to cover the primary side tubes. The water in the shell side transfers the heat from the primary side by boiling off and venting directly to the atmosphere. Makeup to the secondary side is provided through the fire water system or through an alternate makeup source, such as the condensate transfer system.

Only five BWR plants have an IC system; those that don't have the IC have reactor core isolation cooling, which is a pump driven system. Some plants have two ICs, and other plants have one IC that contains two sets of steam cooling tubes. Figure 8-1 shows a typical isolation condenser system.

ALPHA FACTOR AND MGL PARAMETERS
Isolation Condensers

Table 8-1: Summary of Alpha Factor Parameter Estimations - Fail to Transfer Heat

Alpha Factor	**CCCG=2**
α_1	0.9333333
α_2	6.67E-02

Table 8-2: Summary of MGL Parameter Estimations -Transfer Heat

MGL Parameter	**CCCG=2**
1-Beta	9.33E-01
Beta	6.67E-02

Table 8-3: Summary of Average Impact Vectors - Fail to Transfer Heat

Avg. Impact Vector	**CCCG=2**
Adj.Ind.Events	3.00
N_1	0.5000
N_2	0.2500

Total Number of Independent Failure Events: 3
Total Number of Common-Cause Failure Events: 1

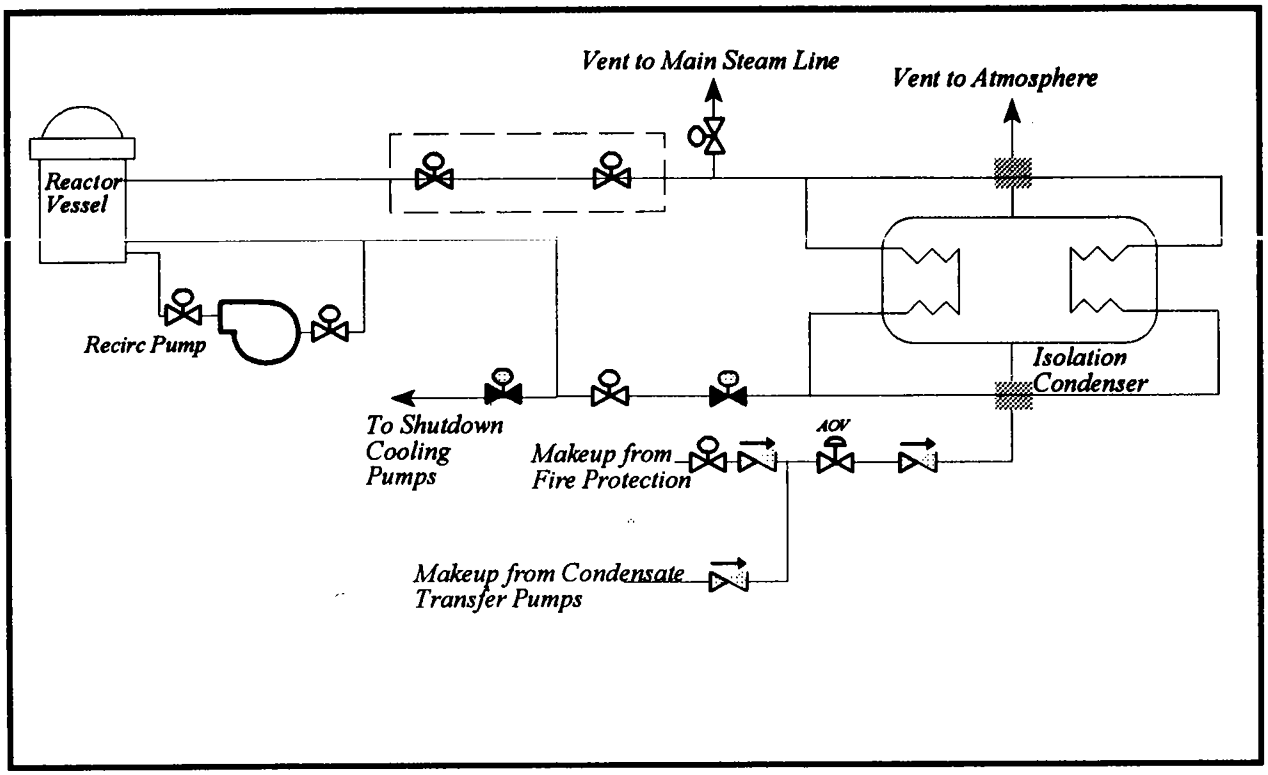

Figure 8-1. Typical isolation condenser system.

3. COMPONENT BOUNDARIES

The main components of a condenser are the tubes, tubesheets and shell.

4. FAILURE EVENT DEFINITION

The function of the isolation condenser is to provide an alternate decay heat removal path , separate from the other systems within the ECCS. The PRA mission for the isolation condenser system is to provide water for heat transfer for the removal of decay heat from the reactor coolant system. Failure of the isolation condenser system is defined as any condition that does not permit either the steam flow from the reactor pressure vessel, or condensate water return to the reactor coolant system (RCS) or makeup water flow to the IC shell flow from the makeup sources.

Only one failure mode was used in evaluating the isolation condenser data:

PG Plugged or Fail to Transfer Heat: The cooling operation must be hampered. Flow blockage, either from internal contamination, or by unintended valve closure is included.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of demand.

If the failure of the IC to perform its heat transfer function was due to a valve failure, the failure would be recorded as a valve failure. If, however, the IC failure was due to human action that misaligned a valve, the failure was recorded as a failure of the IC.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Table 8-4 presents the alpha factor uncertainty distribution summaries for each failure mode and each configuration of condenser. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Isolation Condenser

Table 8-4: Alpha Factor Distribution Summary - Fail to Transfer Heat, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8284946	0.9476364	0.9674894	0.9989285	0.9333333	1.3030E+01	7.200E-01
α_2	1.07E-03	5.24E-02	3.25E-02	1.72E-01	6.67E-02	7.2000E-01	1.3030E+01

9. PWR Auxiliary Feedwater Pumps

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving pumps in the auxiliary feedwater (AFW) system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to start and failure to run. The data cover the time period from 1980 through 1995.

The data review identified 18 common-cause failure-to-start events and 18 common-cause failure-to-run events for all AFW pump (AFP) types; 22 common-cause failure-to-start events and 19 common-cause failure-to-run events for motor-driven AFPs; 19 common-cause failure-to-start events and 23 common-cause failure-to-run events for turbine-driven AFPs. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to start for all pumps are shown in Tables 9-1 and 9-2, respectively. Table 9-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode for all pumps. Tables 9-4 through 9-18 contain the corresponding information for the failure to start and failure to run failure modes for motor-driven and turbine-driven pumps. The size of the affected population of auxiliary feedwater pumps is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 9-19 through 9-32.

2. SYSTEM DESCRIPTION

The auxiliary feedwater system provides a source of feedwater to the steam generators to remove decay heat from the reactor coolant system (RCS) when: (a) the main feedwater system is not available, and (b) RCS pressure is too high to permit heat removal by the residual heat removal (RHR) system. The AFW system is comprised of two, three, or four flow trains, each with an AFP, including the associated pump driver. The combinations of pump-driver sets range from all motor-driven to all turbine-driven AFW pumps and, in a few cases, diesel-driven pumps. Most of the designs incorporate a combination of two full-capacity motor-driven and one double capacity turbine-driven pump. There are no plants with more than one diesel-driven AFP, so CCF analysis of diesel-driven pumps is not applicable. The motor-driven pumps are supplied power from the IE class power system with backup power available from the IE emergency diesel generators (EDG). The water supply for the system is from the condensate storage tank (CST) with a backup source of water (untreated) available from the service water system.

The AFW system is normally in standby. The motor-driven pumps start on one of the following conditions: a safety injection (SI) signal, a low-low level in any steam generator, loss of both main feedwater pumps (MFP), a loss of off-site power (LOSP) or manual initiation. The turbine-driven pump will start on either a low-low level in more than one steam generator or a loss of off-site power. Feedwater flow to the steam generators is controlled from the main control room by air, motor, or hydraulically operated valves. Motor-driven pump run out is controlled by an air or hydraulically controlled regulator valve on the pump discharge. The turbine-driven pump steam supply is controlled by air or hydraulically operated valves. Figure 9-1 shows a typical auxiliary feedwater system.

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Pumps

Table 9-1: Summary of Alpha Factor Parameter Estimations -All AFP Types Fail to Start

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.8803750	0.8666979	0.8673138
α_2	1.20E-01	6.46E-02	4.52E-02
α_3		6.87E-02	3.58E-02
α_4			5.16E-02

Table 9-2: Summary of MGL Parameter Estimations - All AFP Types Fail to Start

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	8.80E-01	8.67E-01	8.67E-01
Beta	1.20E-01	1.33E-01	1.33E-01
Gamma		5.16E-01	6.59E-01
Delta			5.90E-01

Table 9-3: Summary of Average Impact Vectors -All AFP Types Fail to Start

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	54.10	81.15	108.20
N_1	8.7527	5.8630	2.9820
N_2	8.5404	6.4845	5.7989
N_3		6.8985	4.5938
N_4			6.6165

Total Number of Independent Failure Events: 66
Total Number of Common-Cause Failure Events: 18

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Pumps

Table 9-4: Summary of Alpha Factor Parameter Estimations -All AFP Types Fail to Run

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9828422	0.9718415	0.9611720
α_2	1.72E-02	2.21E-02	2.42E-02
α_3		6.11E-03	1.07E-02
α_4			3.89E-03

Table 9-5: Summary of MGL Parameter Estimations -All AFP Types Fail to Run

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.83E-01	9.72E-01	9.61E-01
Beta	1.72E-02	2.82E-02	3.88E-02
Gamma		2.17E-01	3.76E-01
Delta			2.67E-01

Table 9-6: Summary of Average Impact Vectors -All AFP Types Fail to Run

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	158.80	238.20	317.60
N_1	11.8448	11.3830	7.3169
N_2	2.9790	5.6625	8.1891
N_3		1.5690	3.6201
N_4			1.3163

Total Number of Independent Failure Events: 212
Total Number of Common-Cause Failure Events: 18

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Motor-Driven Pumps

Table 9-7: Summary of Alpha Factor Parameter Estimations - Motor-Driven AFPs Fail to Start

Alpha Factor	CCCG=2	CCCG=3
α_1	0.9190320	0.9204196
α_2	8.10E-02	3.16E-02
α_3		4.80E-02

Table 9-8: Summary of MGL Parameter Estimations - Motor-Driven AFPs Fail to Start

MGL Parameter	CCCG=2	CCCG=3
1-Beta	9.19E-01	9.20E-01
Beta	8.10E-02	7.96E-02
Gamma		6.03E-01

Table 9-9: Summary of Average Impact Vectors -Motor-Driven AFPs Fail to Start

Avg. Impact Vector	CCCG=2	CCCG=3
Adj. Ind. Events	118.67	178.01
N_1	9.4857	7.1485
N_2	11.2907	6.3605
N_3		9.6485

Total Number of Independent Failure Events: 143
Total Number of Common-Cause Failure Events: 22

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Motor-Driven Pumps

Table 9-10: Summary of Alpha Factor Parameter Estimations - Motor-Driven AFPs Fail to Run

Alpha Factor	**CCCG=2**	**CCCG=3**
α_1	0.9782316	0.9560107
α_2	2.18E-02	3.60E-02
α_3		8.04E-03

Table 9-11: Summary of MGL Parameter Estimations - Motor-Driven AFPs Fail to Run

MGL Parameter	**CCCG=2**	**CCCG=3**
1-Beta	9.78E-01	9.56E-01
Beta	2.18E-02	4.40E-02
Gamma		1.83E-01

Table 9-12: Summary of Average Impact Vectors - Motor-Driven AFPs Fail to Run

Avg. Impact Vector	**CCCG=2**	**CCCG=3**
Adj.Ind.Events	124.72	187.07
N_1	13.6448	11.3830
N_2	3.0790	7.4625
N_3		1.6690

Total Number of Independent Failure Events: 164
Total Number of Common-Cause Failure Events: 19

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Turbine-Driven Pumps

Table 9-13: Summary of Alpha Factor Parameter Estimations - Turbine-Driven AFPs Fail to Start

Alpha Factor	CCCG=2	CCCG=3
α_1	0.9661927	0.9630709
α_2	3.38E-02	1.90E-02
α_3		1.80E-02

Table 9-14: Summary of MGL Parameter Estimations - Turbine-Driven AFPs Fail to Start

MGL Parameters	CCCG=2	CCCG=3
1-Beta	9.66E-01	9.63E-01
Beta	3.38E-02	3.69E-02
Gamma		4.87E-01

Table 9-15: Summary of Average Impact Vectors - Turbine-Driven AFPs Fail to Start

Avg. Impact Vectors	CCCG=2	CCCG=3
Adj. Ind. Events	246.15	369.23
N_1	9.3530	5.8630
N_2	8.9401	7.3845
N_3		6.9985

Total Number of Independent Failure Events: 304
Total Number of Common-Cause Failure Events: 19

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Turbine-Driven Pumps

Table 9-16: Summary of Alpha Factor Parameter Estimations - Turbine-Driven AFPs Fail to Run

Alpha Factor	CCCG=2	CCCG=3
α_1	0.9770723	0.9712737
α_2	2.29E-02	1.68E-02
α_3		1.19E-02

Table 9-17: Summary of MGL Parameter Estimations - Turbine-Driven AFPs Fail to Run

MGL Parameter	CCCG=2	CCCG=3
1-Beta	9.77E-01	9.71E-01
Beta	2.29E-02	2.87E-02
Gamma		4.15E-01

Table 9-18: Summary of Average Impact Vectors - Turbine-Driven AFPs Fail to Run

Avg. Impact Vector	CCCG=2	CCCG=3
Adj. Ind. Events	236.02	354.02
N_1	14.1620	13.7280
N_2	5.8707	6.3650
N_3		4.5115

Total Number of Independent Failure Events: 308
Total Number of Common-Cause Failure Events: 23

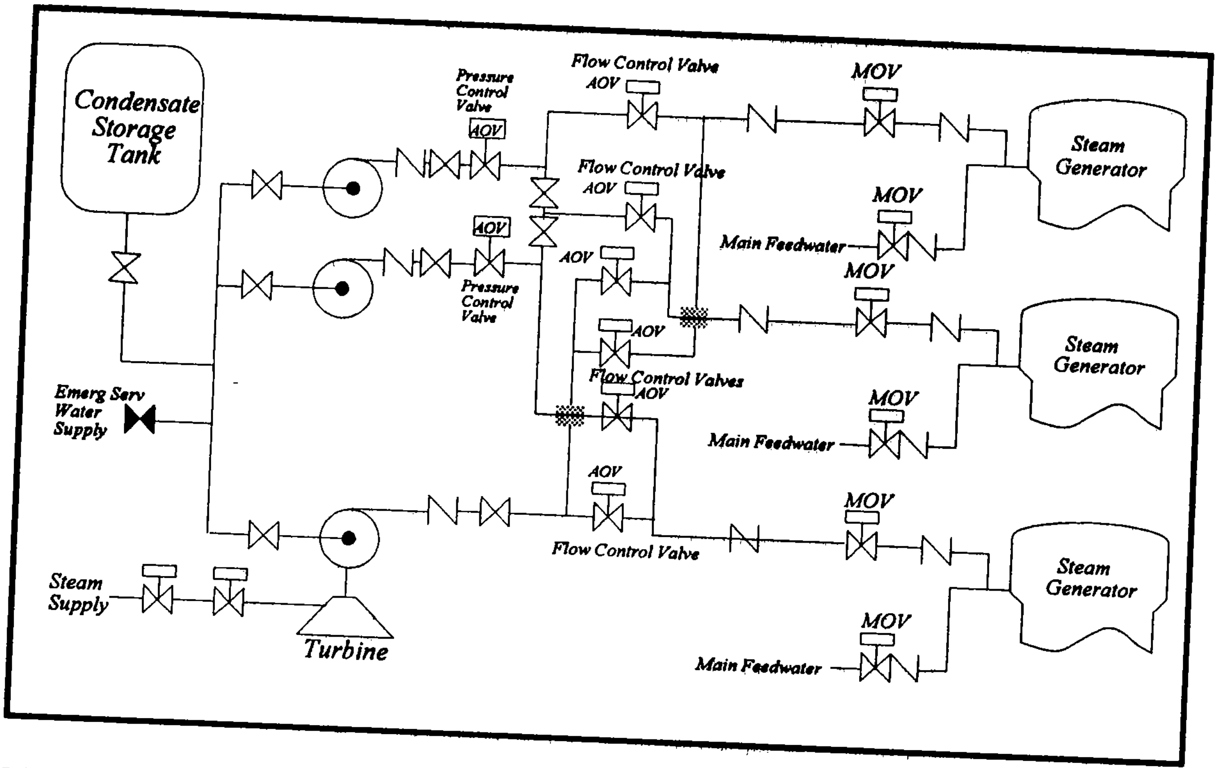

Figure 9-1. Typical auxiliary feedwater system.

3. COMPONENT BOUNDARIES

The main components of an AFW pump are the pump and pump driver. The AFP is normally in standby and is started by sensors actuating the circuit breaker or steam supply valve to the driver which will in turn operate the pump. These pumps can also be started manually via remote control switches. Stopping of the pump is accomplished by operator actions via the control switches or automatic signals designed to protect the pumps or drivers (e.g., overcurrent, overspeed).

The boundaries include the pump itself, the turbine or motor, including governor control or circuit breaker as applicable, lubrication or cooling systems, and any sensors, controls, or indication required for operation of the pump. Only controls and sensors unique to the operation of the individual pump are included in the pump boundary for CCF analysis.

4. FAILURE EVENT DEFINITION

Successful operation of an AFW pump is comprised of two distinct modes of operation. If the AFW system is in the normal standby condition, it must respond to an actuation signal by starting and obtaining design discharge pressure or flow. Once running, the AFW pump must continue to produce design flow or discharge pressure until its service is no longer needed (for the PRA mission time). The respective failure modes used for evaluating the AFP data are:

FS Failure to Start: Examples are:

- circuit breaker fails to close,
- pump fails to achieve design flow or pressure,
- governor fails to control rpm,
- control switch failure, and
- pressure switch failure.

FR Failure to Run: Examples are:

- excessive bearing vibration,
- cavitation,
- decreasing performance (less than design flow or pressure),
- excessive packing leaks, and
- loss of lubrication/cooling.

AFW pump malfunctions are considered to be failures to start and failure to run. Pump failures include those failures that are caused by power supplies or sensors that are unique to the pump-driver combination. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the AFW pumps.

Pump-driver failures are evaluated to determine the effect on pump operability. In general, if the failure causes the pump to fail to operate, it will be considered a failure. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered pump failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of pump demand. The exception to this is if a licensee reported that the pump "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the pump from operating properly on a safety demand. An example is starting up of the normal feedwater system (after outages) when the AFW starting signals are required to be unblocked. On occasion, licensees forgot to unblock the signals when they change modes, resulting in a TS violation, and preventing the pump from starting at the required condition.

Many LERs reported only one actual failure, but the report information indicated that a second AFW pump would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another AFW pump, then the event was identified as a CCF. If, however, the report did not clearly identify that another AFW pump would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to an AFW pump actuation demand (e.g. the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 9-19 through 9-32 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of AFW pumps. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

The data included in the "All AFP Types" analysis are those events that affect multiple types of AFPs, events affecting just the pump portion of multiple motor-driven AFPs, and events affecting just the pump portion of multiple turbine-driven AFPs. The data included in the "Motor-Driven AFP" analysis are events affecting multiple types of AFPs, events affecting just motor-driven AFPs, and events affecting just the AFP motors at plants that have multiple motor-driven AFPs. The data included in the "Turbine-Driven AFP" analysis are events affecting multiple types of AFPs, events affecting just turbine-driven AFPs, and events affecting just the AFP turbines at plants that have multiple turbine-driven AFPs.

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Pumps - All Pumps Types

Table 9-19: Alpha Factor Distribution Summary -All AFP Types Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8274546	0.8892981	0.8924850	0.9402466	0.8803750	7.2383E+01	9.0104E+00
α_2	5.98E-02	1.11E-01	1.08E-01	1.73E-01	1.20E-01	9.0104E+00	7.2383E+01

Table 9-20: Alpha Factor Distribution Summary - All AFP Types Fail to Start, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8250265	0.8781456	0.8803150	0.9238621	0.8666979	1.0221E+02	1.4183E+01
α_2	2.80E-02	5.90E-02	5.65E-02	9.86E-02	6.46E-02	6.8717E+00	1.0952E+02
α_3	3.07E-02	6.28E-02	6.03E-02	1.03E-01	6.87E-02	7.3113E+00	1.0908E+02

Table 9-21: Alpha Factor Distribution Summary - All AFP Types Fail to Start, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8358886	0.8812550	0.8829064	0.9209917	0.8673138	1.3588E+02	1.8309E+01
α_2	1.87E-02	4.12E-02	3.92E-02	7.04E-02	4.52E-02	6.3527E+00	1.4784E+02
α_3	1.24E-02	3.15E-02	2.95E-02	5.75E-02	3.58E-02	4.8564E+00	1.4933E+02
α_4	2.21E-02	4.61E-02	4.41E-02	7.67E-02	5.16E-02	7.101E+00	1.4709E+02

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Pumps-All Pump Types

Table9-22:AlphaFactorDistributionSummary-All AFP Types Fail to Run, CCCG=2

Alpha factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9623646	0.9812176	0.9829349	0.9941993	0.9828422	1.8018E+02	3.4490E+00
α_2	5.80E-03	1.88E-02	1.71E-02	3.76E-02	1.72E-02	3.4490E+00	1.8018E+02

Table 9-23: Alpha Factor Distribution Summary - All AFP Types Fail to Run, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9520280	0.9705603	0.9717014	0.9851865	0.9718415	2.6478E+02	8.0315E+00
α_2	9.78E-03	2.22E-02	2.10E-02	3.85E-02	2.21E-02	6.0497E+00	2.6676E+02
α_3	1.28E-03	7.26E-03	6.10E-03	1.72E-02	6.11E-03	1.9818E+00	2.7083E+02

Table 9-24: Alpha Factor Distribution Summary - All AFP Types Fail to Run, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9422655	0.9603745	0.9612185	0.9756121	0.9611720	3.4962E+02	1.4426E+01
α_2	1.25E-02	2.40E-02	2.32E-02	3.85E-02	2.42E-02	8.7429E+00	3.5530E+02
α_3	3.59E-03	1.07E-02	9.78E-03	2.08E-02	1.07E-02	3.8827E+00	3.6016E+02
α_4	7.67E-04	4.94E-03	4.07E-03	1.21E-02	3.89E-03	1.7999E+00	3.6225E+02

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Motor-Driven Pumps

Table 9-25: Alpha Factor Distribution Summary -Motor-Driven AFPs Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8822534	0.9213053	0.9231795	0.9539436	0.9190320	1.3769E+02	1.1761E+01
α_2	4.61E-02	7.87E-02	7.68E-02	1.18E-01	8.10E-02	1.1761E+01	1.3769E+02

Table 9-26: Alpha Factor Distribution Summary -Motor-Driven AFPs Fail to Start, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8907815	0.9226008	0.9238942	0.9499907	0.9204196	2.036E+02	1.6809E+01
α_2	1.45E-02	3.11E-02	2.96E-02	5.25E-02	3.16E-02	6.7477E+00	2.1042E+02
α_3	2.55E-02	4.63E-02	4.49E-02	7.19E-02	4.80E-02	1.061E+01	2.0711E+02

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Motor-Driven Pumps

Table 9-27: Alpha Factor Distribution Summary - Motor-Driven AFPs Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9534845	0.9765664	0.9786363	0.9925842	0.9782316	1.4790E+02	3.5490E+00
α_2	7.42E-03	2.34E-02	2.14E-02	4.65E-02	2.18E-02	3.5490E+00	1.4790E+02

Table 9-28: Alpha Factor Distribution Summary -Motor-Driven AFPs Fail to Run, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9308810	0.9555799	0.9569313	0.9756581	0.9560107	2.1365E+02	9.9315E+00
α_2	1.75E-02	3.51E-02	3.37E-02	5.74E-02	3.60E-02	7.8497E+00	2.1573E+02
α_3	1.75E-03	9.31E-03	7.89E-03	2.17E-02	8.04E-03	2.0818E+00	2.2150E+02

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Turbine-Driven Pumps

Table 9-29: Alpha Factor Distribution Summary -Turbine-Driven AFPs Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9459550	0.9657117	0.9668360	0.9816230	0.9661927	2.6503E+02	9.4101E+00
α_2	1.84E-02	3.43E-02	3.32E-02	5.41E-02	3.38E-02	9.4101E+00	2.6503E+02

Table 9-30: Alpha Factor Distribution Summary -Turbine-Driven AFPs Fail to Start, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9458789	0.9625548	0.9633151	0.9766418	0.9630709	3.9029E+02	1.5183E+01
α_2	9.48E-03	1.92E-02	1.84E-02	3.15E-02	1.90E-02	7.7717E+00	3.9770E+02
α_3	8.86E-03	1.83E-02	1.75E-02	3.04E-02	1.80E-02	7.4113E+00	3.9806E+02

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Turbine-Driven Pumps

Table 9-31: Alpha Factor Distribution Summary - Turbine-Driven AFPs Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9590514	0.9761673	0.9773541	0.9892347	0.9770723	2.5971E+02	6.3407E+00
α_2	1.08E-02	2.38E-02	2.27E-02	4.10E-02	2.29E-02	6.3407E+00	2.5971E+02

Table 9-32: Alpha Factor Distribution Summary -Turbine-Driven AFPs Fail to Run, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9551773	0.9704112	0.9712046	0.9829430	0.9712737	3.8295E+02	1.1677E+01
α_2	7.94E-03	1.71E-02	1.63E-02	2.90E-02	1.68E-02	6.7522E+00	3.8787E+02
α_3	4.90E-03	1.25E-02	1.17E-02	2.28E-02	1.19E-02	4.9243E+00	3.8970E+02

10. Emergency Service Water Pumps

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving pumps in the emergency service water (ESW) system at both boiling water reactor (BWR) power plants and pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to start and failure to run. The data cover the time period from 1980 through 1995.

The data review identified 61 common-cause failure-to-start events and 80 common-cause failure-to-run events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to start are shown in Tables 10-1 and 10-2, respectively. Table 10-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 10-4 through 10-6 contain the corresponding information for failure to close and failure to remain closed. The size of the affected population of pumps is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 10-7 through 10-16.

2. SYSTEM DESCRIPTION

The emergency service water system is designed to ensure adequate cooling is provided to the safety related equipment during all analyzed accident conditions where Class 1E AC power is available. Service water is supplied from a designated ultimate heat sink (e.g., cooling tower, river lake, ocean etc.) to heat exchangers in closed loop cooling systems This safety function is normally provided by multiple trains of the ESW system, each with an ESW pump and associated driver. Some power plants use storage water in a limited amount via gates and canals.

A variety of pump combinations are utilized across the vendor designs to accomplish this safety function. The combinations range from as few as two, to twelve or more. In most cases, piping configurations allow each ESW pump to supply cooling water to multiple closed loop system heat exchangers. However, BWR ESW system arrangements are split into more sections by location of equipment supplied (e.g., reactor building etc.). Power to the motor-driven ESW pumps is supplied from the Class 1E AC power system which has an emergency source (usually an emergency diesel generator). A simplified schematic diagram of the ESW system is shown in Figure 10-1.

ALPHA FACTOR AND MGL PARAMETERS
Emergency Service Water Pumps

Table 10-1: Summary of Alpha Factor Parameter Estimations - Fail to Start

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9638981	0.9461791	0.9228140	0.9089041	0.9029763
α_2	3.61E-02	4.37E-02	6.20E-02	5.32E-02	4.03E-02
α_3		1.01E-02	8.47E-03	2.83E-02	3.36E-02
α_4			6.74E-03	4.29E-03	1.48E-02
α_5				5.37E-03	5.19E-03
α_6					3.21E-03

Table 10-2: Summary of MGL Parameter Estimations - Fail to Start

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.64E-01	9.46E-01	9.23E-01	9.09E-01	9.03E-01
Beta	3.61E-02	5.38E-02	7.72E-02	9.11E-02	9.70E-02
Gamma		1.88E-01	1.97E-01	4.16E-01	5.85E-01
Delta			4.43E-01	2.55E-01	4.09E-01
Epsilon				5.56E-01	3.62E-01
Mu					3.82E-01

Table 10-3: Summary of Average Impact Vectors - Fail to Start

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	129.01	193.51	258.01	322.52	387.02
N_1	32.3127	37.7868	35.2266	30.4601	26.9867
N_2	6.0422	10.6786	19.6921	20.6534	18.4712
N_3		2.4781	2.6924	10.9742	15.3808
N_4			2.1424	1.6663	6.7800
N_5				2.0839	2.3800
N_6					1.4725

Total Number of Independent Failure Events: 318
Total Number of Common-Cause Failure Events: 61

ALPHA FACTOR AND MGL PARAMETERS
Emergency Service Water Pumps

Table 10-4: Summary of Alpha Factor Parameter Estimations - Fail to Run

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9617605	0.9634743	0.9622712	0.9615668	0.9606430
α_2	3.82E-02	1.44E-02	1.61E-02	1.50E-02	1.28E-02
α_3		2.22E-02	5.49E-03	7.86E-03	8.65E-03
α_4			1.61E-02	2.79E-03	4.73E-03
α_5				1.27E-02	2.38E-03
α_6					1.08E-02

Table 10-5: Summary of MGL Parameter Estimations - Fail to Run

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.62E-01	9.64E-01	9.62E-01	9.62E-01	9.61E-01
Beta	3.82E-02	3.65E-02	3.77E-02	3.84E-02	3.94E-02
Gamma		6.07E-01	5.73E-01	6.09E-01	6.74E-01
Delta			7.46E-01	6.64E-01	6.74E-01
Epsilon				8.20E-01	7.36E-01
Mu					8.19E-01

Table 10-6: Summary of Average Impact Vectors - Fail to Run

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	442.97	664.45	885.93	1107.42	1328.90
N_1	34.4529	35.8558	35.2866	32.1411	29.0731
N_2	18.9823	10.4299	15.4361	17.8229	18.1225
N_3		16.1190	5.2590	9.3180	12.2240
N_4			15.4240	3.3091	6.6851
N_5				15.0975	3.3604
N_6					15.2434

Total Number of Independent Failure Events: 866
Total Number of Common-Cause Failure Events: 80

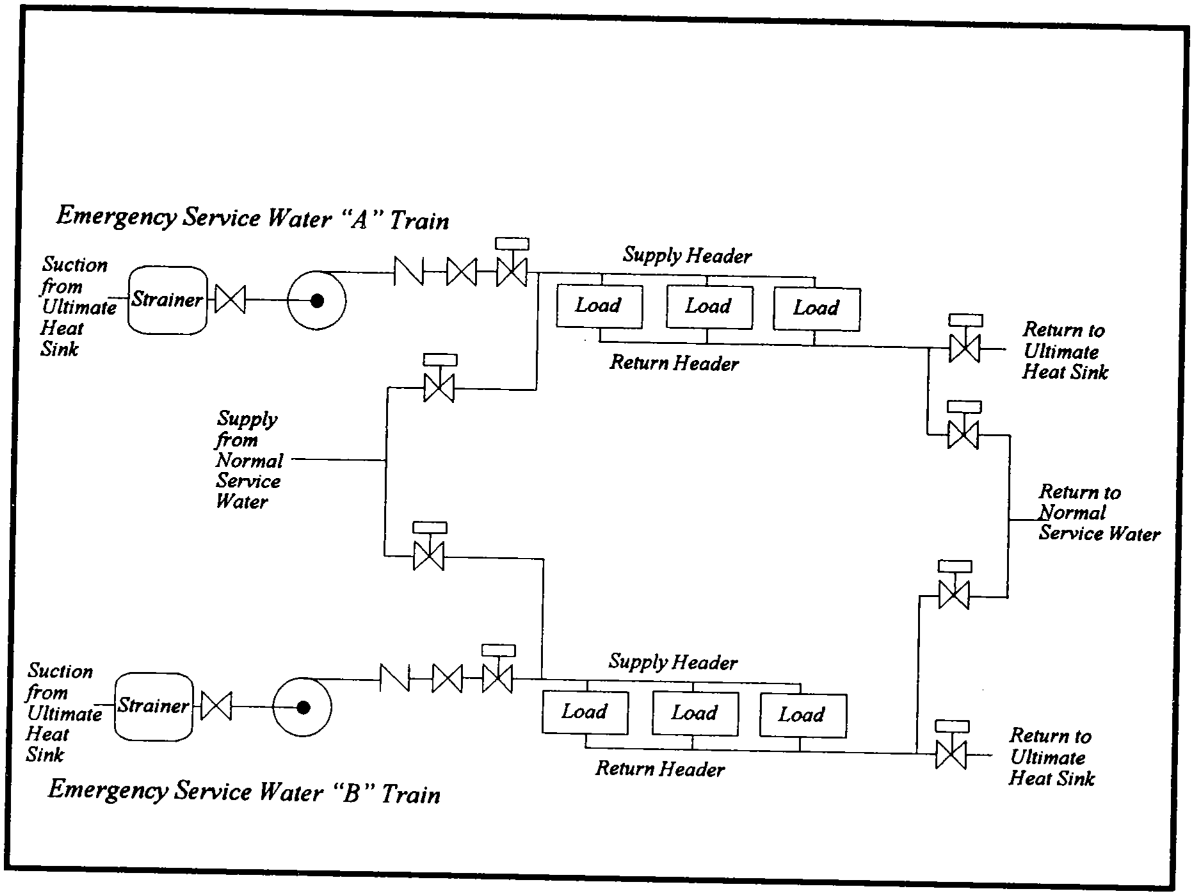

Figure 10-1. Typical service water system.

3. COMPONENT BOUNDARIES

The main component of an ESW pump is the pump itself coupled to an AC electric motor for a driver. This component can be in one of two states, standby or running. In the standby condition, starting is accomplished by sensors actuating a circuit breaker. These pumps can also be started manually via remote control switches. Stopping of the pump is accomplished only by operator actions via the control switches or automatic signals designed to protect the pump or driver (e.g., overcurrent). The boundaries include the pump itself and internal piece-parts, the driver, circuit breaker, lubrication or cooling systems, and any sensors, controls, or indication required for operation of the pump.

4. FAILURE EVENT DEFINITION

Successful operation of an ESW pump is defined for two distinct modes of operation. If the ESW pump is in the standby condition, it must respond to an actuation signal by starting, which includes of obtaining design discharge pressure or flow. Once running, the ESW pump must continue to produce design flow or discharge pressure until its service is no longer needed. The respective failure modes used for evaluating the data are:

FS Failure to Start: Examples are:

- Circuit breaker fails to close,
- Pump fails to achieve design flow or pressure,
- Control switch failure, and
- Pressure switch failure.

FR Failure to Run: Examples are:

- Excessive bearing vibration,
- Cavitation,
- Decreasing performance (less than design flow or pressure) while running,
- Excessive packing leaks, and
- Loss of lubrication/cooling.

ESW pump malfunctions are considered to be failures to start or run on demand. Pump failures include those failures that are caused by power supplies or sensors that are unique to the pump-driver combination. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the ESW pumps.

Pump-driver failures are evaluated to determine the effect on pump operability. In general, if the failure causes the pump to fail to operate, it will be considered a failure. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered pump failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of pump demand. The exception to this is if a licensee reported that the pump "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the pump from operating properly on a safety demand.

Some LERs reported only one actual failure, but the report information indicated that a second ESW pump would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another ESW pump, then the event was identified as a CCF. If, however, the report did not clearly identify that another ESW pump would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to an ESW pump actuation demand (e.g., the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 10-7 through 10-16 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of ESW pumps. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Emergency Service Water Pumps

Table 10-7: Alpha Factor Distribution Summary - Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9375315	0.9632831	0.9650163	0.9831287	0.9638981	1.7085E+02	6.5122E+00
α_2	1.69E-02	3.67E-02	3.50E-02	6.25E-02	3.61E-02	6.5122E+00	1.7085E+02

Table 10-8: Alpha Factor Distribution Summary - Fail to Start, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9217195	0.9464138	0.9475555	0.9672214	0.9461791	2.4650E+02	1.3957E+01
α_2	2.42E-02	4.25E-02	4.13E-02	6.48E-02	4.37E-02	1.1066E+01	2.4939E+02
α_3	2.94E-03	1.11E-02	9.87E-03	2.34E-02	1.01E-02	2.8909E+00	2.5757E+02

Table 10-9: Alpha Factor Distribution Summary - Fail to Start, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9001951	0.9248706	0.9256917	0.9467360	0.9228140	3.1794E+02	2.5827E+01
α_2	3.96E-02	5.89E-02	5.80E-02	8.11E-02	6.20E-02	2.0246E+01	3.2352E+02
α_3	2.32E-03	8.60E-03	7.66E-03	1.81E-02	8.47E-03	2.9550E+00	3.4081E+02
α_4	1.85E-03	7.64E-03	6.71E-03	1.66E-02	6.74E-03	2.6260E+00	3.4114E+02

Table 10-10: Alpha Factor Distribution Summary - Fail to Start, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8894056	0.9128414	0.9134861	0.9340845	0.9089041	3.9102E+02	3.7335E+01
α_2	3.39E-02	4.99E-02	4.92E-02	6.83E-02	5.32E-02	2.1381E+01	4.0697E+02
α_3	1.52E-02	2.66E-02	2.59E-02	4.05E-02	2.83E-02	1.1386E+01	4.1697E+02
α_4	7.40E-04	4.44E-03	3.69E-03	1.07E-02	4.29E-03	1.8999E+00	4.2646E+02
α_5	1.53E-03	6.23E-03	5.48E-03	1.35E-02	5.37E-03	2.6679E+00	4.2569E+02

Table 10-11: Alpha Factor Distribution Summary - Fail to Start, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8862246	0.9080896	0.9086238	0.9281349	0.9029763	4.6448E+02	4.7011E+01
α_2	2.49E-02	3.76E-02	3.70E-02	5.24E-02	4.03E-02	1.9250E+01	4.9224E+02
α_3	1.96E-02	3.11E-02	3.05E-02	4.47E-02	3.36E-02	1.5921E+01	4.9557E+02
α_4	6.58E-03	1.39E-02	1.32E-02	2.33E-02	1.48E-02	7.0927E+00	5.0440E+02
α_5	1.24E-03	5.13E-03	4.50E-03	1.12E-02	5.19E-03	2.6233E+00	5.0887E+02
α_6	7.97E-04	4.15E-03	3.53E-03	9.65E-03	3.21E-03	2.1244E+00	5.0937E+02

ALPHA FACTOR DISTRIBUTIONS
Emergency Service Water Pumps

Table 10-12: Alpha Factor Distribution Summary - Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9465909	0.9615879	0.9621973	0.9745147	0.9617605	4.8695E+02	1.9452E+01
α_2	2.55E-02	3.84E-02	3.78E-02	5.34E-02	3.82E-02	1.9452E+01	4.8695E+02

Table 10-13: Alpha Factor Distribution Summary - Fail to Run, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9511597	0.9631841	0.9636015	0.9737887	0.9634743	7.1551E+02	2.7349E+01
α_2	8.15E-03	1.46E-02	1.41E-02	2.25E-02	1.44E-02	1.0817E+01	7.3204E+02
α_3	1.42E-02	2.23E-02	2.18E-02	3.18E-02	2.22E-02	1.6532E+01	7.2633E+02

Table 10-14: Alpha Factor Distribution Summary - Fail to Run, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9514073	0.9619464	0.9622573	0.9714137	0.9622712	9.4592E+02	3.7420E+01
α_2	1.02E-02	1.63E-02	1.59E-02	2.34E-02	1.61E-02	1.5990E+01	9.6735E+02
α_3	2.35E-03	5.62E-03	5.28E-03	1.0E-02	5.49E-03	5.5216E+00	9.7782E+02
α_4	1.02E-02	1.62E-02	1.59E-02	2.33E-02	1.61E-02	1.5908E+01	9.6743E+02

Table 10-15: Alpha Factor Distribution Summary - Fail to Run, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9517437	0.9612232	0.9614717	0.9698423	0.9615668	1.1776E+03	4.7506E+01
α_2	9.89E-03	1.51E-02	1.49E-02	2.13E-02	1.50E-02	1.8551E+01	1.2066E+03
α_3	4.28E-03	7.94E-03	7.68E-03	1.25E-02	7.86E-03	9.730E+00	1.2154E+03
α_4	9.05E-04	2.89E-03	2.63E-03	5.79E-03	2.79E-03	3.5427E+00	1.2216E+03
α_5	8.01E-03	1.28E-02	1.25E-02	1.85E-02	1.27E-02	1.5682E+01	1.2094E+03

Table 10-16: Alpha Factor Distribution Summary - Fail to Run, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9516203	0.9603430	0.9605500	0.9683479	0.9606430	1.4085E+03	5.8164E+01
α_2	8.45E-03	1.29E-02	1.27E-02	1.81E-02	1.28E-02	1.8902E+01	1.4478E+03
α_3	5.13E-03	8.70E-03	8.48E-03	1.30E-02	8.65E-03	1.2765E+01	1.4539E+03
α_4	2.24E-03	4.77E-03	4.55E-03	8.06E-03	4.73E-03	6.9978E+00	1.4597E+03
α_5	7.79E-04	2.46E-03	2.24E-03	4.89E-03	2.38E-03	3.6037E+00	1.4631E+03
α_6	6.80E-03	1.08E-02	1.06E-02	1.56E-02	1.08E-02	1.5895E+01	1.4508E+03

11. PWR High Pressure Safety Injection Pumps

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving pumps in the high pressure safety injection system (HPSI) system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to start and failure to run. The data cover the time period from 1980 through 1995.

The data review identified 21 common-cause failure-to-start events and 21 common-cause failure-to-run events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to start are shown in Tables 11-1 and 11-2, respectively. Table 11-3 contains the average impact vectors (N_1-N_5) and the number of adjusted independent events for this failure mode. Tables 11-4 through 11-6 contain the corresponding information for the failure to run failure modes. The size of the affected population of PWR high pressure injection pumps is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_5. Beta (β), gamma (γ), delta (δ), and epsilon (ϵ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 11-7 through 11-14.

2. SYSTEM DESCRIPTION

The high pressure safety injection (HPSI) system is a subsystem of the emergency core cooling system (ECCS) that functions to provide emergency coolant injection to maintain reactor coolant inventory and provide adequate decay heat removal following a loss of coolant accident (LOCA). The injection function is performed in a relatively short time interval after initiation of the LOCA. The system is typically comprised of two safety injection (SI) pumps and two or three high pressure centrifugal charging pumps (CCP); one CCP is an installed spare which can be manually aligned to either train. Positive displacement (reciprocating) charging pumps were not included in this study due to the differences in design and operating characteristics between them and centrifugal pumps. CCF events can affect only the SI pumps, only the CCPs, or both SI pumps and CCPs, so the CCCG for events at a single plant can range from two to five.

Both the charging and the SI pumps inject directly into the primary loop cold legs, and the SI pumps can be realigned to inject into the hot legs. The suction source for the HPSI pumps is the refueling water storage tank (RWST) which contains enough highly borated water to satisfy the injection needs of the core. Figure 11-1 illustrates the typical flow path for the HPSI system. All pumps and motor operated valves receive power from the 1E emergency power system backed up by the emergency diesel generators.

The system is normally aligned and in the standby mode. The HPSI pumps are started by the engineered safety features actuation system (ESFAS) or may be manually actuated. A HPSI signal starts the charging and SI pumps, shifts the charging pump suction to the RWST, isolates normal charging and letdown flow and completes additional valve lineup changes. The injection phase ends when the RWST reaches the low level setpoint and the system is realigned for the recirculation phase which takes suction from the containment sump through the RHR system.

ALPHA FACTOR AND MGL PARAMETERS
PWR High Pressure Safety Injection Pumps

Table 11-1: Summary of Alpha Factor Parameter Estimations - Fail to Start

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5
α_1	0.9443582	0.9446865	0.9467303	0.9503090
α_2	5.56E-02	2.58E-02	2.45E-02	1.67E-02
α_3		2.95E-02	6.72E-03	1.17E-02
α_4			2.21E-02	3.53E-03
α_5				1.77E-02

Table 11-2: Summary of MGL Parameter Estimations - Fail to Start

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5
1-Beta	9.44E-01	9.45E-01	9.47E-01	9.50E-01
Beta	5.56E-02	5.53E-02	5.33E-02	4.97E-02
Gamma		5.34E-01	5.40E-01	6.63E-01
Delta			7.66E-01	6.44E-01
Epsilon				8.33E-01

Table 11-3: Summary of Average Impact Vectors - Fail to Start

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5
Adj. Ind. Events	128.66	192.99	257.33	321.66
N_1	8.5527	7.3543	5.7121	4.3340
N_2	8.0846	5.4708	6.8068	5.7440
N_3		6.2598	1.8676	4.0272
N_4			6.1262	1.2119
N_5				6.0629

Total Number of Independent Failure Events: 202
Total Number of Common-Cause Failure Events: 21

ALPHA FACTOR AND MGL PARAMETERS
PWR High Pressure Safety Injection Pumps

Table 11-4: Summary of Alpha Factor Parameter Estimations - Fail to Run

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5
α_1	0.9790682	0.9719681	0.9716753	0.9729580
α_2	2.09E-02	1.96E-02	1.41E-02	9.90E-03
α_3		8.44E-03	8.70E-03	8.44E-03
α_4			5.55E-03	4.57E-03
α_5				4.13E-03

Table 11-5: Summary of MGL Parameter Estimations - Fail to Run

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5
1-Beta	9.79E-01	9.72E-01	9.72E-01	9.73E-01
Beta	2.09E-02	2.80E-02	2.83E-02	2.70E-02
Gamma		3.01E-01	5.03E-01	6.34E-01
Delta			3.89E-01	5.08E-01
Epsilon				4.74E-01

Table 11-6: Summary of Average Impact Vectors - Fail to Run

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5
Adj. Ind. Events	212.98	319.47	425.95	532.44
N_1	9.9688	7.9357	6.3669	5.0404
N_2	4.7665	6.5984	6.2637	5.4699
N_3		2.8441	3.8700	4.6633
N_4			2.4685	2.5257
N_5				2.2796

Total Number of Independent Failure Events: 279
Total Number of Common-Cause Failure Events: 21

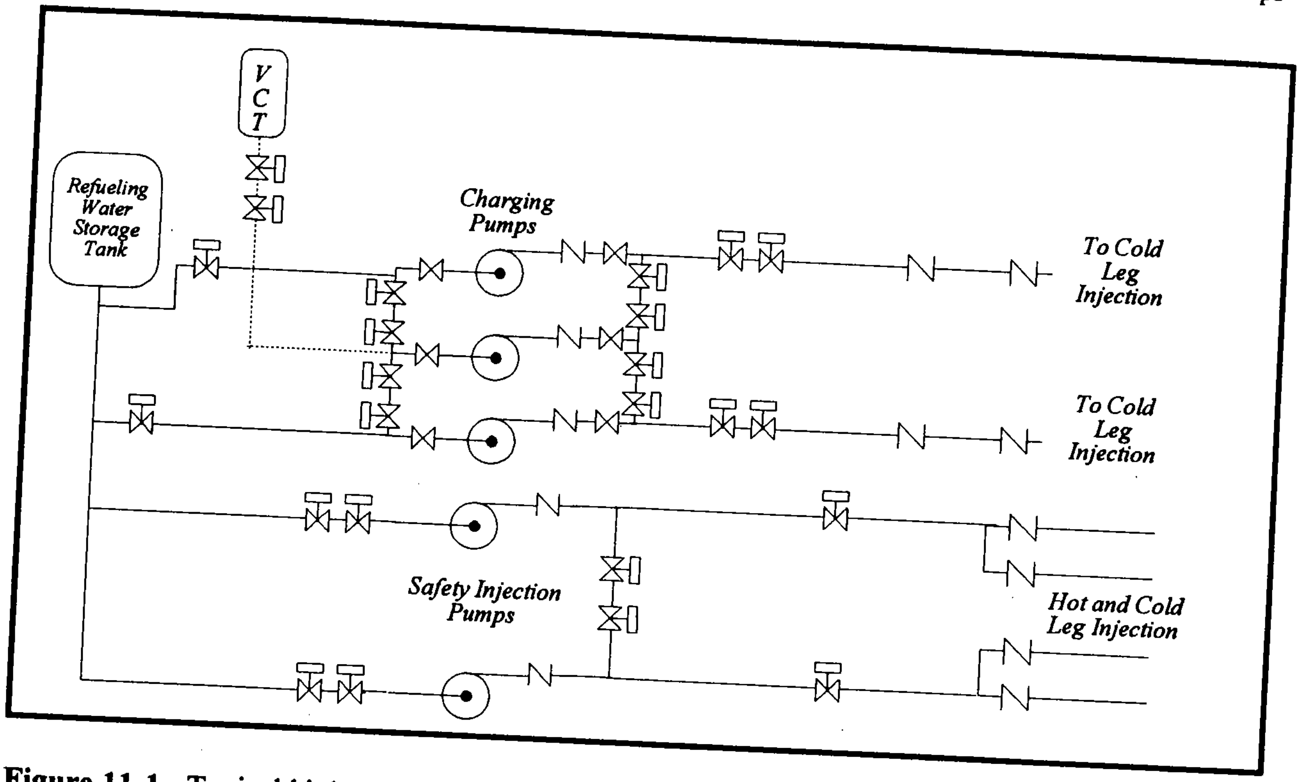

Figure 11-1. Typical high pressure safety injection system.

3. COMPONENT BOUNDARIES

The main component of an HPSI pump is the pump itself. The SI pumps are normally in standby and started by sensors actuating the circuit breaker to the driver which will in turn operate the pump. These pumps can also be started manually via remote control switches. There is usually one charging pump operating, and it will continue running on a LOCA signal. Stopping of the pump is accomplished only by operator actions via the control switches or automatic signals designed to protect the pumps or motors (e.g., overcurrent, overspeed).

The boundaries include the pump itself, the driver including the circuit breaker, lubrication or cooling systems, and any sensors, controls, or indication required for operation of the pump. Sensors or input logic that affect components other than a single SI or charging pump are not included in the component boundaries.

4. FAILURE EVENT DEFINITION

Successful operation of an HPSI pump is defined for two distinct modes of operation. If the HPSI is in the normal standby condition, it must respond to an actuation signal by starting which consists of obtaining design discharge pressure and flow. Once running, the HPSI pump must continue to produce design flow and discharge pressure until its service is no longer needed. The respective failure modes used for evaluating the HPSI pump data are:

FS Failure to Start: Examples are:

- Circuit breaker fails to close,
- Pump fails to achieve design flow or pressure,
- Control switch failure, and
- Pressure switch failure.

FR Failure to Run: Examples are:

- Excessive bearing vibration,
- Cavitation,
- Decreasing performance (less than design flow or pressure) while running,
- Excessive packing leaks, and
- Loss of lubrication/cooling.

HPSI pump malfunctions are considered to be failures to start or failures to run. Pump failures include those failures that are caused by power supplies or sensors that are unique to the pump-driver combination. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the HPSI pumps.

Pump motor failures are evaluated to determine the effect on pump operability. In general, if the failure causes the pump to fail to operate, it will be considered a failure. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered pump failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of pump demand. The exception to this is if a licensee reported that the pump "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the pump from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second HPSI pump would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another HPSI pump, the event was identified as a CCF. If, however, the report did not clearly identify that another pump would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another HPSI pump operation demand (e.g. the condition was found during inspection, and no actual pump start was attempted), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 11-7 through 11-14 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of pumps. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
PWR High Pressure Safety Injection Pumps

Table 11-7: Alpha Factor Distribution Summary - Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9119826	0.9449137	0.9468151	0.9713447	0.9443582	1.4674E+02	8.5546E+00
α_2	2.87E-02	5.51E-02	5.32E-02	8.80E-02	5.56E-02	8.5546E+00	1.4674E+02

Table 11-8: Alpha Factor Distribution Summary - Fail to Start, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9182689	0.9450582	0.9463533	0.9674159	0.9446865	2.1554E+02	1.2531E+01
α_2	1.12E-02	2.57E-02	2.43E-02	4.49E-02	2.58E-02	5.8580E+00	2.2221E+02
α_3	1.36E-02	2.93E-02	2.79E-02	4.96E-02	2.95E-02	6.6726E+00	2.2140E+02

Table 11-9: Alpha Factor Distribution Summary - Fail to Start, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9243639	0.9470097	0.9479904	0.9663187	0.9467303	2.8774E+02	1.6101E+01
α_2	1.17E-02	2.42E-02	2.32E-02	4.03E-02	2.45E-02	7.3606E+00	2.9648E+02
α_3	1.35E-03	7.01E-03	5.96E-03	1.63E-02	6.72E-03	2.1302E+00	3.0171E+02
α_4	1.0E-02	2.18E-02	2.07E-02	3.71E-02	2.21E-02	6.6098E+00	2.9723E+02

Table 11-10: Alpha Factor Distribution Summary - Fail to Start, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9309180	0.9503879	0.9511725	0.9671870	0.9503090	3.6404E+02	1.904E+01
α_2	7.69E-03	1.69E-02	1.61E-02	2.90E-02	1.67E-02	6.4720E+00	3.7657E+02
α_3	4.27E-03	1.16E-02	1.08E-02	2.18E-02	1.17E-02	4.4392E+00	3.7860E+02
α_4	4.17E-04	3.77E-03	2.95E-03	9.94E-03	3.53E-03	1.4455E+00	3.8160E+02
α_5	8.0E-03	1.74E-02	1.65E-02	2.96E-02	1.77E-02	6.6469E+00	3.7640E+02

ALPHA FACTOR DISTRIBUTIONS
PWR High Pressure Safety Injection Pumps

Table 11-11: Alpha Factor Distribution Summary - Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9604043	0.9779717	0.9792973	0.9910095	0.9790682	2.3248E+02	5.2365E+00
α_2	8.99E-03	2.20E-02	2.07E-02	3.96E-02	2.09E-02	5.2365E+00	2.3248E+02

Table 11-12: Alpha Factor Distribution Summary - Fail to Run, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9549345	0.9709723	0.9718611	0.9839909	0.9719681	3.4261E+02	1.0243E+01
α_2	9.35E-03	1.98E-02	1.89E-02	3.33E-02	1.96E-02	6.9856E+00	3.4587E+02
α_3	2.71E-03	9.23E-03	8.32E-03	1.89E-02	8.44E-03	3.2569E+00	3.4960E+02

Table 11-13: Alpha Factor Distribution Summary - Fail to Run, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9566302	0.9704788	0.9711466	0.9820622	0.9716753	4.5702E+02	1.3902E+01
α_2	6.75E-03	1.45E-02	1.38E-02	2.45E-02	1.41E-02	6.8175E+00	4.6411E+02
α_3	3.08E-03	8.78E-03	8.09E-03	1.68E-02	8.70E-03	4.1326E+00	4.6679E+02
α_4	1.69E-03	6.27E-03	5.59E-03	1.32E-02	5.55E-03	2.9521E+00	4.6797E+02

Table 11-14: Alpha Factor Distribution Summary - Fail to Run, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9594095	0.9714794	0.9720066	0.9817424	0.9729580	5.7552E+02	1.6896E+01
α_2	4.65E-03	1.05E-02	9.92E-03	1.81E-02	9.90E-03	6.1979E+00	5.8622E+02
α_3	3.42E-03	8.57E-03	8.02E-03	1.56E-02	8.44E-03	5.0753E+00	5.8734E+02
α_4	1.18E-03	4.66E-03	4.11E-03	1.0E+01	4.57E-03	2.7593E+00	5.8966E+02
α_5	1.27E-03	4.83E-03	4.29E-03	1.03E-02	4.13E-03	2.8636E+00	5.8955E+02

12. BWR Low Pressure Coolant Injection Pumps

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving pumps in the low pressure coolant injection (LPCI) system, including RHR pumps in the injection mode, at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to start and failure to run. The data cover the time period from 1980 through 1995.

The data review identified seven common-cause failure-to-start events and two common-cause failure-to-run events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to start are shown in Tables 12-1 and 12-2, respectively. Table 12-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode. Tables 12-4 through 12-6 contain the corresponding information for the failure to run failure modes. The size of the affected population of BWR low pressure injection pumps is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 12-7 through 12-12.

2. SYSTEM DESCRIPTION

LPCI is a mode of the residual heat removal (RHR) subsystem of the emergency core cooling system (ECCS) or a specific separate system in early BWR designs that serves several functions by operating in different modes:

- Low pressure coolant injection (LPCI) mode - to provide low pressure makeup water to the reactor vessel for core cooling under loss of coolant accident (LOCA) conditions,
- Containment spray mode - to reduce primary containment pressure and temperature following a LOCA, and
- Suppression pool cooling mode - to remove heat from the suppression pool.

Under accident conditions, the LPCI mode is automatically initiated. All other modes require manual system alignment for proper operation. The LPCI mode takes suction from the suppression pool and discharges to the reactor vessel penetrations. The RHR heat exchangers are bypassed in this mode. The containment spray mode protects the containment structure from possible over pressurization from steam which might bypass the suppression pool, including system breaks within the containment volume. In this mode water is pumped from the suppression pool through heat exchangers to spray nozzles located high in the containment space. The suppression pool cooling mode is designed to limit the long term bulk temperature rise of the suppression pool water following a design basis LOCA. A closed path from the suppression pool through the RHR loops to the reactor vessel and back to the suppression pool through the break can be maintained for decay heat removal from the core.

A simplified schematic drawing of a typical BWR LPCI system configuration in presented in Figure 12-1.

ALPHA FACTOR AND MGL PARAMETERS
BWR Low Pressure Coolant Injection Pumps

Table 12-1: Summary of Alpha Factor Parameter Estimations - Fail to Start

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9894718	0.9789343	0.9682947
α_2	1.05E-02	2.10E-02	3.15E-02
α_3		8.21E-05	2.18E-04
α_4			7.78E-06

Table 12-2: Summary of MGL Parameter Estimations - Fail to Start

MGL Parameters	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.90E-01	9.76E-01	9.68E-01
Beta	1.05E-02	2.11E-02	3.17E-02
Gamma		3.90E+03	7.12E+03
Delta			3.45E+02

Table 12-3: Summary of Average Impact Vectors - Fail to Start

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj.Ind.Events	28.00	42.00	56.00
N_1	4.4616	5.6695	6.2110
N_2	0.3454	1.0218	2.0225
N_3		0.0040	0.0140
N_4			0.0005

Total Number of Independent Failure Events: 56
Total Number of Common-Cause Failure Events: 7

ALPHA FACTOR AND MGL PARAMETERS
BWR Low Pressure Coolant Injection Pumps

Table 12-4: Summary of Alpha Factor Parameter Estimations - Fail to Run

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9978412	0.9956831	0.9935106
α_2	2.16E-03	4.32E-03	6.49E-03
α_3		0.00E+00	0.00E+00
α_4			0.00E+00

Table 12-5: Summary of MGL Parameter Estimations - Fail to Run

MGL Parameters	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.98E-01	9.96E-01	9.94E-01
Beta	2.16E-03	4.32E-03	6.49E-03
Gamma		0.00E+00	0.00E+00
Delta			0.00E+00

Table 12-6: Summary of Average Impact Vectors - Fail to Run

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	38.00	57.00	76.00
N_1	1.3802	1.8150	2.0800
N_2	0.0852	0.2550	0.5100
N_3		0.0000	0.0000
N_4			0.0000

Total Number of Independent Failure Events: 76
Total Number of Common-Cause Failure Events: 2

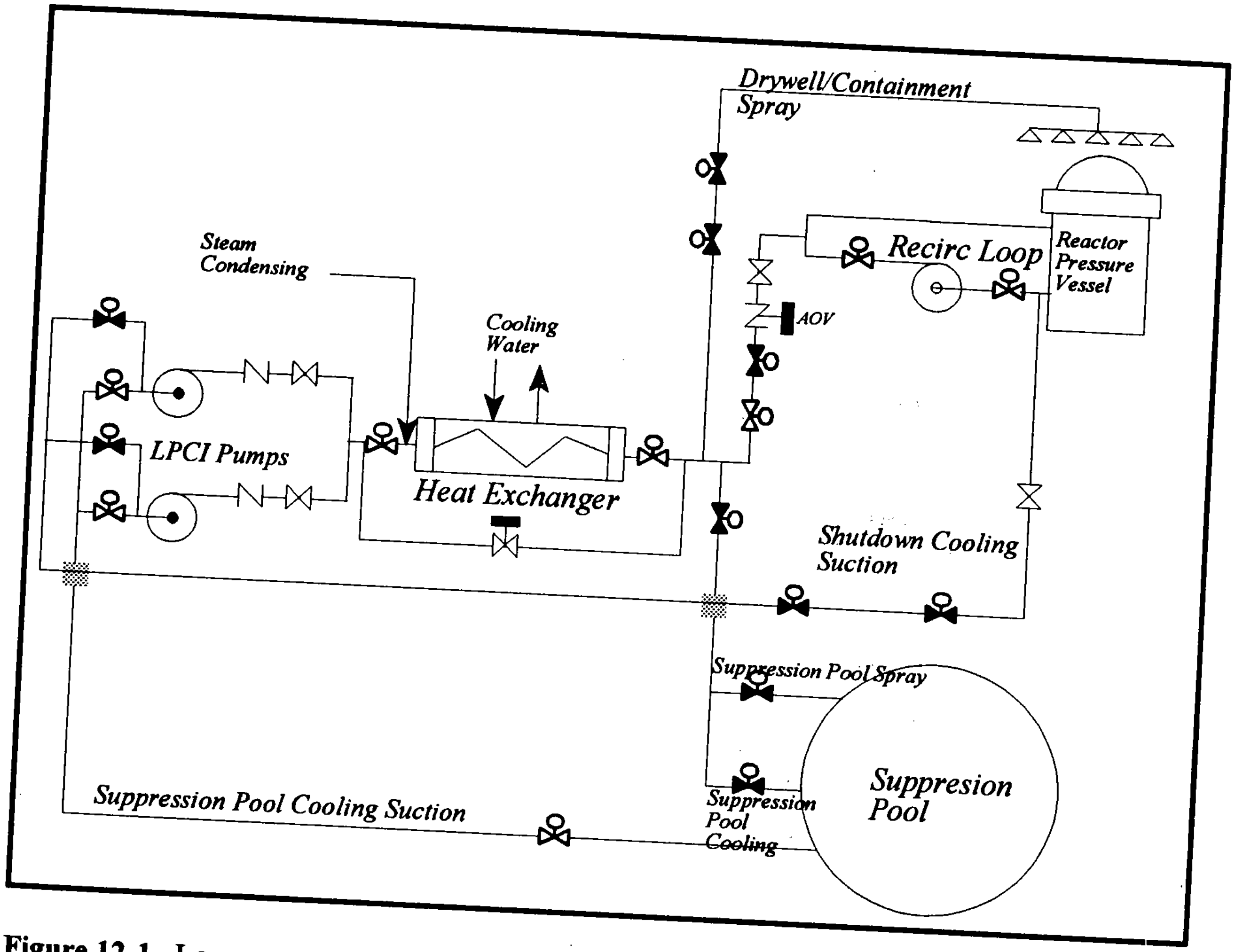

Figure 12-1. Low pressure coolant injection system.

3. COMPONENT BOUNDARIES

The main component of a LPCI pump is the pump itself. This component is normally in standby and is started by sensors actuating the circuit breaker to the driver which will in turn operate the pump. These pumps can also be started up manually via remote control switches. Stopping of the pump is accomplished only by operator actions via the control switches or automatic signals designed to protect the pumps or motors (e.g., overcurrent).

The boundaries include the pump itself, the motor including the circuit breaker, lubrication or cooling systems, and any sensors, controls, or indication required for operation of the pump. Sensors or input logic that affect components other than a single LPCI pump are not included in the component boundaries.

4. FAILURE EVENT DEFINITION

Successful operation of a LPCI pump is defined for two distinct modes of operation. If the system is in the normal standby condition, it must respond to an actuation signal by starting which consists of obtaining design discharge pressure and flow. Once running, the LPCI pump must continue to produce design flow and discharge pressure until its service is no longer needed. The respective failure modes used for evaluating the LPCI pump data are:

FS Failure to Start: Examples are:

- Circuit breaker fails to close,
- Pump fails to achieve design flow or pressure,
- Control switch failure, and
- Flow switch failure.

FR Failure to Run: Examples are:

- Excessive bearing vibration,
- Cavitation,
- Decreasing performance (less than design flow or pressure) while running,
- Excessive packing leaks, and
- Loss of lubrication/cooling.

LPCI pump malfunctions are considered to be failures to start or failures to run. Pump failures include those failures that are caused by power supplies or sensors that are unique to the pump-driver combination. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the LPCI pumps.

Pump motor failures are evaluated to determine the effect on pump operability. In general, if the failure causes the pump to fail to operate, it will be considered a failure. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered pump failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of pump demand. The exception to this is if a licensee reported that the pump "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the pump from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second LPCI pump would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another LPCI pump, the event was identified as a CCF. If, however, the report did not clearly identify that another LPCI pump would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another LPCI pump operation demand (e.g. the condition was found during inspection, and no actual pump start was attempted), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 12-7 through 12-12 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of pumps. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
BWR Low Pressure Coolant Injection Pumps

Table 12-7: Alpha Factor Distribution Summary - Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9392302	0.9809519	0.9877585	0.9994319	0.9894718	4.1992E+01	8.1540E-01
α_2	5.65E-04	1.91E-02	1.22E-02	6.08E-02	1.05E-02	8.1540E-01	4.1992E+01

Table 12-8: Alpha Factor Distribution Summary - Fail to Start, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9319679	0.9717787	0.9764931	0.9954600	0.9789343	6.2870E+01	1.8258E+00
α_2	2.34E-03	2.18E-02	1.71E-02	5.73E-02	2.10E-02	1.4090E+00	6.3287E+01
α_3	8.85E-06	6.44E-03	2.47E-03	2.63E-02	8.21E-05	4.1680E-01	6.4279E+01

Table 12-9: Alpha Factor Distribution Summary - Fail to Start, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9257452	0.9630241	0.9664008	0.9887644	0.9682947	8.6911E+01	3.3370E+00
α_2	6.86E-03	2.86E-02	2.51E-02	6.19E-02	3.15E-02	2.5763E+00	8.7672E+01
α_3	1.52E-07	3.07E-03	6.54E-04	1.44E-02	2.18E-04	2.7660E-01	8.9971E+01
α_4	1.79E-05	5.36E-03	2.39E-03	2.08E-02	7.78E-06	4.8410E-01	8.9764E+01

ALPHA FACTOR DISTRIBUTIONS
BWR Low Pressure Coolant Injection Pumps

Table 12-10: Alpha Factor Distribution Summary - Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9586822	0.9887760	0.9943569	0.9999262	0.9978412	4.8910E+01	5.5520E-01
α_2	7.56E-05	1.12E-02	5.65E-03	4.13E-02	2.16E-03	5.5520E-01	4.8910E+01

Table 12-11: Alpha Factor Distribution Summary - Fail to Run, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9589755	0.9859465	0.9899666	0.9991654	0.9956831	7.4015E+01	1.0550E+00
α_2	1.08E-04	8.56E-03	4.76E-03	2.99E-02	4.32E-03	6.4220E-01	7.4428E+01
α_3	7.09E-06	5.50E-03	2.08E-03	2.26E-02	0.00E+00	4.1280E-01	7.4657E+01

Table 12-12: Alpha Factor Distribution Summary - Fail to Run, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9579508	0.9826943	0.9856679	0.9972736	0.9935106	1.0278E+02	1.8100E+00
α_2	6.12E-04	1.02E-02	7.27E-03	2.97E-02	6.49E-03	1.0638E+00	1.0353E+02
α_3	7.27E-08	2.51E-03	4.86E-04	1.20E-02	0.00E+00	2.6260E-01	1.0433E+02
α_4	1.53E-05	4.62E-03	2.05E-03	1.79E-02	0.00E+00	4.8360E-01	1.0411E+02

13. PWR Low Pressure Safety Injection Pumps

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving pumps in the low pressure safety injection (LPSI) system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to start and failure to run. The data cover the time period from 1980 through 1995.

The data review identified six common-cause failure-to-start events and 19 common-cause failure-to-run events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to start are shown in Tables 13-1 and 13-2, respectively. Table 13-3 contains the average impact vectors (N_1-N_2) and the number of adjusted independent events for this failure mode. Tables 13-4 through 13-6 contain the corresponding information for the failure to run failure mode. The size of the affected population of low pressure safety injection pumps is denoted as CCCG, and is two for all plants. The alpha factor model parameters are denoted by α_1-α_2. Beta (β) is the multiple Greek letter model parameter. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 13-7 and 13-8.

2. SYSTEM DESCRIPTION

The low pressure safety injection system (LPSI) is a subsystem of the emergency core cooling system (ECCS) that functions to provide emergency coolant injection to maintain reactor coolant inventory and provide adequate long term decay heat removal following a loss of coolant accident (LOCA). The low pressure safety injection function is performed over a relatively long time interval after initiation of the LOCA. The LPSI pumps inject directly into the primary loop cold legs and can be realigned to inject into the hot legs. The initial suction source for the LPSI pumps is the refueling water storage tank (RWST) which contains enough highly borated water to satisfy the injection needs of the core. During the recirculation phase the pumps take a suction from the containment sump and supply flow to the loops or to the suction of the high pressure safety injection pumps. These pumps also provide for the shutdown cooling function. Figure 13-1 illustrates the typical flow path for the LPSI system. The system is typically comprised of two high capacity centrifugal pumps. The pumps receive power from the 1E emergency power system and are backed up by the emergency diesel generators.

The system is normally aligned and in the standby mode. The LPSI pumps are started by the engineered safety features actuation system or may be manually actuated. A safety injection (SI) signal starts the pumps and aligns the pump suction to the RWST. The injection phase ends when the RWST reaches the low level setpoint and the system is realigned for the recirculation phase.

ALPHA FACTOR AND MGL PARAMETERS
PWR Low Pressure Safety Injection Pumps

Table 13-1: Summary of Alpha Factor Parameter Estimations - Fail to Start

Alpha Factor	CCCG=2
α_1	0.9368421
α_2	6.32E-02

Table 13-2: Summary of MGL Parameter Estimations - Fail to Start

MGL Parameter	CCCG=2
1-Beta	9.37E-01
Beta	6.32E-02

Table 13-3: Summary of Average Impact Vectors - Fail to Start

Avg. Impact Vector	CCCG=2
Adj.Ind.Events	89
N_1	0.0000
N_2	6.0000

Total Number of Independent Failure Events: 89
Total Number of Common-Cause Failure Events: 6

ALPHA FACTOR AND MGL PARAMETERS
PWR Low Pressure Safety Injection Pumps

Table 13-4: Summary of Alpha Factor Parameter Estimations - Fail to Run

Alpha Factor	**CCCG=2**
α_1	0.9465153
α_2	5.35E-02

Table 13-5: Summary of MGL Parameter Estimations - Fail to Run

MGL Parameter	**CCCG=2**
1-Beta	9.47E-01
Beta	5.35E-02

Table 13-6: Summary of Average Impact Vectors - Fail to Run

Avg. Impact Vector	**CCCG=2**
Adj.Ind.Events	273
N_1	1.5698
N_2	15.5151

Total Number of Independent Failure Events: 273
Total Number of Common-Cause Failure Events: 19

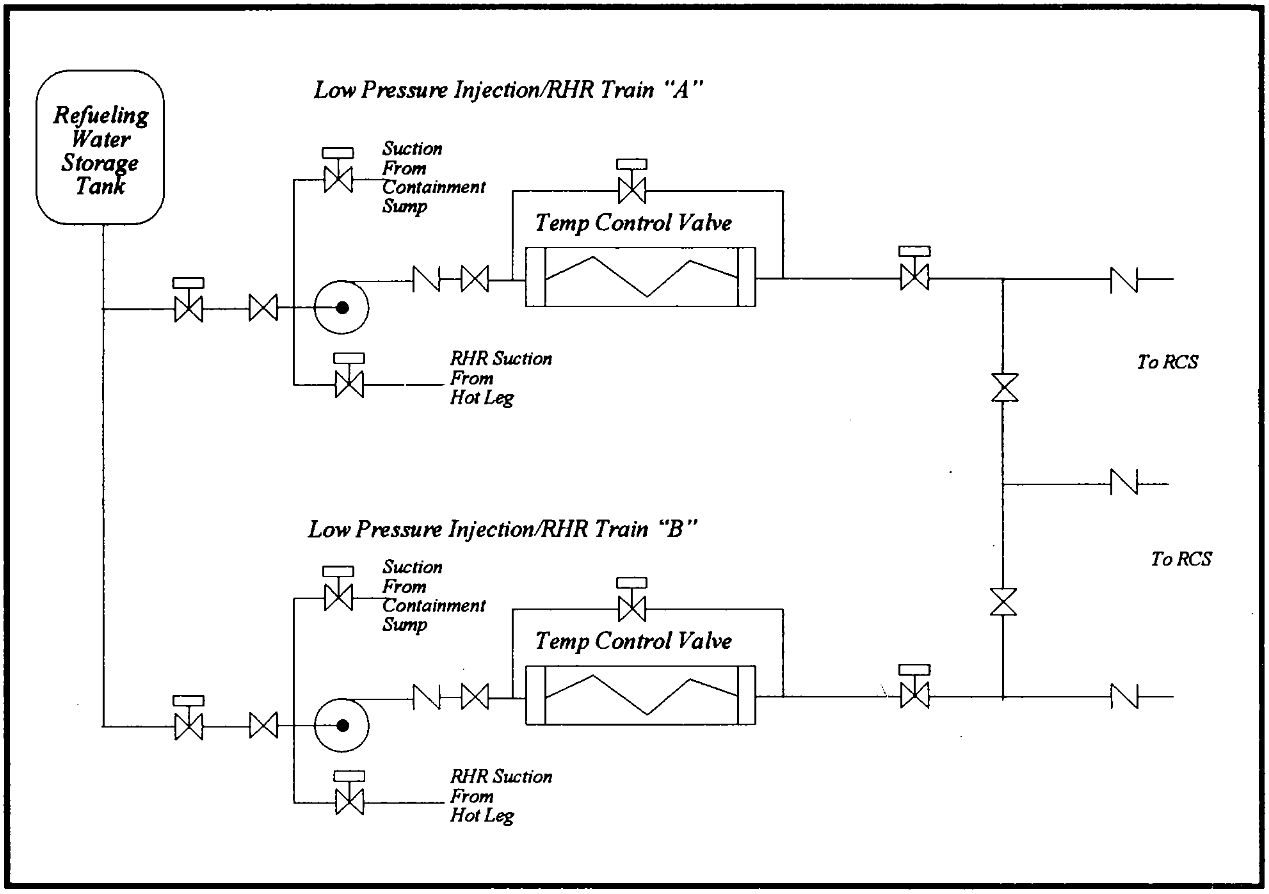

Figure 13-1. PWR low pressure safety injection/residual heat removal system.

3. COMPONENT BOUNDARIES

The main component of an LPSI pump is the pump itself. This component is normally in a standby mode and is started by sensors actuating the circuit breaker to the driver which will in turn operate the pump. These pumps can also be started up manually via remote control switches. Stopping of the pump is accomplished only by operator actions via the control switches or automatic signals designed to protect the pumps or motors (e.g., overcurrent, overspeed).

The boundaries include the pump itself, the driver including the circuit breaker, lubrication or cooling systems, and any sensors, controls, or indications required for operation of the pump. Sensors or input logic that affect components other than a single LPSI pump are not included in the component boundaries.

4. FAILURE EVENT DEFINITION

Successful operation of a LPSI pump is defined for two distinct modes of operation. If the LPSI system is in the normal standby condition, it must respond to an actuation signal by starting which consists of obtaining design discharge pressure and flow. Once running, the LPSI pump must continue to produce design flow and discharge pressure until its service is no longer needed. The respective failure modes used for evaluating the LPSI pump data are:

FS Failure to Start: Examples are:

- Circuit breaker fails to close,
- Pump fails to achieve design flow or pressure,
- Control switch failure, and
- Pressure switch failure.

FR Failure to Run: Examples are:

- Excessive bearing vibration,
- Cavitation,
- Decreasing performance (less than design flow or pressure) while running,
- Excessive packing leaks, and
- Loss of lubrication/cooling.

LPSI pump malfunctions are considered to be failures to start or failures to run. Pump failures include those failures that are caused by power supplies or sensors that are unique to the pump motor combination. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the LPSI pumps.

Pump motor failures are evaluated to determine the effect on pump operability. In general, if the failure causes the pump to fail to operate, it will be considered a failure. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered pump failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of pump demand. The exception to this is if a licensee reported that the pump "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the pump from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second LPSI pump would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another LPSI pump, the event was identified as a CCF. If, however, the report did not clearly identify that another LPSI pump would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another LPSI pump operation demand (e.g. the condition was found during inspection, and no actual pump start was attempted), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 13-7 and 13-8 present the alpha factor uncertainty distribution summaries for each failure mode. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
PWR Low Pressure Safety Injection Pumps

Table 13-7: Alpha Factor Distribution Summary - Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8957730	0.9383810	0.9411541	0.9715172	0.9368421	9.8530E+01	6.470E+00
α_2	2.85E-02	6.16E-02	5.89E-02	1.04E-01	6.32E-02	6.470E+00	9.8530E+01

ALPHA FACTOR DISTRIBUTIONS
PWR Low Pressure Safety Injection Pumps

Table 13-8: Alpha Factor Distribution Summary - Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9238843	0.9467318	0.9477241	0.9662029	0.9465153	2.8410E+02	1.5985E+01
α_2	3.38E-02	5.33E-02	5.23E-02	7.61E-02	5.35E-02	1.5985E+01	2.8410E+02

14. BWR Standby Liquid Control Pumps

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving pumps in the standby liquid control (SLC) system at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to start and failure to run. The data cover the time period from 1980 through 1995.

The data review identified two common-cause failure-to-start events and eight common-cause failure-to-run events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to start are shown in Tables 14-1and 14-2, respectively. Table 14-3 contains the average impact vectors (N_1-N_2) and the number of adjusted independent events for this failure mode. Tables 14-4 through 14-6 contain the corresponding information for the failure to run failure mode. The size of the affected population of standby liquid control pumps is denoted as CCCG and is two for all plants. The alpha factor model parameters are denoted by α_1-α_2. Beta (β) is the multiple Greek letter model parameter. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Distributions of the mean values of the alpha factor estimates are also included in this report in Tables 14-7 and 14-8 .

2. SYSTEM DESCRIPTION

The standby liquid control system is a backup to the control rod reactor scram system designed to shut down the reactor by chemical poisoning in the event the control rods fail to shut down the reactor. The SLC system, illustrated in Figure 14-1, consists of a heated storage tank, two suction valves, two positive displacement pumps, two explosive actuated valves, and piping necessary to inject the neutron absorber into the reactor vessel. The storage tank contains enough neutron absorbing solution (sodium pentaborate) to shutdown the reactor anytime in core life without the use of the control rods. The SLC is initiated with a keylock switch located in the control room. When the SLC control switch for a train is placed in the run position, the explosive valve opens, the appropriate train's motor operated suction valve (for the plants that have the motor-operated suction valves) opens, the reactor water cleanup system isolates and the SLC pump starts.

ALPHA FACTOR AND MGL PARAMETERS
BWR Standby Liquid Control Pumps

Table 14-1: Summary of Alpha Factor Parameter Estimations - Fail to Start

Alpha Factor	CCCG=2
α_1	0.9019608
α_2	9.80E-02

Table 14-2: Summary of MGL Parameter Estimations - Fail to Start

MGL Parameter	CCCG=2
1-Beta	9.02E-01
Beta	9.80E-02

Table 14-3: Summary of Average Impact Vectors - Fail to Start

Avg. Impact Vector	CCCG=2
Adj. Ind. Events	11.00
N_1	0.5000
N_2	1.2500

Total Number of Independent Failure Events: 11
Total Number of Common-Cause Failure Events: 2

ALPHA FACTOR AND MGL PARAMETERS
BWR Standby Liquid Control Pumps

Table 14-4: Summary of Alpha Factor Parameter Estimations - Fail to Run

Alpha Factor	**CCCG=2**
α_1	0.9676016
α_2	3.24E-02

Table 14-5: Summary of MGL Parameter Estimations - Fail to Run

MGL Parameter	**CCCG=2**
1-Beta	9.68E-01
Beta	3.24E-02

Table 14-6: Summary of Average Impact Vectors - Fail to Run

Avg. Impact Vector	**CCCG=2**
Adj. Ind. Events	59.00
N_1	2.3890
N_2	2.0555

Total Number of Independent Failure Events: 59
Total Number of Common-Cause Failure Events: 8

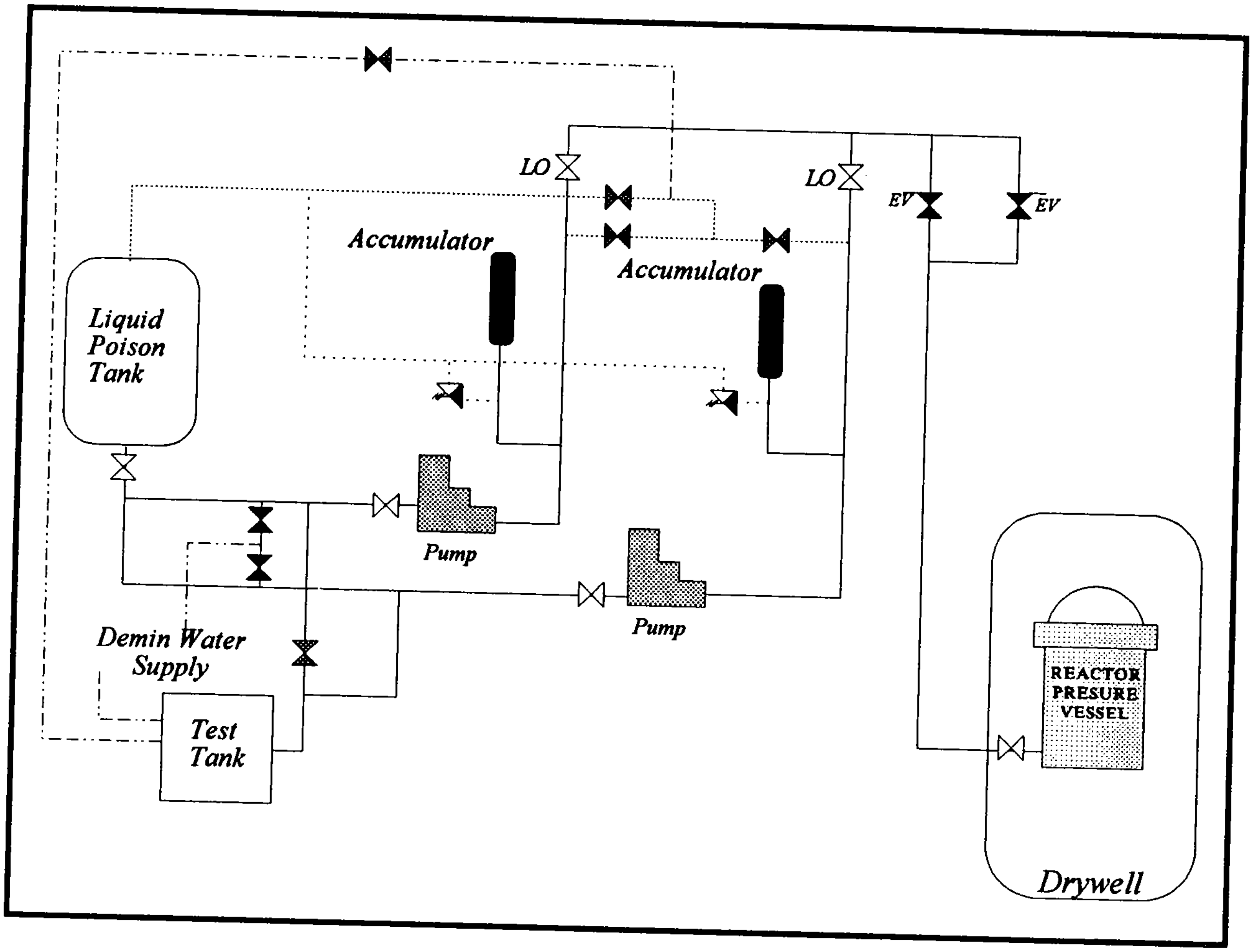

Figure 14-1. Standby liquid control system.

3. COMPONENT BOUNDARIES

The main component of a SLC pump is the pump itself coupled to an AC electric motor for a driver. This component can be in one of two states, standby or running. In the standby condition, starting is accomplished by a keylock control switch actuating a circuit breaker. These pumps can also be started manually at the SLC pump breakers. Stopping of the pump is accomplished only by operator actions via the control switches or automatic signals designed to protect the pump or driver (e.g., overcurrent).

The boundaries include the pump itself and internal piece-parts, the motor, circuit breaker, lubrication or cooling systems, and any sensors, controls, or indication required for operation of the pump. Sensors or input logic that affect components other than a single SLC pump are not included in the component boundaries.

4. FAILURE EVENT DEFINITION

The function of the standby liquid control pumps is to allow borated water flow to the reactor vessel. The pumps must respond to an initiation signal by starting, including reaching design discharge pressure and flow. Once running, the SLC pumps must continue to produce design flow and discharge pressure until their service is no longer needed. The failure modes used in evaluating the SLC system pump data are:

FS Failure to Start: Examples are:

- Circuit breaker fails to close,
- Pump fails to achieve design flow or pressure, and
- Control switch failure.

FR Failure to Run: Examples are:

- Excessive bearing vibration,
- Cavitation,
- Decreasing performance (less than design flow or pressure),
- Excessive packing leaks, and
- Loss of lubrication/cooling.

SLC pump malfunctions are considered to be failures to start or failures to run. Pump failures include those failures that are caused by power supplies or sensors that are unique to the pump motor combination. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the SLC pumps.

Pump motor failures are evaluated to determine the effect on pump operability. In general, if the failure causes the pump to fail to operate, it will be considered a failure. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered pump failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of pump demand. The exception to this is if a licensee reported that the pump "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the pump from operating properly on a safety demand.

Some LERs reported only one pump actual failure, but the report information indicated that failure of a second pump would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of the other pump, the event was identified as a CCF. If, however, the report did not clearly identify that another pump would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before a pump operation demand (e.g. the condition was found during inspection, and no actual pump start was attempted), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 14-7 and 14-8 present the alpha factor uncertainty distribution summaries for each failure mode. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
BWR Standby Liquid Control Pumps

Table 14-7: Alpha Factor Distribution Summary - Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8184919	0.9243956	0.9366053	0.9884081	0.9019608	2.1030E+01	1.7200E+00
α_2	1.16E-02	7.56E-02	6.34E-02	1.82E-01	9.80E-02	1.7200E+00	2.1030E+01

ALPHA FACTOR DISTRIBUTIONS
BWR Standby Liquid Control Pumps

Table 14-8: Alpha Factor Distribution Summary - Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9251711	0.9656135	0.9697558	0.9918786	0.9676016	7.0919E+01	2.5255E+00
α_2	8.12E-03	3.44E-02	3.02E-02	7.48E-02	3.24E-02	2.5255E+00	7.0919E+01

15. BWR High Pressure Coolant Injection and Reactor Core Isolation Cooling Pumps

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving pumps in the high pressure coolant injection (HPCI) and reactor core isolation cooling (RCIC) systems at boiling water reactor (BWRs) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to start, and failure to run. The data cover the time period from 1980 through 1995.

The data review identified one common-cause failure-to-start event and one common-cause failure-to-run event. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to start are shown in Tables 15-1 and 15-2, respectively. Table 15-3 contains the average impact vectors (N_1-N_2) and the number of adjusted independent events for this failure mode. Tables 15-4 through 15-6 contain the corresponding information for the failure to run failure mode. The size of the affected population of high pressure coolant injection pumps is denoted as CCCG and is two for all plants. The alpha factor model parameters are denoted by α_1-α_2. Beta (β) is the multiple Greek letter model parameter. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 15-7 and 15-8.

2. SYSTEM DESCRIPTION

BWRs can have HPCI and RCIC systems, only a RCIC system for late model BWR's, or only a HPCI system (if an Isolation Condenser is present). Both the HPCI and the RCIC are single train systems, and are not consequently subject to CCF events by themselves. This analysis combined the failures of pumps across the system boundaries to examine CCFs.

The HPCI system supplies high volume, high pressure make-up water to the reactor pressure vessel (RPV) in the event of a small break LOCA which does not result in a rapid depressurization of the reactor vessel. The HPCI system consists of a turbine driven pump, system piping, valves and controls. The HPCI system is normally in standby when the plant is at power. The HPCI system is normally aligned to take a suction on the Condensate Storage Tank (CST) but suction is automatically switched from the CST to the suppression pool upon low CST level or high suppression pool water level. The HPCI system is automatically started in response to decreasing RPV water level or high dry well pressure and is injected into the reactor via the feedwater header which injects outside the RPV shroud. HPCI is the primary source of makeup if RCS pressure remains high. The HPCI turbine steam supply is from main steam. Figure 15-1 shows a typical HPCI system.

The RCIC system provides low volume, high pressure makeup water to the RPV for core cooling when the main steam lines are isolated or the condensate/feedwater system is not available. The RCIC system consists of a turbine driven pump, piping, valves, and controls. The RCIC system is normally shut down and aligned in standby, if the plant is at power. The RCIC system is normally aligned for suction from the CST, but suction is automatically switched from the CST to the suppression pool on low CST level or high suppression pool water level. The RCIC system is automatically started in response to decreasing RPV water level and is injected into the RPV via the feedwater line. Steam to drive the RCIC turbine is routed from main steam. The RCIC system is similar to the HPCI system in terms of components and configuration.

ALPHA FACTOR AND MGL PARAMETERS
BWR High Pressure Coolant Injection/ Reactor Core Isolation Cooling Pumps

Table 15-1: Summary of Alpha Factor Parameter Estimations - Fail to Start

Alpha Factor	**CCCG=2**
α_1	0.9986092
α_2	1.39E-03

Table 15-2: Summary of MGL Parameter Estimations - Fail to Start

MGL Parameter	**CCCG=2**
1-Beta	9.99E-01
Beta	1.39E-03

Table 15-3: Summary of Average Impact Vectors - Fail to Start

Avg. Impact Vector	**CCCG=2**
Adj. Ind. Events	178
N_1	1.5000
N_2	0.2500

Total Number of Independent Failure Events: 178
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
BWR High Pressure Coolant Injection/ Reactor Core Isolation Cooling Pumps

Table 15-4: Summary of Alpha Factor Parameter Estimations - Fail to Run

Alpha Factor	**CCCG=2**
α_1	0.9998494
α_2	1.51E-04

Table 15-5: Summary of MGL Parameter Estimations - Fail to Run

MGL Parameter	**CCCG=2**
1-Beta	1.00E+01
Beta	1.51E-04

Table 15-6: Summary of Average Impact Vectors - Fail to Run

Avg. Impact Vector	**CCCG=2**
Adj. Ind. Events	165.00
N_1	0.9500
N_2	0.0250

Total Number of Independent Failure Events: 165
Total Number of Common-Cause Failure Events: 1

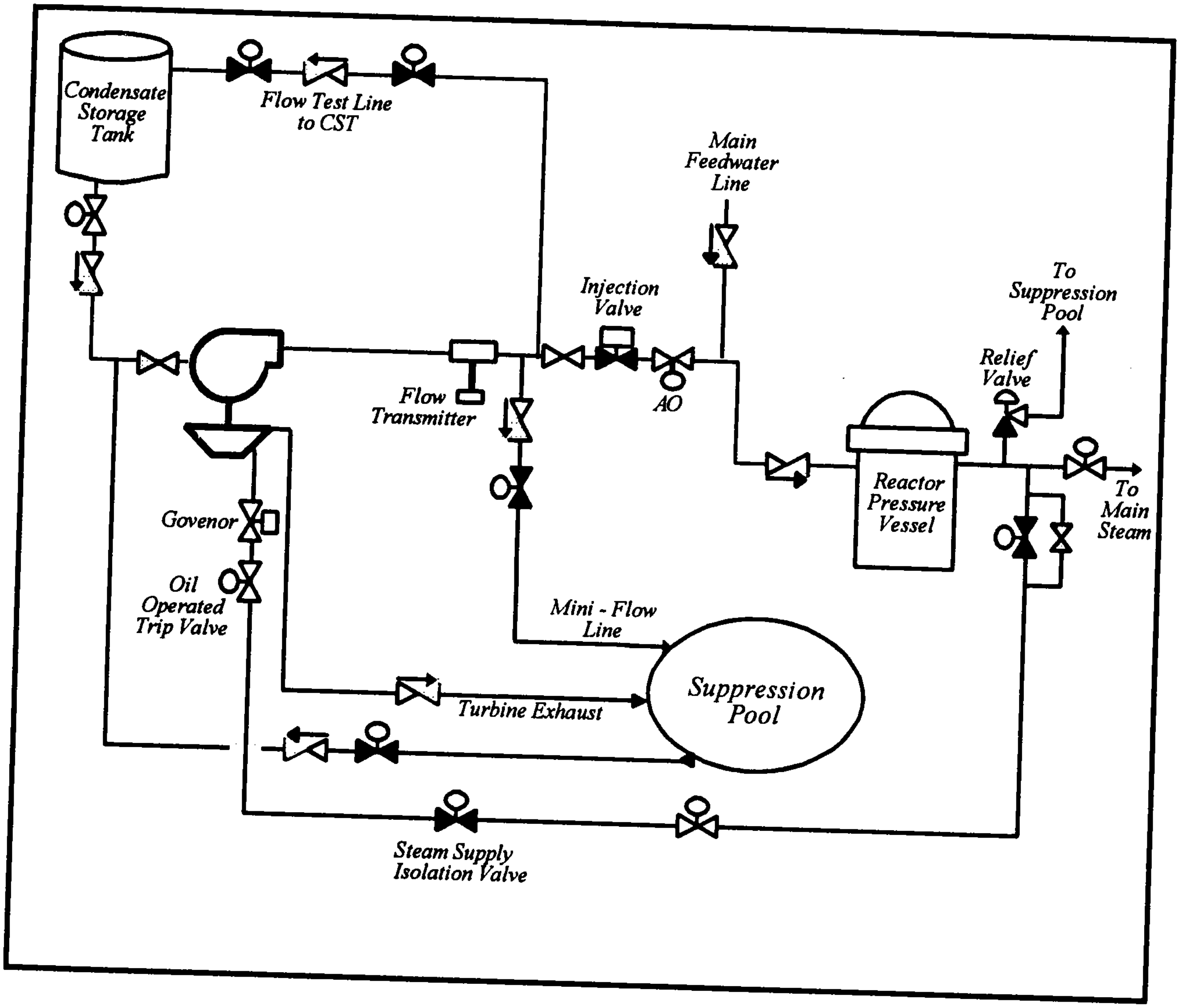

Figure 15-1. BWR high pressure coolant injection system.

3. COMPONENT BOUNDARIES

The main component of an HPCI/RCIC pump is the pump itself. This component is normally in a standby mode and is started up by a sensor opening the steam inlet valve to start the steam turbine, which will in turn operate the pump. These pumps can also be started manually via remote control switches. Stopping of the pump is accomplished only by operator actions via the control switches or automatic signals designed to protect the pumps or turbines (e.g., overspeed).

The boundaries include the pump itself, the driver including the governor system, lubrication or cooling systems, and any sensors, controls, or indication required for operation of the pump. Sensors or input logic that affect components other than a single HPCI/RCIC pump are not included in the component boundaries.

4. FAILURE EVENT DEFINITION

Successful operation of a HPCI/RCIC pump is defined for two distinct modes of operation. If the HPCI/RCIC is in the normal standby condition, it must respond to an actuation signal by starting which consists of obtaining design discharge pressure and flow. Once running, the HPCI/RCIC pump must continue to produce design flow and discharge pressure until its service is no longer needed. The respective failure modes used for evaluating the HPCI/RCIC pump data are:

FS Failure to Start: Examples are:
- Steam supply valve fails to opens.
- Pump fails to achieve design flow or pressure,
- Governor fails to control rpm, and
- Control switch failure.

FR Failure to Run: Examples are:
- Excessive bearing vibration,
- Cavitation,
- Decreasing performance (less than design flow or pressure) while running,
- Excessive packing leaks, and
- Loss of lubrication/cooling.

HPCI/RCIC pump malfunctions are considered to be failures to start or failures to run. Pump failures include those failures that are caused by power supplies or sensors that are unique to the pump-driver combination. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the HPCI/RCIC pumps.

Pump-turbine failures are evaluated to determine the effect on pump operability. In general, if the failure causes the pump to fail to operate, it will be considered a failure. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered pump failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of pump demand. The exception to this is if a licensee reported that the pump "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the pump from operating properly on a safety demand. An example is starting up the plant following an outage when the HPCI/RCIC starting signals are required to be unblocked. On occasion, licensees forget to unblock the signals when they change modes, resulting in a TS violation, and preventing the HPCI/RCIC pumps from starting at the required condition.

Many LERs reported only one actual failure, but the report information indicated that failure of a second HPCI/RCIC pump would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another HPCI/RCIC pump, the event was identified as a CCF. If, however, the report did not clearly identify that another HPCI/RCIC pump would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another HPCI/RCIC pump operation demand (e.g. the condition was found during inspection, and no actual pump start was attempted), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 15-7 and 15-8 present the alpha factor uncertainty distribution summaries for each failure mode. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
BWR High Pressure Coolant Injection/ Reactor Core Isolation Cooling Pumps

Table 15-7: Alpha Factor Distribution Summary - Fail to Start, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9872374	0.9962055	0.9977501	0.9999251	0.9986092	1.8903E+02	7.2000E-01
α_2	7.33E-05	3.79E-03	2.25E-03	1.28E-02	1.39E-03	7.2000E-01	1.8903E+02

ALPHA FACTOR DISTRIBUTIONS
High Pressure Coolant Injection/ Reactor Core Isolation Cooling Pumps

Table 15-8: Alpha Factor Distribution Summary - Fail to Run, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9891709	0.9971871	0.9987245	0.9999906	0.9998494	1.7548E+02	4.9500E-01
α_2	1.05E-05	2.81E-03	1.27E-03	1.08E-02	1.51E-04	4.9500E-01	1.7548E+02

16. BWR Suppression Pool Strainers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common cause failure (CCF) parameters of various models using operational data involving suppression pool strainers at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common cause failure events. The only failure mode analyzed are failure to is failure to allow flow. The data cover the time period from 1980 through 1995.

The data review identified two common cause failure-to-allow flow events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to allow flow are shown in Tables 16-1 and 16-2, respectively. Table 16-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 16-4 through 16-8.

2. SYSTEM DESCRIPTION

The suppression pool in a BWR plant serves as the primary means of containment pressure suppression during a large break loss of coolant accident (LOCA). The primary containment design is such that the steam from a large break LOCA is directed through the water in the suppression pool, where the steam is condensed and much of the fission product activity in the coolant is scrubbed. The suppression pool also serves as a source of water for emergency core cooling (ECCS) pumps. High pressure ECCS pump suction paths can be switched between a condensate storage tank (CST) outside of containment, and the suppression pool. These systems normally take their suction first from the CST, and then switch to the suppression pool upon a low level in the CST or a high level in the suppression pool. The plant Technical Specifications normally only require the suction from the suppression pool for system operability. The low pressure ECCS subsystems take a suction only from the suppression pool. All of the high and low pressure ECCS pumps have a suction strainer to filter any debris which may be present in the suppression pool. Figures 16-1 and 16-2 show typical suppression pool configurations.

After a large break LOCA, much of the residual heat from the reactor will have been transferred to the suppression pool. Core cooling will be maintained by the ECCS pumps recirculating water from the suppression pool (through the suction strainers) to the reactor vessel and core, and back out to the suppression pool through the break in the primary coolant system. This heat is then removed from the suppression pool via one or more low pressure ECCS trains using heat exchangers in the injection flow path or being switched from the injection mode to the suppression pool cooling mode. In this mode, suppression pool water is circulated by the residual heat removal (RHR) system from the suppression pool (through the RHR suction strainers), through heat exchangers cooled by service water, and back to the suppression pool.

ALPHA FACTOR AND MGL PARAMETERS
BWR Suppression Pool Strainers

Table 16-1: Summary of Alpha Factor Parameter Estimations - Fail to Allow Flow

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.8148148	0.8400000	0.8586387	0.8747244	0.8886809
α_2	1.85E-01	4.00E-02	3.14E-02	2.16E-02	1.38E-02
α_3		1.20E-01	2.09E-02	2.16E-02	1.84E-02
α_4			8.90E-02	1.08E-02	1.38E-02
α_5				7.13E-02	5.52E-03
α_6					5.98E-02

Table 16-2: Summary of MGL Parameter Estimations - Fail to Allow Flow

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	8.15E-01	8.40E-01	8.59E-01	8.75E-01	8.89E-01
Beta	1.85E-01	1.60E-01	1.41E-01	1.25E-01	1.11E-01
Gamma		7.50E-01	7.78E-01	8.28E-01	8.76E-01
Delta			8.10E-01	7.92E-01	8.11E-01
Epsilon				8.68E-01	8.26E-01
Mu					9.15E-01

Table 16-3: Summary of Average Impact Vectors - Fail to Allow Flow

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	5.00	7.50	10.00	12.50	15.00
N_1	0.5000	0.3750	0.2500	0.1563	0.0938
N_2	1.2500	0.3750	0.3750	0.3125	0.2344
N_3		1.1250	0.2500	0.3125	0.3125
N_4			1.0625	0.1563	0.2344
N_5				1.0313	0.0938
N_6					1.0156

Total Number of Independent Failure Events: 5
Total Number of Common-Cause Failure Events: 2

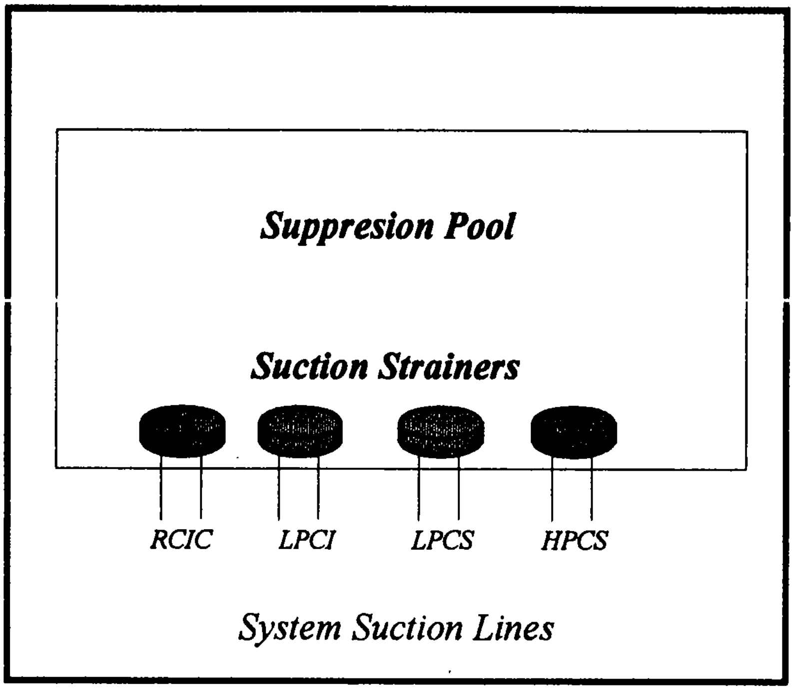

Figure 16-1. BWR suppression pool suction strainers.

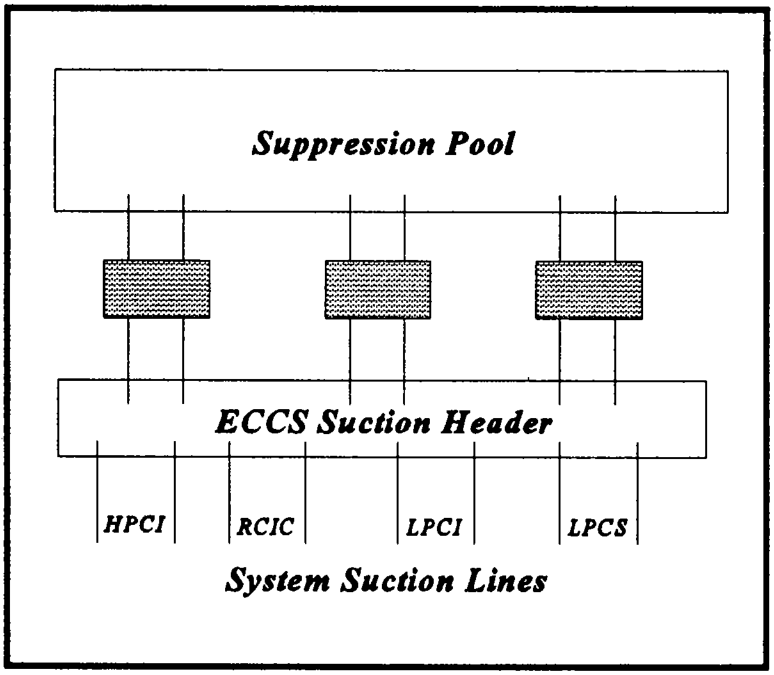

Figure 16-2. BWR Mark 1 suppression pool strainer.

3. COMPONENT BOUNDARIES

The main component of a sump strainer is the strainer itself. This component is normally in a standby mode and is a passive component with no moving parts.

4. FAILURE EVENT DEFINITION

Successful operation of the containment sump strainer is allowing flow from the sump to the pumps. The only failure mode used for evaluating the sump strainer data is:

PG Plugged, or Failure to Allow Flow. Examples are:
- Physical damage (to screens) that reduces flow cross-section, and
- Accumulation of debris in sump.

Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of strainer demand. The exception to this is if a licensee reported that the strainer "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the strainers from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second pool strainer would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another pool strainer, the event was identified as a CCF. If, however, the report did not clearly identify that another pool strainer would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another pool strainer operation demand (e.g. the condition was found during inspection, and no actual strainer demand was initiated), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 16-4 through 16-8 present the alpha factor uncertainty distribution summaries for each configuration of suppression pool strainers. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
BWR Suppression Pool Strainers

Table 16-4: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7569184	0.8973134	0.9129722	0.9839224	0.8148148	1.5030E+01	1.720E+00
α_2	1.61E-02	1.03E-01	8.70E-02	2.43E-01	1.85E-01	1.720E+00	1.5030E+01

Table 16-5: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8022571	0.9093596	0.9200261	0.9798831	0.8400000	2.3075E+01	2.3000E+00
α_2	7.28E-04	3.00E-02	1.88E-02	9.76E-02	4.00E-02	7.6220E-01	2.4613E+01
α_3	7.76E-03	6.06E-02	4.94E-02	1.52E-01	1.20E-01	1.5378E+00	2.3837E+01

Table 16-6: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8396673	0.9212521	0.9285998	0.9776719	0.8586387	3.4950E+01	2.9875E+00
α_2	1.06E-03	2.45E-02	1.68E-02	7.43E-02	3.14E-02	9.2880E-01	3.7090E+01
α_3	6.17E-05	1.35E-02	6.39E-03	5.11E-02	2.09E-02	5.1260E-01	3.7425E+01
α_4	5.18E-03	4.08E-02	3.30E-02	1.03E-01	8.90E-02	1.5461E+00	3.6391E+01

Table 16-7: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8670792	0.9307816	0.9360191	0.9765710	0.8747244	5.0698E+01	3.7702E+00
α_2	1.10E-03	1.91E-02	1.36E-02	5.59E-02	2.16E-02	1.0405E+00	5.3428E+01
α_3	2.66E-04	1.33E-02	7.99E-03	4.44E-02	2.16E-02	7.2450E-01	5.3744E+01
α_4	6.31E-06	7.16E-03	2.55E-03	2.99E-02	1.08E-02	3.8990E-01	5.4078E+01
α_5	4.00E-03	2.97E-02	2.41E-02	7.43E-02	7.13E-02	1.6153E+00	5.2853E+01

Table 16-8: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8832959	0.9368672	0.9409990	0.9763009	0.8886809	6.5566E+01	4.4183E+00
α_2	7.79E-04	1.45E-02	1.02E-02	4.29E-02	1.38E-02	1.0135E+00	6.8971E+01
α_3	4.11E-04	1.22E-02	7.96E-03	3.84E-02	1.84E-02	8.5310E-01	6.9131E+01
α_4	4.89E-05	7.82E-03	3.87E-03	2.90E-02	1.38E-02	5.4710E-01	6.9437E+01
α_5	1.42E-06	4.82E-03	1.42E-03	2.12E-02	5.52E-03	3.3710E-01	6.9647E+01
α_6	3.36E-03	2.38E-02	1.95E-02	5.93E-02	5.98E-02	1.6675E+00	6.8317E+01

17. PWR Containment Sump Strainers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving containment sump strainers at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify CCF events. The only failure mode analyzed is failure to allow flow. The data cover the time period from 1980 through 1993.

The data review identified one common-cause failure-to-allow-flow event. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to allow flow are shown in Tables 17-1 and 17-2, respectively. Table 17-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events. The size of the affected population of strainers is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 17-4 through 17-6.

2. SYSTEM DESCRIPTION

The containment sump strainers are stationary screens in the emergency core cooling system (ECCS) that function to protect the ECCS pumps and prevent plugging of containment spray nozzles from debris that may be in containment when the sump is used as a coolant source. The containment is used a suction source for the containment recirculation spray pumps, the residual heat removal pumps, and the high pressure safety injection pumps.

The sump screen assembly is divided into two or more sections to prevent damage and large debris on one side from affecting the other side. Typically the sump strainers are a combination of a heavy grate (to keep out large debris) and smaller mesh strainers to strain out small debris such as insulation fibers. The containment sump strainers do not have any moving parts or electrical connections. Figure 17-1 illustrates the configuration of the containment sump strainers.

ALPHA FACTOR AND MGL PARAMETERS
PWR Containment Sump Strainers

Table 17-1: Summary of Alpha Factor Parameter Estimations - Fail to Allow Flow

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.8750000	0.8426966	0.8565031
α_2	1.25E-01	8.99E-02	3.75E-02
α_3		6.74E-02	6.62E-02
α_4			3.97E-02

Table 17-2: Summary of MGL Parameter Estimations - Fail to Allow Flow

CCCG	2	3	4
1-Beta	8.75E-01	8.43E-01	8.57E-01
Beta	1.25E-01	1.57E-01	1.44E-01
Gamma		4.29E-01	7.39E-01
Delta			3.75E-01

Table 17-3: Summary of Average Impact Vectors - Fail to Allow Flow

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	3.00	4.50	6.00
N_1	0.5000	0.1875	0.0625
N_2	0.5000	0.5000	0.2656
N_3		0.3750	0.4688
N_4			0.2813

Total Number of Independent Failure Events: 3
Total Number of Common Cause Failure Events: 1

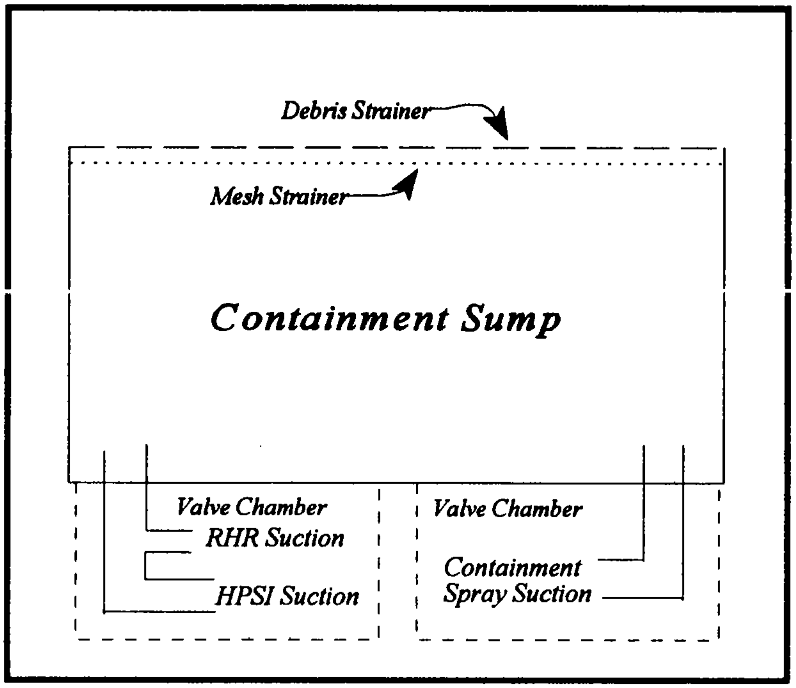

Figure 17-1. PWR containment sump strainers.

3. COMPONENT BOUNDARIES

The containment sump strainer includes the strainer screens used to filter debris and the sump area that serves to accumulate coolant for ECCS pump suction.

4. FAILURE EVENT DEFINITION

Successful operation of the containment sump strainer is allowing flow from the sump to the pumps. The only failure mode used for evaluating the sump strainer data is:

PG Plugged, or Failure to Allow Flow. Examples are:
- Physical damage (to screens) that reduces flow cross-section, and
- Accumulation of debris in sump.

Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of flow demand. The exception to this is if a licensee reported that the strainer "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the strainer from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second sump strainer would have occurred from the same cause if flow had been required. When the cause of the actual failure would have clearly caused failure of another sump strainer, the event was identified as a CCF. If, however, the report did not clearly identify that another sump strainer would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another sump strainer operation demand (e.g. the condition was found during inspection, and no actual flow was required), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 17-4 through 17-6 present the alpha factor uncertainty distribution summaries for each configuration of containment sump strainers. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

Alpha Factor Distributions
PWR Containment Sump Strainers

Table 17-4: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7979730	0.9307143	0.9502500	0.9964643	0.8750000	1.3030E+01	9.7000E-01
α_2	3.53E-03	6.93E-02	4.98E-02	2.02E-01	1.25E-01	9.7000E-01	1.3030E+01

Table 17-5: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8121409	0.9223207	0.9351384	0.9885157	0.8426966	1.9888E+01	1.6750E+00
α_2	1.60E-03	4.11E-02	2.80E-02	1.26E-01	8.99E-02	8.8720E-01	2.0676E+01
α_3	9.93E-04	3.65E-02	2.34E-02	1.17E-01	6.74E-02	7.8780E-01	2.0775E+01

Table 17-6: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8461229	0.9299942	0.9385474	0.9845584	0.8565031	3.0763E+01	2.3157E+00
α_2	7.51E-04	2.48E-02	1.60E-02	7.87E-02	3.75E-02	8.1940E-01	3.2259E+01
α_3	4.61E-04	2.21E-02	1.35E-02	7.32E-02	6.62E-02	7.3140E-01	3.2347E+01
α_4	5.62E-04	2.31E-02	1.44E-02	7.53E-02	3.97E-02	7.6490E-01	3.2314E+01

18. Emergency Service Water Strainers

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving strainers in the emergency service water (ESW) system at both pressurized water reactor (PWR) and boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify CCF events. The only failure mode analyzed is failure to allow flow. The data cover the time period from 1980 through 1995.

The data review identified 34 common-cause failure-to-allow-flow events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to allow flow are shown in Tables 18-1 and 18-2, respectively. Table 18-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events. The size of the affected population of strainers is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 18-4 through 18-8.

2. SYSTEM DESCRIPTION

The emergency service water system is designed to provide cooling water to the safety related equipment during all analyzed accident conditions where class 1E AC power is available. Service water is supplied from a designated ultimate heat sink (e.g., cooling tower, river lake, ocean etc.) to heat exchangers in closed loop cooling systems. This safety function is normally provided by multiple trains of the ESW system, each with an ESW pump, strainer, and associated equipment.

Water from the ultimate heat sink is drawn to the pump suction through trash racks and/or traveling screens to eliminate large debris from damaging the pumps and plugging the suction flow. Self-cleaning strainers are on the discharge of each pump to clear small debris and organic material out of the ESW system.

A variety of pump/strainer combinations are utilized across the plant designs to help accomplish this safety function. Some plants have as few as two ESW pumps and others have up to twelve ESW pumps. In most cases, piping configurations allow each ESW pump to supply cooling water to multiple closed loop system heat exchangers, however, the BWR ESW system arrangements are split into more sections by location of equipment supplied (e.g., reactor building etc.). Power to the motor-driven ESW strainers is supplied from the class 1E AC electrical system which has an emergency source, usually an emergency diesel generator. A simplified schematic of the ESW system is shown in Figure 18-1.

ALPHA FACTOR AND MGL PARAMETERS
Emergency Service Water Strainers

Table 18-1: Summary of Alpha Factor Parameter Estimations - Fail to Allow Flow

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.8672708	0.8660779	0.8605542	0.8756065	0.8917825
α_2	1.33E-01	5.37E-02	5.23E-02	2.61E-02	1.86E-02
α_3		8.03E-02	2.61E-02	3.29E-02	1.88E-02
α_4			6.10E-02	1.57E-02	1.04E-02
α_5				4.97E-02	2.31E-02
α_6					3.74E-02

Table 18-2: Summary of MGL Parameter Estimations - Fail to Allow Flow

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	8.67E-01	8.66E-01	8.61E-01	8.76E-01	8.92E-01
Beta	1.33E-01	1.34E-01	1.39E-01	1.24E-01	1.08E-01
Gamma		5.99E-01	6.25E-01	7.90E-01	8.28E-01
Delta			7.0E-01	6.65E-01	7.90E-01
Epsilon				7.60E-01	8.53E-01
Mu					6.18E-01

Table 18-3: Summary of Average Impact Vectors - Fail to Allow Flow

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	81.61	122.42	163.22	204.03	244.84
N_1	17.0640	16.1167	12.1884	12.3096	12.7428
N_2	15.1013	8.5824	10.6612	6.4496	5.3710
N_3		12.8396	5.3267	8.1299	5.4326
N_4			12.4356	3.8778	3.0019
N_5				12.2771	6.6644
N_6					10.7877

Total Number of Independent Failure Events: 162
Total Number of Common-Cause Failure Events: 34

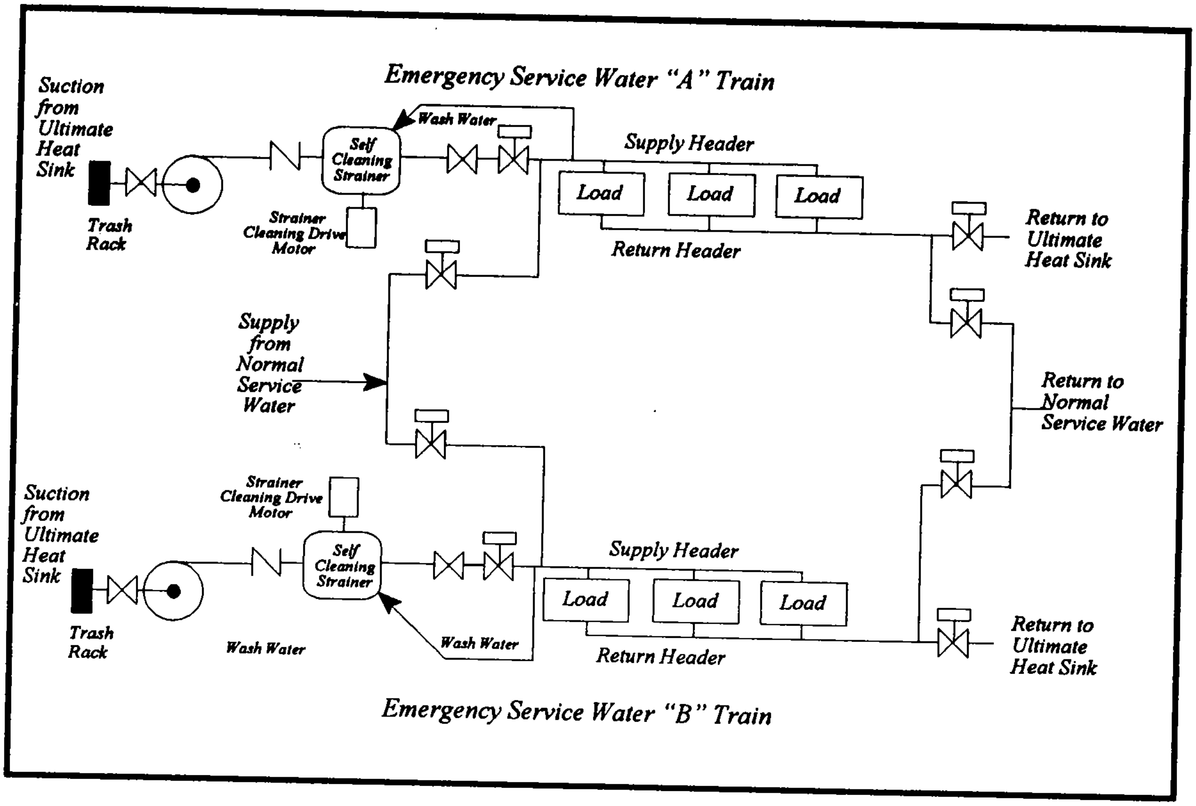

Figure 18-1. Emergency service water system.

3. COMPONENT BOUNDARIES

The main component of an ESW strainer is the strainer itself coupled to an AC electric motor for a driver that rotates the strainer for continuous cleaning. This component can be in one of two states, standby or operation, in conjunction with the associated pump. Typically, the strainers will start and operate whenever the pump is running unless there is a problem, such as strainer motor overload. These strainers can also be started manually via remote control switches. Stopping of the strainer is accomplished by operator actions via the control switches or automatic signals designed to protect the strainer or driver (e.g., overcurrent). The boundaries include the strainer itself and internal piece-parts, the motor, circuit breaker, lubrication or cooling systems, and any sensors, controls, or indication required for operation of the strainer.

4. FAILURE EVENT DEFINITION

Successful operation of an ESW strainer is starting from the standby condition, and allowing flow to the downstream portion of the system. The only failure mode used for evaluating the ESW strainer data is:

PG Failure to Allow Flow. Examples are:

- Clogging due to grass/seaweed, and
- Fouling due to organic buildup.

ESW strainer malfunctions are considered to be failures to allow flow, including loss of the motor, since plugging of the strainer will follow shortly. Strainer failures include those failures that are caused by power supplies or sensors that are unique to the strainer-driver combination. Failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the ESW strainer.

Strainer motor failures are evaluated to determine the effect on strainer operability. In general, if the failure causes the strainer to fail to operate, it will be considered a failure. Failures of the sensors or control circuitry to provide input in other systems (e.g., interlocks or indication) will not be considered strainer failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of pump/strainer demand. The exception to this is if a licensee reported that the strainer "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the strainer from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that a second ESW strainer would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another ESW strainer, then the event was identified as a CCF. If, however, the report did not clearly identify that another ESW strainer would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to an ESW strainer actuation demand (e.g., the condition was found during inspection, and no actual strainer operation was attempted), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 18-4 through 18-8 present the alpha factor uncertainty distribution summaries for each configuration of ESW strainers. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Emergency Service Water Strainers

Table 18-4: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8221297	0.8741951	0.8762136	0.9193713	0.8672708	1.0820E+02	1.5571E+01
α_2	8.06E-02	1.26E-01	1.24E-01	1.78E-01	1.33E-01	1.5571E+01	1.0820E+02

Table 18-5: Alpha Factor Distribution Summary - Fail to Allow Flow CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8303452	0.8737134	0.8751326	0.9122456	0.8660779	1.5374E+02	2.2222E+01
α_2	2.70E-02	5.10E-02	4.93E-02	8.08E-02	5.37E-02	8.9696E+00	1.6699E+02
α_3	4.56E-02	7.53E-02	7.37E-02	1.11E-01	8.03E-02	1.3252E+01	1.6271E+02

Table 18-6: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8325878	0.8706745	0.8717481	0.9050882	0.8605542	2.011E+02	2.9723E+01
α_2	2.79E-02	4.88E-02	4.75E-02	7.41E-02	5.23E-02	1.1215E+01	2.1862E+02
α_3	1.03E-02	2.43E-02	2.30E-02	4.30E-02	2.61E-02	5.5893E+00	2.2424E+02
α_4	3.37E-02	5.62E-02	5.49E-02	8.32E-02	6.10E-02	1.2919E+01	2.1691E+02

Table 18-7: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8538732	0.8861195	0.8870187	0.9153050	0.8756065	2.5438E+02	3.2692E+01
α_2	1.20E-02	2.50E-02	2.39E-02	4.18E-02	2.61E-02	7.1776E+00	2.7989E+02
α_3	1.54E-02	2.98E-02	2.87E-02	4.79E-02	3.29E-02	8.5419E+00	2.7853E+02
α_4	5.02E-03	1.43E-02	1.32E-02	2.74E-02	1.57E-02	4.1114E+00	2.8296E+02
α_5	2.67E-02	4.48E-02	4.38E-02	6.65E-02	4.97E-02	1.2861E+01	2.7421E+02

Table 18-8: Alpha Factor Distribution Summary - Fail to Allow Flow, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8733800	0.9011671	0.9019509	0.9262804	0.8917825	3.0806E+02	3.3786E+01
α_2	7.99E-03	1.80E-02	1.71E-02	3.12E-02	1.86E-02	6.1501E+00	3.3570E+02
α_3	7.64E-03	1.75E-02	1.65E-02	3.05E-02	1.88E-02	5.9732E+00	3.3587E+02
α_4	2.89E-03	9.70E-03	8.76E-03	1.97E-02	1.04E-02	3.3146E+00	3.3853E+02
α_5	9.49E-03	2.02E-02	1.93E-02	3.41E-02	2.31E-02	6.9077E+00	3.3494E+02
α_6	1.92E-02	3.35E-02	3.26E-02	5.08E-02	3.74E-02	1.1440E+01	3.3041E+02

19. Main Steam Isolation Air-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving Main Steam Isolation air-operated valves (MSIVs) in the main steam (MS) system at both pressurized water reactors (PWR) and boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. The only failure modes of interest for these valves is failure to close. The data cover the time period from 1980 through 1995.

The data review identified 78 failure-to-close events . The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to remain close are shown in Tables 19-1 and 19-2, respectively. Table 19-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode. The size of the affected population of MSIVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 19-4 through 19-8.

2. SYSTEM DESCRIPTION

The main steam system is part of the PWR Steam Generating system that transfers sensible and decay heat from the reactor coolant system to the turbine and steam auxiliaries during normal operation. Steam leaves the steam generator through a steam line at the top of the steam generator. Each steam line has a main steam isolation valve (MSIVs) outside of the containment building.

The main steam system is part of the BWR core cooling system that transfers sensible and decay heat from the reactor coolant system to the turbine and steam auxiliaries during normal operation. Steam leaves the reactor vessel through four steam lines. Each steam line has two main steam isolation valves (MSIVs) one inside and one outside of the containment building.

Typically the steam lines join outside of the containment building through a cross-connect header and then split into two main steam headers that supply main and auxiliary steam to the turbine and other auxiliaries.

Figure 19-1 shows a typical PWR main steam isolation valve arrangement and Figure 19-2 illustrates a typical BWR arrangement.

ALPHA FACTOR AND MGL PARAMETERS
Main Steam Isolation Air-Operated Valves

Table 19-1: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.8605790	0.8433169	0.8251480	0.8068196	0.8023736
α_2	1.39E-01	8.44E-02	9.21E-02	9.10E-02	7.04E-02
α_3		7.23E-02	3.03E-02	4.38E-02	5.40E-02
α_4			5.24E-02	1.48E-02	2.23E-02
α_5				4.35E-02	1.17E-02
α_6					3.93E-02

Table 19-2: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	8.61E-01	8.43E-01	8.25E-01	8.07E-01	8.02E-01
Beta	1.39E-01	1.57E-01	1.75E-01	1.93E-01	1.98E-01
Gamma		4.61E-01	4.73E-01	5.29E-01	6.44E-01
Delta			6.34E-01	5.71E-01	5.76E-01
Epsilon				7.46E-01	6.96E-01
Mu					7.70E-01

Table 19-3: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	72.16	108.24	144.32	180.40	216.48
N_1	33.6037	35.1840	33.1870	26.0231	22.5532
N_2	17.1346	14.3566	19.8179	23.2837	20.9665
N_3		12.2907	6.5196	11.2148	16.0911
N_4			11.2769	3.7911	6.6306
N_5				11.1352	3.4864
N_6					11.6998

Total Number of Independent Failure Events: 197
Total Number of Common-Cause Failure Events: 78

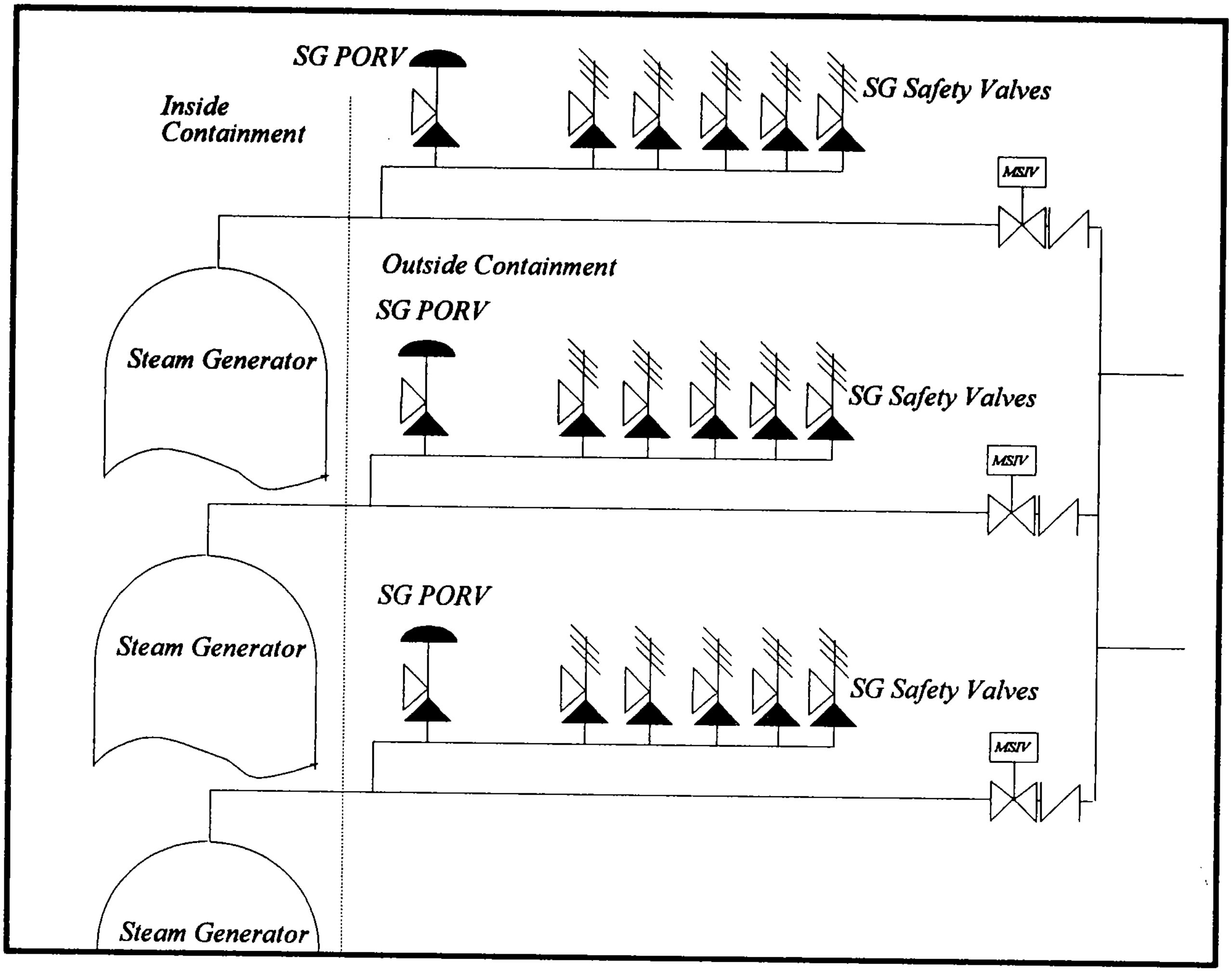

Figure 19-1. Typical PWR MSIV arrangement.

3. COMPONENT BOUNDARIES

The main components of an air-operated valve are the valve, including its internal piece-part components (e.g. disk, seat, stem, packing), and the operator. The operator includes the internal air operator piece-parts, the air supply lines specific to the AOV, sensors, solenoids to control the air supply, and the power leads to these solenoids as piece-parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. Some AOVs have manual handwheels, and can be manually operated or blocked. AC or DC power is required for solenoid and sensor operation.

The AOVs in the main steam system are used to control steam flow to the main steam headers.

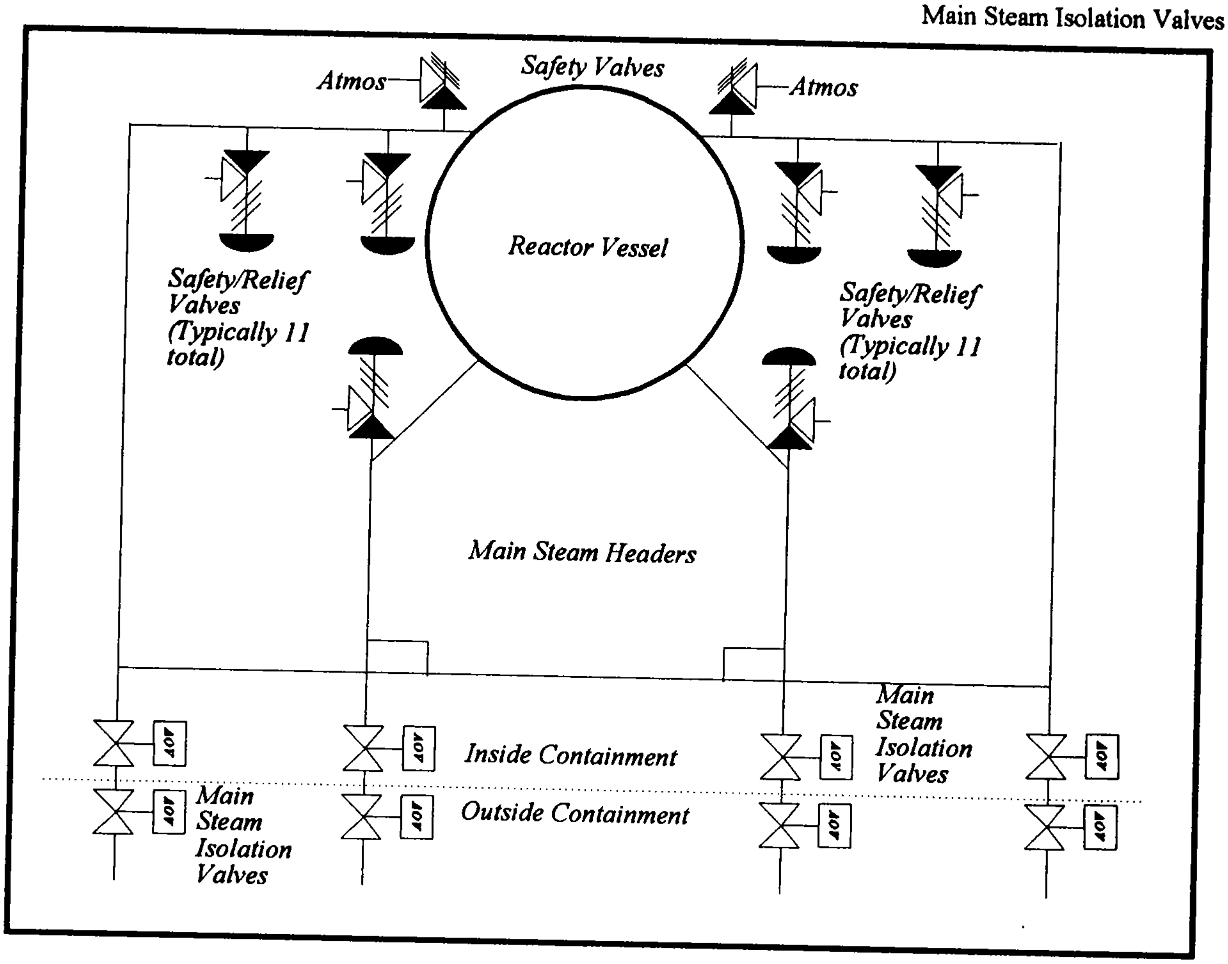

Figure 19-2. Typical BWR MSIV arrangement.

4. FAILURE EVENT DEFINITION

The function of the main steam isolation AOVs is to isolate steam flow to the steam headers to the turbines. The PRA mission for the main steam system is to provide steam to the turbine and steam auxiliaries. The event boundary for the main steam system isolation valves is defined as any condition that does not permit control of the flow either from the steam generators (PWR) or the reactor coolant system (BWR).

The only failure mode used in evaluating the main steam isolation valve data are:

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are loss of instrument air to the valve operator, control power de-energized, and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the pneumatic operator without coincident failure of the manual operator is considered as a failure. These events were considered individually to determine of the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. Many LERs reported only one actual failure, but the report information indicated that failure of a second MSIV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MSIV, the event was identified as a CCF. If, however, the report did not clearly identify that another MSIV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MSIV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 19-4 through 19-8 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of MSIVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Main Steam Isolation Air-Operated Valves

Table 19-4: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8163661	0.8675270	0.8693744	0.9123854	0.8605790	1.1529E+02	1.7605E+01
α_2	8.76E-02	1.33E-01	1.31E-01	1.84E-01	1.39E-01	1.7605E+01	1.1529E+02

Table 19-5: Alpha Factor Distribution Summary - Fail to Close, CCCG=3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8077681	0.8524840	0.8537502	0.8928843	0.8433169	1.5862E+02	2.7448E+01
α_2	4.95E-02	7.92E-02	7.77E-02	1.14E-01	8.44E-02	1.4744E+01	1.7132E+02
α_3	4.08E-02	6.83E-02	6.67E-02	1.01E-01	7.23E-02	1.2704E+01	1.7336E+02

Table 19-6: Alpha Factor Distribution Summary - Fail to Close, CCCG=4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7981769	0.8386100	0.8395484	0.8758441	0.8251480	2.0221E+02	3.8915E+01
α_2	5.72E-02	8.45E-02	8.33E-02	1.16E-01	9.21E-02	2.0372E+01	2.2075E+02
α_3	1.31E-02	2.81E-02	2.68E-02	4.75E-02	3.03E-02	6.7822E+00	2.3434E+02
α_4	2.83E-02	4.88E-02	4.75E-02	7.35E-02	5.24E-02	1.1761E+01	2.2936E+02

Table 19-7: Alpha Factor Distribution Summary - Fail to Close, CCCG=5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7889344	0.8263234	0.8270579	0.8611977	0.8068196	2.4447E+02	5.1383E+01
α_2	5.68E-02	8.12E-02	8.02E-02	1.09E-01	9.10E-02	2.4012E+01	2.7184E+02
α_3	2.27E-02	3.93E-02	3.83E-02	5.95E-02	4.38E-02	1.1627E+01	2.8423E+02
α_4	4.70E-03	1.36E-02	1.25E-02	2.62E-02	1.48E-02	4.0247E+00	2.9183E+02
α_5	2.29E-02	3.96E-02	3.86E-02	5.98E-02	4.35E-02	1.1719E+01	2.8413E+02

Table 19-8: Alpha Factor Distribution Summary - Fail to Close, CCCG=6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7906780	0.8250193	0.8256347	0.8572556	0.8023736	2.8951E+02	6.1403E+01
α_2	4.23E-02	6.20E-02	6.11E-02	8.44E-02	7.04E-02	2.1746E+01	3.2917E+02
α_3	3.03E-02	4.74E-02	4.65E-02	6.74E-02	5.40E-02	1.6632E+01	3.3428E+02
α_4	9.31E-03	1.98E-02	1.89E-02	3.34E-02	2.23E-02	6.9433E+00	3.4397E+02
α_5	3.47E-03	1.06E-02	9.71E-03	2.09E-02	1.17E-02	3.7297E+00	3.4718E+02
α_6	2.07E-02	3.52E-02	3.43E-02	5.27E-02	3.93E-02	1.2352E+01	3.3856E+02

20. BWR Isolation Condenser Air-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving air-operated valves (AOVs) in the isolation condenser (IC) system at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified one common-cause failure-to-remain closed event. No common-cause failure-to-open or failure-to-close events were identified during the data review. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to remain open are shown in Tables 20-1 and 20-2, respectively. Table 20-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode. The size of the affected population of AOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), and delta (δ)) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 20-4 through 20-6.

2. SYSTEM DESCRIPTION

The isolation condenser is part of the BWR emergency core cooling system (ECCS) that transfers residual and decay heat from the reactor coolant system to the atmosphere in the event that the main condenser is not available, or when a high reactor pressure condition exists. The IC system may be placed into service either manually or automatically. The IC system operates using natural circulation as the driving head through the isolation condenser tubes, and is available for operation when there is no electrical power. The primary side of the isolation condenser system is a closed loop from the reactor pressure vessel steam space through the tubes in the isolation condenser, with the condensate returning back to the recirculation loops. During normal plant operations, the secondary (shell) side of the isolation condenser contains sufficient water to cover the primary side tubes. The water in the shell side transfers the heat from the primary side by boiling off and venting directly to the atmosphere. Makeup to the secondary side is provided through the fire water system or through an alternate makeup source, such as the condensate transfer system.

Only five BWR plants have an IC system; those that don't have the IC have reactor core isolation cooling, which is a pump driven system. Some plants have two ICs, and other plants have one IC that contains two sets of steam cooling tubes. Figure 20-1 shows a typical isolation condenser system.

ALPHA FACTOR AND MGL PARAMETERS
Isolation Condenser Air-Operated Valves

Table 20-1: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9997851	0.9995236	0.9992861
α_2	2.15E-04	4.76E-04	7.14E-04
α_3		0.00E+00	0.00E+00
α_4			0.00E+00

Table 20-2: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	1.00E+01	1.00E+01	9.99E+01
Beta	2.15E-04	4.76E-04	7.14E-04
Gamma		0.00E+00	0.00E+00
Delta			0.00E+00

Table 20-3: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj.Ind.Events	1.33	2.00	2.67
N_1	0.0659	0.0980	0.1294
N_2	0.0003	0.0010	0.0020
N_3		0.0000	0.0000
N_4			0.0000

Total Number of Independent Failure Events: 4
Total Number of Common-Cause Failure Events: 1

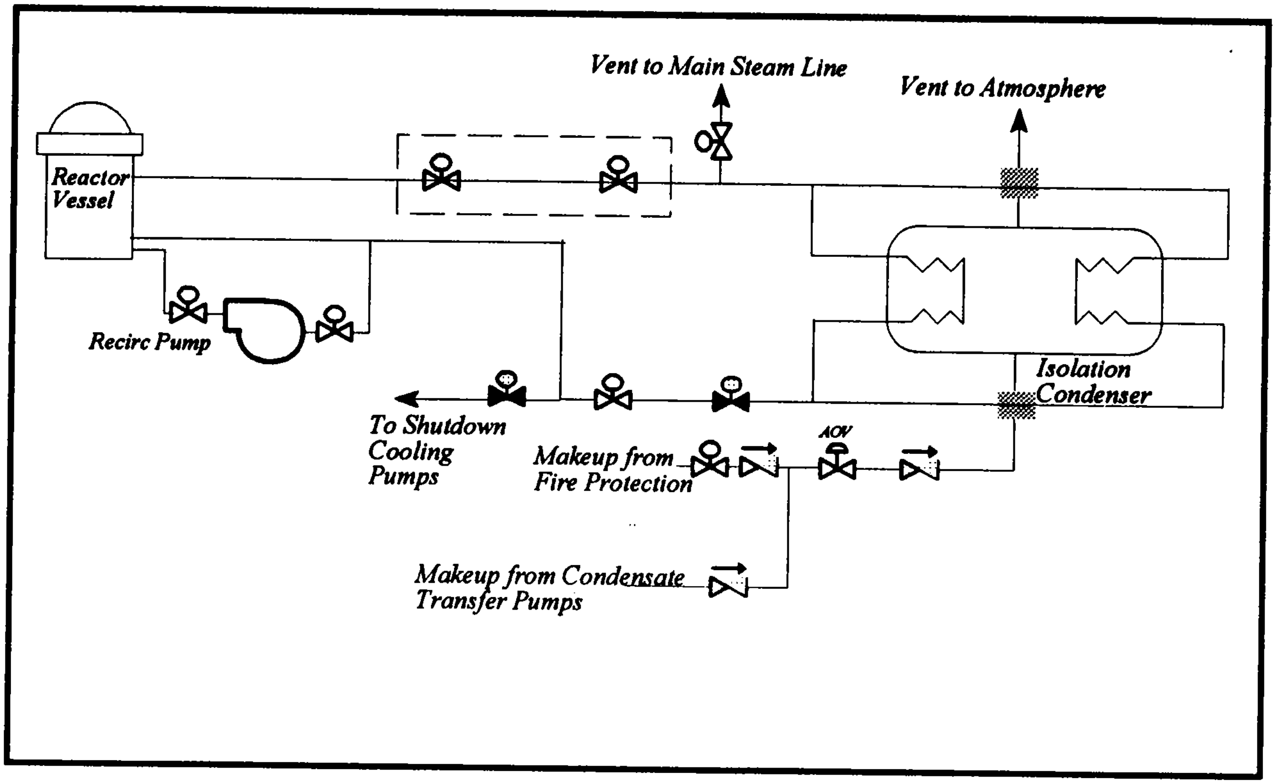

Figure 20-1. Typical isolation condenser system.

3. COMPONENT BOUNDARIES

The main components of an air-operated valve are the valve, including its internal piece-part components (e.g. disk, seat, stem, packing), and the operator. The operator includes the internal air operator piece-parts, the air supply lines specific to the AOV, sensors, solenoids to control the air supply, and the power leads to these solenoids as piece-parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. Some AOVs have manual hand wheels, and can be manually operated or blocked. AC or DC power is required for solenoid and sensor operation.

The AOVs in the isolation condenser system are used to control condensing water flow to the isolation condenser and to provide a vent path from the steam inlet line to a main steam line during standby conditions.

4. FAILURE EVENT DEFINITION

The function of the isolation condenser AOVs is to control makeup flow to the IC shell from the and to vent the steam inlet line. The PRA mission for the isolation condenser system is to provide for the removal of decay heat from the reactor coolant system when the main condenser is not available. The event boundary for the isolation condenser system AOVs is defined as any condition that does not permit control of the makeup flow to the IC shell or prevents venting the steam inlet line.

The failure modes used in evaluating the isolation condenser AOV data are:

CC Fail to Open: The valve must be in the demanded (open) position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: Leakage through the valve following a successful closure. This is intended to capture leakage events that affect the operation of the system or the plant, and not minor leakage resulting in failure of local leak rate tests.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are loss of instrument air to the valve operator, control power de-energized, and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the pneumatic operator without coincident failure of the manual operator is considered as a failure. These events were considered individually to determine of the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a loss of instrument air to the operator may cause the valve to cycle to its fail-safe position, but the resulting effect on the valve is failure to reposition so the failure mode is failure to operate to that position (if it is readily discernable, otherwise a failure of "CC" is assigned.)

Many LERs reported only one actual failure, but the report information indicated that failure of a second AOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another AOV, the event was identified as a CCF. If, however, the report did not clearly identify that another AOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an AOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 20-4 through 20-8 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of AOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Isolation Condenser Air-Operated Valves

Table 20-4: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8410731	0.9587323	0.9812171	0.9998778	0.9997851	1.0926E+01	4.7030E-01
α_2	1.24E-04	4.13E-02	1.88E-02	1.59E-01	2.15E-04	4.7030E-01	1.0926E+01

Table 20-5: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8598532	0.9557434	0.9712154	0.9987228	0.9995236	1.7298E+01	8.0100E-01
α_2	1.88E-05	2.15E-02	7.78E-03	8.94E-02	4.76E-04	3.8820E-01	1.7711E+01
α_3	3.03E-05	2.28E-02	8.88E-03	9.29E-02	0.00E+00	4.1280E-01	1.7686E+01

Table 20-6: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8792452	0.9547932	0.9649005	0.9957107	0.9992861	2.7499E+01	1.3020E+00
α_2	1.32E-04	1.93E-02	9.81E-03	7.07E-02	7.14E-04	5.5580E-01	2.8245E+01
α_3	2.68E-07	9.12E-03	1.79E-03	4.35E-02	0.00E+00	2.6260E-01	2.8538E+01
α_4	5.67E-05	1.68E-02	7.58E-03	6.48E-02	0.00E+00	4.8360E-01	2.8317E+01

21. High Pressure Coolant Injection and Reactor Core Isolation Cooling Air Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common cause failure (CCF) parameters of various models using operational data involving air operated valves (AOVs) in the high pressure coolant injection (HPCI) and reactor core isolation cooling (RCIC) system at boiling water reactors (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified two common cause failure-to-open events. There were no failure-to-close or failure-to-remain-open events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 21-1 and 21-2, respectively. Table 21-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. The size of the affected population of AOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 21-4 through 21-6.

2. SYSTEM DESCRIPTION

BWRs can have HPCI and RCIC systems or only a HPCI system (if an Isolation Condenser is present). Both the HPCI and the RCIC are single train systems, and are consequently not subject to CCF events by themselves. This analysis combined the failures of AOVs across the system boundaries to identify CCF events.

The HPCI system supplies high volume, high pressure make-up water to the reactor pressure vessel (RPV) in the event of a small break LOCA which does not result in a rapid depressurization of the reactor vessel. The HPCI system consists of a turbine driven pump, system piping, valves and controls. The HPCI system is normally in standby, and is aligned to take a suction on the condensate storage tank (CST) but suction is automatically switched from the CST to the suppression pool upon low CST level or high suppression pool water level. The HPCI system is automatically started in response to decreasing RPV water level and is injected into the reactor via the RPV shroud. HPCI serves as the primary source of makeup if RCS pressure remains high. Steam to drive the HPCI turbine is routed from main steam.

The RCIC system is provided to provide low volume, high pressure makeup water to the RPV for core cooling when the main steam lines are isolated or the condensate and feedwater system is not available. The RCIC system consists of a turbine driven pump, system piping, valves and controls. The RCIC system is normally in standby, and is normally aligned to take a suction on the CST but suction is automatically switched from the CST to the suppression pool upon low CST level or high suppression pool water level. The RCIC system is automatically started in response to decreasing RPV water level and is injected into the reactor via the feedwater line. Steam for the RCIC turbine-driven pump is routed from main steam. Figure 21-1 shows a typical HPCI system; the configuration of the RCIC system is similar.

ALPHA FACTOR AND MGL PARAMETERS
High Pressure Coolant Injection/Reactor Core Isolation Cooling
Air Operated Valves

Table 21-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

CCCG	2	3	4
α_1	0.9994513	0.9989236	0.9983845
α_2	5.49E-04	1.08E-03	1.62E-03
α_3		0.00E+00	0.00E+00
α_4			0.00E+00

Table 21-2: Summary of MGL Parameter Estimations - Fail to Open

CCCG	2	3	4
1-Beta	1.0E+01	9.99E-01	9.98E-01
Beta	5.49E-04	1.08E-03	1.62E-03
Gamma		0.00E+00	0.00E+00
Delta			0.00E+00

Table 21-3: Summary of Average Impact Vectors - Fail to Open

CCCG	2	3	4
Adj. Ind. Events	6.00	9.00	12.00
N_1	0.1934	0.2800	0.3600
N_2	0.0034	0.0100	0.0200
N_3		0.0000	0.0000
N_4			0.0000

Total Number of Independent Failure Events: 12
Total Number of Common Cause Failure Events: 2

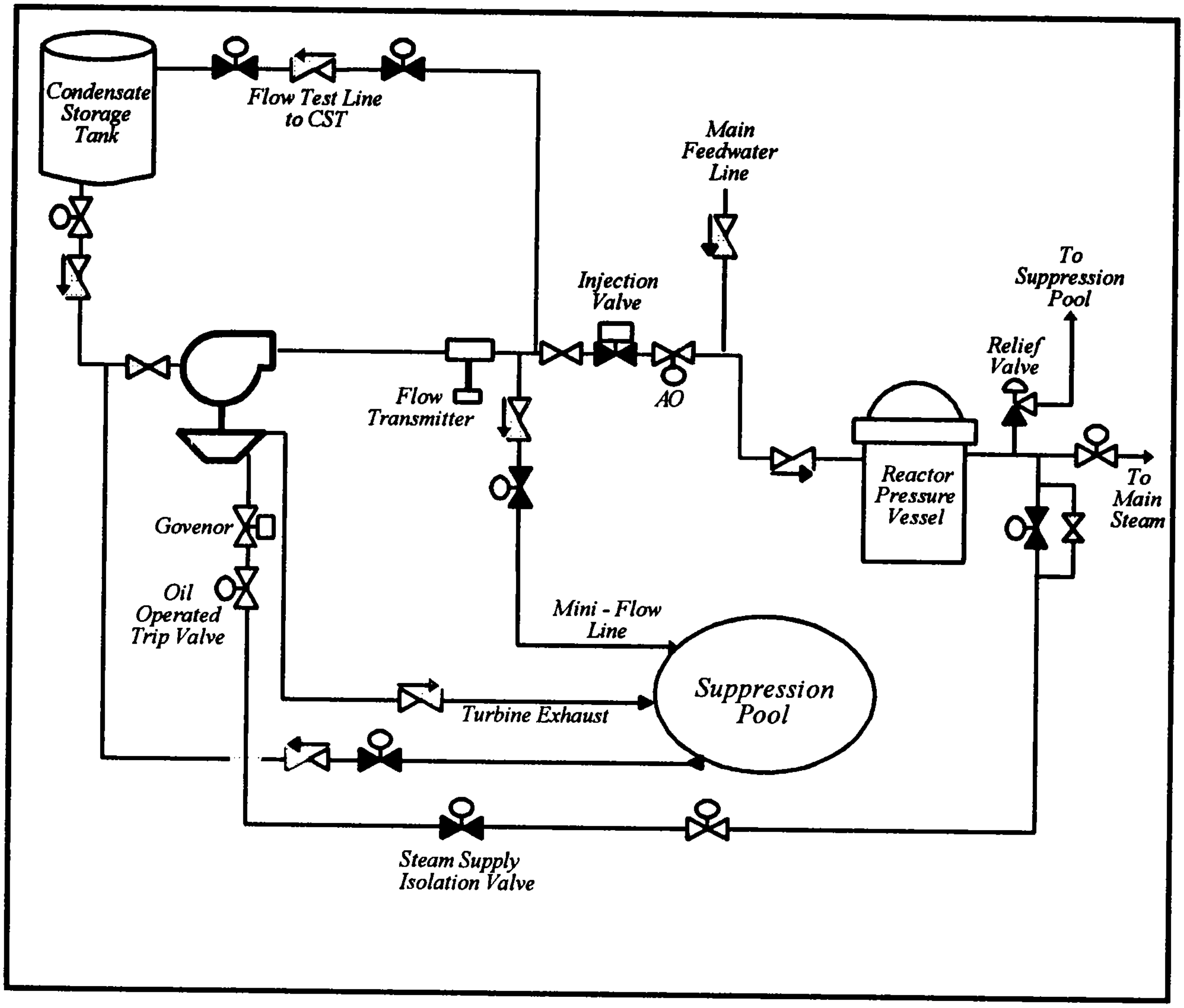

Figure 21-1. High pressure coolant injection system.

3. COMPONENT BOUNDARIES

The main components of an air-operated valve are the valve, including its internal piece-part components (e.g. disk, seat, stem, packing), and the operator. The operator includes the internal air operator piece-parts, the air supply lines specific to the AOV, sensors, solenoids to control the air supply, and the power leads to these solenoids as piece-parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. Some AOVs have manual hand wheels, and can be manually operated or blocked. AC or DC power is required for solenoid and sensor operation.

The AOVs in the HPCI/RCIC systems are used in the following applications:

- controlling flow from the pumps to the RPV,
- controlling steam condensate drains.

4. FAILURE EVENT DEFINITION

The function of the injection AOVs is to initiate steam flow to the turbines and to allow injection flow to the primary system. During normal plant operations, most of the AOVs remain closed to isolate the high pressure and low pressure portions of the system. All valves serve as a system containment boundary and would need to close to isolate leaks. The failure modes used in evaluating the HPCI/RCIC AOV data are:

CC Fail to Open: The valve must be fully open. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: Leakage through the valve following a successful closure. This is intended to capture leakage events that affect the operation of the system or the plant, and not minor leakage resulting in failure of local leak rate tests.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are loss of instrument air to the valve operator, control power de-energized, and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the pneumatic operator without coincident failure of the manual operator is still coded as a failure.

Failures of the operator were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a loss of instrument air may cause the valve to cycle to its fail-safe position, but the resulting effect on the valve is failure to reposition, so the failure mode is failure to operate to that position (if it is readily discernable, otherwise a failure of "CC" is assigned.)

Many LERs reported only one actual failure, but the report information indicated that failure of a second AOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another AOV, the event was identified as a CCF. If, however, the report did not clearly identify that another AOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an AOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 21-4 through 21-6 present the alpha factor uncertainty distribution summaries for failure to open and each configuration of AOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
High Pressure Coolant Injection/Reactor Core Isolation Cooling Air-Operated Valves

Table 21-4: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8870097	0.9707713	0.9868360	0.9999123	0.9994513	1.5723E+01	4.7340E-01
α_2	8.94E-05	2.92E-02	1.32E-02	1.13E-01	5.49E-04	4.7340E-01	1.5723E+01

Table 21-5: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8982831	0.9679715	0.9792719	0.9990517	0.9989236	2.4480E+01	8.1000E-01
α_2	1.60E-05	1.57E-02	5.79E-03	6.51E-02	1.08E-03	3.9720E-01	2.4893E+01
α_3	2.14E-05	1.63E-02	6.29E-03	6.67E-02	0.00E+00	4.1280E-01	2.4877E+01

Table 21-6: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9080375	0.9656071	0.9733435	0.9966872	0.9983845	3.7060E+01	1.320E+00
α_2	1.18E-04	1.50E-02	7.74E-03	5.43E-02	1.62E-03	5.7380E-01	3.7806E+01
α_3	2.00E-07	6.84E-03	1.34E-03	3.26E-02	0.00E+00	2.6260E-01	3.8117E+01
α_4	4.22E-05	1.26E-02	5.66E-03	4.87E-02	0.00E+00	4.8360E-01	3.7896E+01

22. PWR Auxiliary Feedwater Air-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving air-operated valves (AOVs) in the auxiliary feedwater (AFW) system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified seven common-cause failure-to-open events, 13 common-cause failure-to-close events, and nine failure-to-remain-closed CCF events for steam generator injection flow control valves. For pump turbine steam inlet air-operated valves, the data review identified one failure to open common-cause events, five common-cause failure to close events, and three common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 22-1 and 22-2, respectively. Table 22-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 22-4 through 22-18 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of AOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 22-19 through 22-48.

2. SYSTEM DESCRIPTION

The auxiliary feedwater system provides a source of feedwater to the steam generators to remove decay heat from the reactor coolant system (RCS) when: (a) the main feedwater system is not available, and (b) RCS pressure is too high to permit heat removal by the residual heat removal (RHR) system. The AFW system is typically comprised of two motor-driven, full capacity, pumps and a steam driven, double capacity pump along with valves and control systems to allow control of steam generator level and feedwater flow rate. The motor-driven pumps are supplied power from the IE class power system with backup power available from the IE emergency diesel generators (EDG). The water supply for the system is from the condensate storage tank (CST) with a backup source of water (untreated) available from the service water system.

The AFW system is normally in standby, whether the plant is at power or shutdown. The motor-driven pumps start on one of the following conditions: a safety injection (SI) signal, a low-low level in any steam generator, loss of both main feedwater pumps (MFP), a loss of off-site power (LOSP) or manual initiation. The turbine-driven pump will start on either a low-low level in more than one steam generator or a loss of off-site power. Flow to the steam generators is a two stage process at some plants. First the pumps start on demand from a steam generator low level signal. Control valves regulate the flow as needed. Feedwater flow to the steam generators is controlled from the main control room by air, motor, or hydraulically operated valves. Motor-driven pump run out is controlled by an air or hydraulically controlled regulator valve on the pump discharge. The turbine-driven pump steam supply is controlled by AOVs or hydraulically operated valves. Figure 22-1 shows a typical auxiliary feedwater system.

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Air-Operated Valves
Steam Generator Injection Flow Control Valves

Table 22-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9724137	0.9545685	0.9543692	0.9542087	0.9542531
α_2	2.76E-02	4.00E-02	2.66E-02	2.33E-02	2.13E-02
α_3		5.48E-03	1.69E-02	1.28E-02	1.12E-02
α_4			2.21E-03	8.63E-03	5.36E-03
α_5				1.08E-03	5.27E-03
α_6					2.63E-03

Table 22-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.72E-01	9.55E-01	9.54E-01	9.54E-01	9.54E-01
Beta	2.76E-02	4.54E-02	4.56E-02	4.58E-02	4.58E-02
Gamma		1.21E-01	4.18E-01	4.92E-01	5.35E-01
Delta			1.16E-01	4.31E-01	5.42E-01
Epsilon				1.12E-01	5.96E-01
Mu					3.33E-01

Table 22-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	27.04	40.55	54.07	67.59	81.11
N_1	3.2255	3.0145	3.1367	3.0995	2.9806
N_2	0.8586	1.8233	1.5924	1.7225	1.8763
N_3		0.2501	1.0103	0.9502	0.9866
N_4			0.1325	0.6393	0.4725
N_5				0.0803	0.4642
N_6					0.2317

Total Number of Independent Failure Events: 83
Total Number of Common-Cause Failure Events: 7

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Air-Operated Valves
Steam Generator Injection Flow Control Valves

Table 22-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9880192	0.9769070	0.9641062	0.9519127	0.9397404
α_2	1.20E-02	2.30E-02	3.56E-02	4.74E-02	5.91E-02
α_3		1.19E-04	3.41E-04	6.86E-04	1.13E-03
α_4			2.72E-06	1.10E-05	2.23E-05
α_5				0.00E+00	1.86E-06
α_6					0.00E+00

Table 22-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.88E-01	9.77E-01	9.64E-01	9.52E-01	9.40E-01
Beta	1.20E-02	2.31E-02	3.59E-02	4.81E-02	6.03E-02
Gamma		5.13E-03	9.56E-03	1.45E-02	1.91E-02
Delta			7.94E-03	1.58E-02	2.10E-02
Epsilon				0.00E+00	7.69E-02
Mu					0.00E+00

Table 22-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	15.32	22.98	30.64	38.30	45.95
N_1	3.2516	4.2167	4.7507	4.8404	4.5649
N_2	0.2252	0.6396	1.3050	2.1477	3.1772
N_3		0.0033	0.0125	0.0311	0.0607
N_4			0.0001	0.0005	0.0012
N_5				0.0000	0.0001
N_6					0.0000

Total Number of Independent Failure Events: 53
Total Number of Common-Cause Failure Events: 13

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Air-Operated Valves
Steam Generator Injection Flow Control Valves

Table 22-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9703467	0.9506596	0.9402541	0.9369419	0.9382050
α_2	2.97E-02	4.32E-02	4.37E-02	3.60E-02	2.58E-02
α_3		6.10E-03	1.52E-02	2.33E-02	2.65E-02
α_4			9.15E-04	3.76E-03	9.55E-03
α_5				0.00E+00	4.42E-06
α_6					0.00E+00

Table 22-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.70E-01	9.51E-01	9.40E-01	9.37E-01	9.38E-01
Beta	2.97E-02	4.93E-02	5.98E-02	6.31E-02	6.18E-02
Gamma		1.24E-01	2.69E-01	4.29E-01	5.83E-01
Delta			5.69E-02	1.39E-01	2.65E-01
Epsilon				0.00E+00	4.62E-04
Mu					0.00E+00

Table 22-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	6.21	9.32	12.42	15.53	18.63
N_1	1.6599	1.9726	2.1750	2.3714	2.6119
N_2	0.2405	0.5136	0.6777	0.6885	0.5830
N_3		0.0725	0.2355	0.4445	0.5998
N_4			0.0142	0.0718	0.2162
N_5				0.0000	0.0001
N_6					0.0000

Total Number of Independent Failure Events: 20
Total Number of Common-Cause Failure Events: 9

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Air-Operated Valves
Pump Turbine Steam Supply Control Valves

Table 22-10: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9230769	0.9473684	0.9600000	0.9677419	0.9729730
α_2	7.69E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
α_3		5.26E-02	0.00E+00	0.00E+00	0.00E+00
α_4			4.00E-02	0.00E+00	0.00E+00
α_5				3.23E-02	0.00E+00
α_6					2.70E-02

Table 22-11: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.23E-01	9.47E-01	9.60E-01	9.68E-01	9.73E-01
Beta	7.69E-02	5.26E-02	4.00E-02	3.23E-02	2.70E-02
Gamma		1.00E+00	1.00E+00	1.00E+00	1.00E+00
Delta			1.00E+00	1.00E+00	1.00E+00
Epsilon				1.00E+00	1.00E+00
Mu					1.00E+00

Table 22-12: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	12.00	18.00	24.00	30.00	36.00
N_1	0.0000	0.0000	0.0000	0.0000	0.0000
N_2	1.0000	0.0000	0.0000	0.0000	0.0000
N_3		1.0000	0.0000	0.0000	0.0000
N_4			1.0000	0.0000	0.0000
N_5				1.0000	0.0000
N_6					1.0000

Total Number of Independent Failure Events: 12
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Air-Operated Valves
Pump Turbine Steam Supply Control Valves

Table 22-13: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
α_1	0.9833373	0.9664044	0.9490796	0.9554160	0.9592296
α_2	1.67E-02	3.35E-02	5.06E-02	2.60E-02	1.72E-02
α_3		1.16E-04	3.19E-04	1.85E-02	1.60E-02
α_4			8.86E-06	3.58E-05	7.60E-03
α_5				0.00E+00	6.02E-06
α_6					0.00E+00

Table 22-14: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
1-Beta	9.83E-01	9.66E-01	9.49E-01	9.55E-01	9.59E-01
Beta	1.67E-02	3.36E-02	5.09E-02	4.46E-02	4.08E-02
Gamma		3.46E-03	6.44E-03	4.16E-01	5.78E-01
Delta			2.70E-02	1.93E-03	3.23E-01
Epsilon				0.00E+00	7.92E-04
Mu					0.00E+00

Table 22-15: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
Adj. Ind. Events	10.00	15.00	20.00	25.00	30.00
N_1	1.4783	1.6410	1.4268	1.6648	1.8658
N_2	0.1945	0.5765	1.1422	0.7268	0.5716
N_3		0.0020	0.0072	0.5165	0.5302
N_4			0.0002	0.0010	0.2524
N_5				0.0000	0.0002
N_6					0.0000

Total Number of Independent Failure Events: 18
Total Number of Common-Cause Failure Events: 5

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Air-Operated Valves
Pump Turbine Steam Supply Control Valves

Table 22-16: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9961272	0.9514549	0.9361668	0.9331861	0.9352109
α_2	3.87E-03	4.74E-02	4.51E-02	3.37E-02	2.32E-02
α_3		1.20E-03	1.83E-02	2.53E-02	2.43E-02
α_4			4.61E-04	7.62E-03	1.39E-02
α_5				1.85E-04	3.30E-03
α_6					8.04E-05

Table 22-17: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.96E-01	9.52E-01	9.36E-01	9.33E-01	9.35E-01
Beta	3.87E-03	4.86E-02	6.38E-02	6.68E-02	6.48E-02
Gamma		2.46E-02	2.94E-01	4.96E-01	6.41E-01
Delta			2.46E-02	2.36E-01	4.16E-01
Epsilon				2.36E-02	1.96E-01
Mu					2.38E-02

Table 22-18: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	6.00	8.99	11.99	14.99	17.98
N_1	1.1247	0.9665	0.8030	0.6907	0.6292
N_2	0.0277	0.4955	0.6160	0.5660	0.4623
N_3		0.0125	0.2500	0.4255	0.4831
N_4			0.0063	0.1281	0.2766
N_5				0.0031	0.0656
N_6					0.0016

Total Number of Independent Failure Events: 11
Total Number of Common-Cause Failure Events: 3

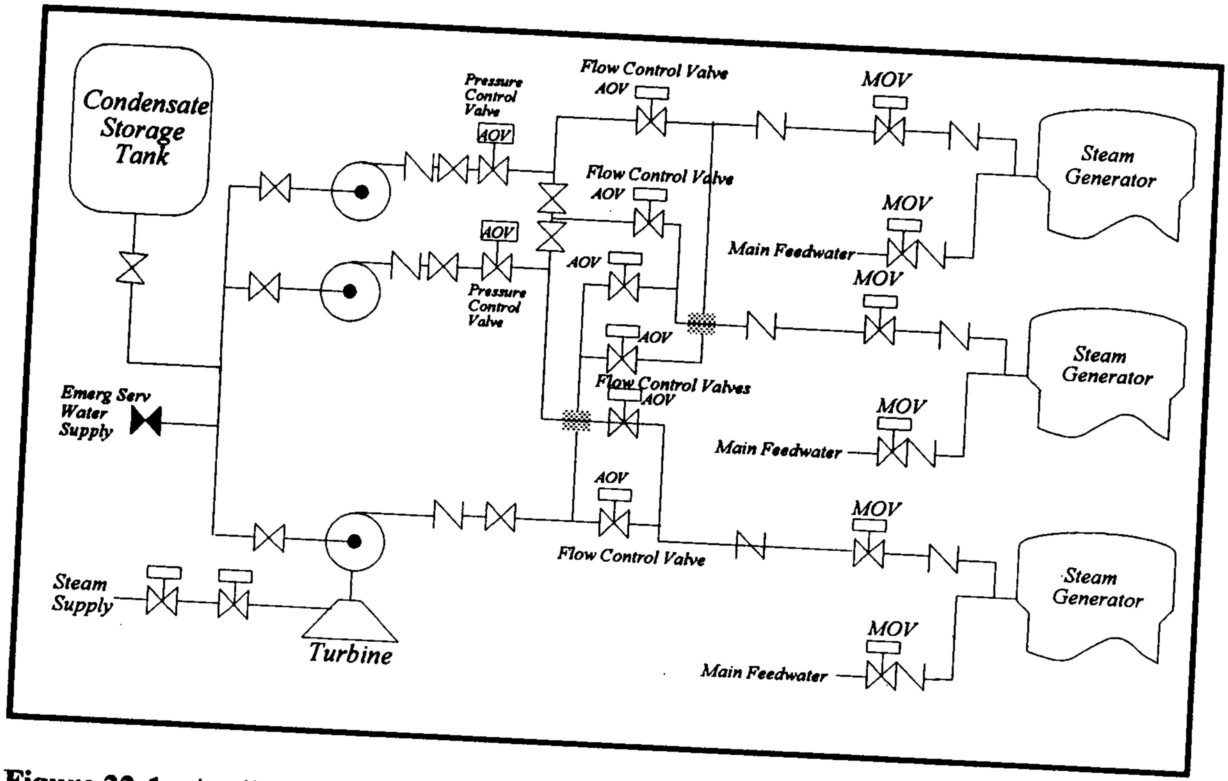

Figure 22-1. Auxiliary feedwater system

3. COMPONENT BOUNDARIES

The main components of an air-operated valve are the valve, including its internal piece-part components (e.g. disk, seat, stem, packing), and the operator. The operator includes the internal air operator piece-parts, the air supply lines specific to the AOV, sensors, solenoids to control the air supply, and the power leads to these solenoids as piece-parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. Some AOVs have manual hand wheels, and can be manually operated or blocked. AC or DC power is required for solenoid and sensor operation.

The AOVs in the AFW system are used in the following applications:

- Controlling feedwater flow from the pumps to the steam generators,
- Controlling pump discharge pressure to limit motor-driven pump run out, and
- Controlling and/or admitting steam flow to the turbine-driven AFW pump.

The number of air-operated valves in the AFW system varies from two to ten, depending on the number of trains and pumps in the system; six is a typical value. The pump recirculation valves, the steam condensate drain valves, and the steam line warming valves are not included in this data set, since they are not considered in PRA applications. For parameter estimations, the steam generator flow control valves (water flow) were separated from the pump turbine steam supply valves (steam flow).

4. FAILURE EVENT DEFINITION

The function of the AFW AOVs is to control feedwater flow to the steam generators from the AFW pumps and, in some plants, to supply steam to the turbine-driven pump. The PRA mission for the AFW system is to provide water to the steam generators for the removal of decay heat from the reactor coolant system. The event boundary for the AFW System AOVs is defined as any condition that does not permit control of the flow either from the AFW pumps to the steam generators, or from the main steam system to the pump turbine.

The failure modes used in evaluating the AFW AOV data are:

CC Fail to Open: A successful operation of the valve is the valve in the demanded (open) position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: Leakage through the valve following a successful closure. This is intended to capture leakage events that affect the operation of the system or the plant, and not minor leakage resulting in failure of local leak rate tests.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are loss of instrument air to the valve operator, control power de-energized, and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the pneumatic operator without coincident failure of the manual operator is considered as a failure. These events were considered individually to determine of the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a loss of instrument air may cause the valve to cycle to its fail-safe position, but the resulting effect on the valve is failure to reposition so the failure mode is failure to operate to that position (if it is readily discernable, otherwise a failure of "CC" is assigned.)

Many LERs reported only one actual failure, but the report information indicated that failure of a second AOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another AOV, the event was identified as a CCF. If, however, the report did not clearly identify that another AOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an AOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 22-19 through 22-48 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of AOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS

AFW Air-Operated Valves - Steam Generator Injection Flow Control Valves

Table 22-19: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9137163	0.9676933	0.9749427	0.9968562	0.9724137	3.9796E+01	1.3286E+00
α_2	3.15E-03	3.23E-02	2.51E-02	8.63E-02	2.76E-02	1.3286E+00	3.9796E+01

Table 22-20: Alpha Factor Distribution Summary - Fail to Open, CCCG=3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9027648	0.9533830	0.9582186	0.9874551	0.9545685	5.8765E+01	2.8734E+00
α_2	7.35E-03	3.59E-02	3.10E-02	8.12E-02	4.00E-02	2.2105E+00	5.9428E+01
α_3	1.54E-04	1.08E-02	6.12E-03	3.71E-02	5.48E-03	6.6290E-01	6.0976E+01

Table 22-21: Alpha Factor Distribution Summary - Fail to Open, CCCG=4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9106820	0.9530475	0.9565265	0.9835098	0.9543692	8.1907E+01	4.0352E+00
α_2	4.91E-03	2.50E-02	2.14E-02	5.73E-02	2.66E-02	2.1462E+00	8.3796E+01
α_3	1.31E-03	1.48E-02	1.13E-02	4.05E-02	1.69E-02	1.2729E+00	8.4669E+01
α_4	7.62E-05	7.17E-03	3.87E-03	2.55E-02	2.21E-03	6.1610E-01	8.5326E+01

Table 22-22: Alpha Factor Distribution Summary - Fail to Open, CCCG=5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9167885	0.9531039	0.9557304	0.9804316	0.9542087	1.0873E+02	5.3499E+00
α_2	4.88E-03	2.15E-02	1.88E-02	4.74E-02	2.33E-02	2.4505E+00	1.1163E+02
α_3	1.20E-03	1.19E-02	9.23E-03	3.20E-02	1.28E-02	1.3622E+00	1.1272E+02
α_4	2.75E-04	7.65E-03	5.03E-03	2.40E-02	8.63E-03	8.7290E-01	1.1321E+02
α_5	8.37E-05	5.82E-03	3.30E-03	2.01E-02	1.08E-03	6.6430E-01	1.1342E+02

Table 22-23: Alpha Factor Distribution Summary - Fail to Open, CCCG=6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9212745	0.9535222	0.9556554	0.9784914	0.9542531	1.3456E+02	6.5589E+00
α_2	4.63E-03	1.88E-02	1.66E-02	4.06E-02	2.13E-02	2.6554E+00	1.3846E+02
α_3	1.32E-03	1.08E-02	8.61E-03	2.79E-02	1.12E-02	1.5272E+00	1.3959E+02
α_4	1.44E-04	5.56E-03	3.47E-03	1.81E-02	5.36E-03	7.8520E-01	1.4033E+02
α_5	9.11E-05	5.01E-03	2.95E-03	1.70E-02	5.27E-03	7.0750E-01	1.4041E+02
α_6	2.33E-04	6.26E-03	4.14E-03	1.95E-02	2.63E-03	8.8360E-01	1.4024E+02

ALPHA FACTOR DISTRIBUTIONS
AFW Air-Operated Valves-Steam Generator Injection Flow Control Valves

Table 22-24: Alpha Factor Distribution Summary - Fail to Close, CCCG=2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9186363	0.9758588	0.9856882	0.9995765	0.9880192	2.8102E+01	6.9520E-01
α_2	4.21E-04	2.41E-02	1.43E-02	8.14E-02	1.20E-02	6.9520E-01	2.8102E+01

Table 22-25: Alpha Factor Distribution Summary - Fail to Close, CCCG=3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9145232	0.9670870	0.9739114	0.9962905	0.9769070	4.2397E+01	1.4429E+00
α_2	1.31E-03	2.34E-02	1.67E-02	6.87E-02	2.30E-02	1.0268E+00	4.2813E+01
α_3	1.30E-05	9.49E-03	3.65E-03	3.88E-02	1.19E-04	4.1610E-01	4.3424E+01

Table 22-26: Alpha Factor Distribution Summary - Fail to Close, CCCG=4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9103869	0.9582577	0.9630479	0.9897359	0.9641062	6.091E+01	2.6176E+00
α_2	4.89E-03	2.96E-02	2.48E-02	7.10E-02	3.56E-02	1.8588E+00	6.0850E+01
α_3	2.06E-07	4.39E-03	9.30E-04	2.06E-02	3.41E-04	2.7510E-01	6.2434E+01
α_4	2.57E-05	7.71E-03	3.44E-03	2.99E-02	2.72E-06	4.8370E-01	6.2225E+01

Table 22-27: Alpha Factor Distribution Summary - Fail to Close, CCCG=5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9083948	0.9515125	0.9550110	0.9826704	0.9519127	8.1182E+01	4.1369E+00
α_2	9.01E-03	3.37E-02	3.01E-02	7.07E-02	4.74E-02	2.8757E+00	8.2443E+01
α_3	1.04E-05	5.19E-03	2.12E-03	2.08E-02	6.86E-04	4.4310E-01	8.4876E+01
α_4	2.18E-08	2.74E-03	4.20E-04	1.36E-02	1.10E-05	2.3410E-01	8.5085E+01
α_5	5.77E-05	6.85E-03	3.56E-03	2.48E-02	0.00E+00	5.840E-01	8.4735E+01

Table 22-28: Alpha Factor Distribution Summary - Fail to Close, CCCG=6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9060239	0.9459819	0.9487481	0.9764798	0.9397404	1.099E+02	5.7668E+00
α_2	1.28E-02	3.71E-02	3.42E-02	7.11E-02	5.91E-02	3.9563E+00	1.0280E+02
α_3	5.39E-05	5.63E-03	2.99E-03	2.02E-02	1.13E-03	6.0130E-01	1.0616E+02
α_4	4.75E-07	2.94E-03	7.75E-04	1.33E-02	2.23E-05	3.1390E-01	1.0644E+02
α_5	2.86E-08	2.28E-03	3.79E-04	1.11E-02	1.86E-06	2.4340E-01	1.0651E+02
α_6	8.16E-05	6.11E-03	3.42E-03	2.13E-02	0.00E+00	6.5190E-01	1.0611E+02

ALPHA FACTOR DISTRIBUTIONS
AFW Air-Operated Valves - Steam Generator Injection Flow Control Valves

Table 22-29: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8698964	0.9607686	0.9761159	0.9992420	0.9703467	1.740E+01	7.1050E-01
α_2	7.55E-04	3.92E-02	2.39E-02	1.30E-01	2.97E-02	7.1050E-01	1.740E+01

Table 22-30: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8702592	0.9502817	0.9606724	0.9946930	0.9506596	2.6493E+01	1.3861E+00
α_2	1.30E-03	3.23E-02	2.19E-02	9.88E-02	4.32E-02	9.0800E-01	2.6978E+01
α_3	5.99E-05	1.74E-02	7.89E-03	6.71E-02	6.10E-03	4.8530E-01	2.7394E+01

Table 22-31: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8798252	0.9463567	0.9533923	0.9887817	0.9402541	3.9295E+01	2.2274E+00
α_2	2.49E-03	2.97E-02	2.25E-02	8.14E-02	4.37E-02	1.2315E+00	4.0291E+01
α_3	4.71E-05	1.20E-02	5.52E-03	4.59E-02	1.52E-02	4.9810E-01	4.1024E+01
α_4	4.69E-05	1.20E-02	5.52E-03	4.59E-02	9.15E-04	4.9780E-01	4.1025E+01

Table 22-32: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8916493	0.9464956	0.9514760	0.9843010	0.9369419	5.5943E+01	3.1624E+00
α_2	2.60E-03	2.40E-02	1.88E-02	6.29E-02	3.60E-02	1.4165E+00	5.7689E+01
α_3	4.96E-04	1.45E-02	9.50E-03	4.55E-02	2.33E-02	8.5650E-01	5.8249E+01
α_4	6.58E-07	5.17E-03	1.31E-03	2.35E-02	3.76E-03	3.0540E-01	5.8800E+01
α_5	8.37E-05	9.88E-03	5.15E-03	3.57E-02	0.00E+00	5.8400E-01	5.8521E+01

Table 22-33: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9007214	0.9480875	0.9520031	0.9820644	0.9382050	7.1714E+01	3.9267E+00
α_2	1.81E-03	1.80E-02	1.40E-02	4.80E-02	2.58E-02	1.3621E+00	7.4279E+01
α_3	1.07E-03	1.51E-02	1.11E-02	4.28E-02	2.65E-02	1.1404E+00	7.4500E+01
α_4	3.70E-05	6.99E-03	3.37E-03	2.62E-02	9.55E-03	5.2890E-01	7.5112E+01
α_5	4.05E-08	3.22E-03	5.36E-04	1.57E-02	4.42E-06	2.4340E-01	7.5397E+01
α_6	1.16E-04	8.62E-03	4.84E-03	3.00E-02	0.00E+00	6.5190E-01	7.4989E+01

ALPHA FACTOR DISTRIBUTIONS
AFW Air-Operated Valves - Pump Turbine Steam Supply Control Valves

Table 22-34: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8376352	0.9360870	0.9483768	0.9923674	0.9230769	2.1530E+01	1.4700E+00
α_2	7.63E-03	6.39E-02	5.16E-02	1.62E-01	7.69E-02	1.4700E+00	2.1530E+01

Table 22-35: Alpha Factor Distribution Summary - Fail to Open, CCCG=3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8768240	0.9485714	0.9569053	0.9917545	0.9473684	3.3200E+01	1.8000E+00
α_2	9.36E-06	1.11E-02	3.93E-03	4.63E-02	0.00E+00	3.8720E-01	3.4613E+01
α_3	4.42E-03	4.04E-02	3.19E-02	1.05E-01	5.26E-02	1.4128E+00	3.3587E+01

Table 22-36: Alpha Factor Distribution Summary - Fail to Open, CCCG=4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8995526	0.9549019	0.9607363	0.9902813	0.9600000	4.8700E+01	2.300E+00
α_2	7.22E-05	1.09E-02	5.45E-03	4.00E-02	0.00E+00	5.5380E-01	5.0446E+01
α_3	1.50E-07	5.15E-03	1.00E-03	2.46E-02	0.00E+00	2.6260E-01	5.0737E+01
α_4	3.43E-03	2.91E-02	2.32E-02	7.50E-02	4.00E-02	1.4836E+00	4.9516E+01

Table 22-37: Alpha Factor Distribution Summary - Fail to Open, CCCG=5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9136494	0.9583435	0.9625853	0.9885298	0.9677419	6.8042E+01	2.9576E+00
α_2	2.08E-004	1.03E-002	6.16E-003	3.42E-002	0.00E+000	7.2800E-01	7.0272E+01
α_3	7.39E-06	5.80E-03	2.20E-03	2.38E-02	0.00E+00	4.1200E-01	7.0588E+01
α_4	2.56E-08	3.29E-03	5.02E-04	1.63E-02	0.00E+00	2.3360E-01	7.0766E+01
α_5	2.91E-03	2.23E-02	1.80E-02	5.65E-02	3.23E-02	1.5840E+00	6.9416E+01

Table 22-38: Alpha Factor Distribution Summary - Fail to Open, CCCG=6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9225296	0.9608043	0.9641727	0.9875497	0.9729730	8.6472E+01	3.5276E+00
α_2	2.20E-04	8.66E-03	5.39E-03	2.82E-02	0.00E+00	7.7910E-01	8.9221E+01
α_3	3.54E-05	6.01E-03	2.94E-03	2.24E-02	0.00E+00	5.4060E-01	8.9459E+01
α_4	5.44E-07	3.47E-03	9.11E-04	1.57E-02	0.00E+00	3.1270E-01	8.9687E+01
α_5	3.38E-08	2.70E-03	4.49E-04	1.32E-02	0.00E+00	2.4330E-01	8.9756E+01
α_6	2.54E-03	1.84E-02	1.49E-02	4.59E-02	2.70E-02	1.6519E+00	8.8348E+01

ALPHA FACTOR DISTRIBUTIONS
AFW Air-Operated Valves - Pump Turbine Steam Supply Control Valves

Table 22-39: Alpha Factor Distribution Summary - Fail to Close, CCCG=2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8953226	0.9693390	0.9821908	0.9995423	0.9833373	2.108E+01	6.6450E-01
α_2	4.55E-04	3.07E-02	1.78E-02	1.05E-01	1.67E-02	6.6450E-01	2.108E+01

Table 22-40: Alpha Factor Distribution Summary - Fail to Close, CCCG=3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8910472	0.9585033	0.9673470	0.9956436	0.9664044	3.1841E+01	1.3785E+00
α_2	1.40E-03	2.90E-02	2.02E-02	8.67E-02	3.35E-02	9.6370E-01	3.2256E+01
α_3	1.68E-05	1.25E-02	4.81E-03	5.10E-02	1.16E-04	4.1480E-01	3.2805E+01

Table 22-41: Alpha Factor Distribution Summary - Fail to Close, CCCG=4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8900255	0.9495724	0.9556381	0.9883432	0.9490796	4.6127E+01	2.4496E+00
α_2	5.09E-03	3.49E-02	2.87E-02	8.59E-02	5.06E-02	1.6960E+00	4.6881E+01
α_3	2.15E-07	5.55E-03	1.14E-03	2.63E-02	3.19E-04	2.6980E-01	4.8307E+01
α_4	3.33E-05	9.96E-03	4.46E-03	3.86E-02	8.86E-06	4.8380E-01	4.8093E+01

Table 22-42: Alpha Factor Distribution Summary - Fail to Close, CCCG=5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9046086	0.9528500	0.9572419	0.9860702	0.9554160	6.4707E+01	3.2019E+00
α_2	2.43E-03	2.14E-02	1.69E-02	5.58E-02	2.60E-02	1.4548E+00	6.6454E+01
α_3	5.87E-04	1.37E-02	9.28E-03	4.18E-02	1.85E-02	9.2850E-01	6.6980E+01
α_4	2.83E-08	3.46E-03	5.32E-04	1.71E-02	3.58E-05	2.3460E-01	6.7674E+01
α_5	7.27E-05	8.60E-03	4.48E-03	3.11E-02	0.00E+00	5.8400E-01	6.7325E+01

Table 22-43: Alpha Factor Distribution Summary - Fail to Close, CCCG=6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9134252	0.9549757	0.9584602	0.9846184	0.9592296	8.2338E+01	3.8820E+00
α_2	1.55E-03	1.57E-02	1.21E-02	4.20E-02	1.72E-02	1.3507E+00	8.4869E+01
α_3	7.60E-04	1.24E-02	8.90E-03	3.61E-02	1.60E-02	1.0708E+00	8.5149E+01
α_4	4.76E-05	6.55E-03	3.32E-03	2.40E-02	7.60E-03	5.6510E-01	8.5655E+01
α_5	3.56E-08	2.82E-03	4.71E-04	1.38E-02	6.02E-06	2.4350E-01	8.5977E+01
α_6	1.01E-04	7.56E-03	4.24E-03	2.63E-02	0.00E+00	6.5190E-01	8.5568E+01

ALPHA FACTOR DISTRIBUTIONS
AFW Air-Operated Valves - Pump Turbine Steam Supply Control Valves

Table 22-44: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8898437	0.9709842	0.9863462	0.9998810	0.9961272	1.6655E+01	4.9770E-01
α_2	1.16E-04	2.90E-02	1.37E-02	1.10E-01	3.87E-03	4.9770E-01	1.6655E+01

Table 22-45: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8684788	0.9505763	0.9614947	0.9952527	0.9514549	2.5157E+01	1.3080E+00
α_2	1.27E-03	3.34E-02	2.25E-02	1.03E-01	4.74E-02	8.8270E-01	2.5582E+01
α_3	2.55E-05	1.61E-02	6.39E-03	6.50E-02	1.20E-03	4.2530E-01	2.6040E+01

Table 22-46: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8764422	0.9452342	0.9525784	0.9888548	0.9361668	3.7493E+01	2.1723E+00
α_2	2.23E-03	2.95E-02	2.20E-02	8.24E-02	4.51E-02	1.1698E+00	3.8496E+01
α_3	5.90E-05	1.29E-02	6.11E-03	4.89E-02	1.83E-02	5.1260E-01	3.9153E+01
α_4	4.44E-05	1.24E-02	5.61E-03	4.75E-02	4.61E-04	4.8990E-01	3.9175E+01

Table 22-47: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8894154	0.9457725	0.9509453	0.9844292	0.9331861	5.3723E+01	3.0803E+00
α_2	2.09E-03	2.28E-02	1.75E-02	6.17E-02	3.37E-02	1.2940E+00	5.5509E+01
α_3	4.72E-04	1.47E-02	9.56E-03	4.67E-02	2.53E-02	8.3750E-01	5.5966E+01
α_4	3.27E-06	6.37E-03	2.06E-03	2.73E-02	7.62E-03	3.6170E-01	5.6442E+01
α_5	8.97E-05	1.03E-02	5.41E-03	3.73E-02	1.85E-04	5.8710E-01	5.6216E+01

Table 22-48: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG=6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8991427	0.9476418	0.9516950	0.9822636	0.9352109	6.9081E+01	3.8168E+00
α_2	1.44E-03	1.70E-02	1.29E-02	4.69E-02	2.32E-02	1.2414E+00	7.1656E+01
α_3	7.74E-04	1.40E-02	9.91E-03	4.14E-02	2.43E-02	1.0237E+00	7.1874E+01
α_4	7.11E-05	8.08E-03	4.24E-03	2.92E-02	1.39E-02	5.8930E-01	7.2309E+01
α_5	5.96E-07	4.24E-03	1.09E-03	1.92E-02	3.30E-03	3.0890E-01	7.2589E+01
α_6	1.21E-04	8.97E-03	5.04E-03	3.11E-02	8.04E-05	6.5350E-01	7.2244E+01

23. BWR Low Pressure Coolant Injection Check Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving check valves in low pressure coolant injection, including RHR check valves in the injection mode, (LPCI) systems at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified three common-cause failure to open events, five common-cause failure to close events, and 15 common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 23-1 and 23-2, respectively. Table 23-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 23-4 through 23-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of BWR LPCI check valves is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 23-10 through 23-24.

2. SYSTEM DESCRIPTION

LPCI is a mode of the residual heat removal (RHR) emergency core cooling system, or a specific separate system in early BWR designs, (ECCS) that serves several functions by operating in different modes:

- Low pressure coolant injection (LPCI) mode - to provide low pressure makeup water to the reactor vessel for core cooling under loss of coolant accident (LOCA) conditions,
- Containment spray mode - to reduce primary containment pressure and temperature following a LOCA, and
- Suppression pool cooling mode - to remove heat from the suppression pool.

Under accident conditions, the LPCI mode is automatically initiated. All other modes require manual system alignment for proper operation. The LPCI mode takes suction from the suppression pool and discharges to the reactor vessel penetrations. The RHR heat exchangers are bypassed in this mode, until manually placed into service. The containment spray mode protects the containment structure from possible over pressurization from steam which might bypass the suppression pool, including system breaks within the containment volume. In this mode water is pumped from the suppression pool through heat exchangers to spray nozzle, usually located high in the containment space. The suppression pool cooling mode is designed to limit the long term bulk temperature rise of the suppression pool water following a design basis LOCA. A closed path from the suppression pool through the RHR loops to the reactor vessel and back to the suppression pool through the break can be maintained for decay heat removal from the core.

A simplified schematic drawing of a typical BWR LPCI system configuration in presented in Figure 23-1.

ALPHA FACTOR AND MGL PARAMETERS
BWR Low Pressure Coolant Injection Check Valves

Table 23-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9172037	0.8447060	0.8367443	0.8411186	0.8410325
α_2	8.28E-02	1.53E-01	8.44E-02	6.25E-02	4.83E-02
α_3		2.50E-03	7.89E-02	5.63E-02	4.37E-02
α_4			0.00E+00	4.01E-02	2.23E-02
α_5				0.0E+00	2.98E-02
α_6					1.49E-02

Table 23-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.17E-01	8.45E-01	8.37E-01	8.41E-01	8.41E-01
Beta	8.28E-02	1.55E-01	1.63E-01	1.59E-01	1.59E-01
Gamma		1.61E-02	4.83E-01	6.07E-01	6.96E-01
Delta			0.00E+00	4.16E-01	6.06E-01
Epsilon				0.00E+00	6.67E-01
Mu					3.33E-01

Table 23-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	3.48	5.21	6.95	8.69	10.43
N_1	1.4441	0.8843	0.8754	0.6248	0.7231
N_2	0.4445	1.1024	0.7891	0.6917	0.6400
N_3		0.0180	0.7377	0.6234	0.5792
N_4			0.0000	0.4444	0.2963
N_5				0.0000	0.3951
N_6					0.1975

Total Number of Independent Failure Events: 11
Total Number of Common-Cause Failure Events: 3

ALPHA FACTOR AND MGL PARAMETERS
BWR Low Pressure Coolant Injection Check Valves

Table 23-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9888835	0.9807538	0.9724399	0.9677596	0.9648915
α_2	1.11E-02	1.81E-02	2.44E-02	2.53E-02	2.42E-02
α_3		1.15E-03	2.91E-03	6.46E-03	9.50E-03
α_4			2.86E-04	4.72E-04	1.32E-03
α_5				1.72E-05	7.42E-05
α_6					2.06E-06

Table 23-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.89E-01	9.81E-01	9.72E-01	9.68E-01	9.65E-01
Beta	1.11E-02	1.93E-02	2.76E-02	3.22E-02	3.51E-02
Gamma		5.96E-02	1.16E-01	2.16E-01	3.10E-01
Delta			8.96E-02	7.03E-02	1.28E-01
Epsilon				3.52E-02	5.45E-02
Mu					2.70E-02

Table 23-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	14.71	22.06	29.41	36.77	44.12
N_1	1.8536	2.3082	2.5435	2.6423	2.7278
N_2	0.1862	0.4497	0.8007	1.0300	1.1755
N_3		0.0285	0.0955	0.2631	0.4612
N_4			0.0094	0.0192	0.0642
N_5				0.0007	0.0036
N_6					0.0001

Total Number of Independent Failure Events: 50
Total Number of Common-Cause Failure Events: 5

ALPHA FACTOR AND MGL PARAMETERS
BWR Low Pressure Coolant Injection Check Valves

Table 23-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9939654	0.9875786	0.9794613	0.9573996	0.9425989
α_2	6.04E-03	1.23E-02	1.99E-02	3.92E-02	4.79E-02
α_3		1.75E-04	6.46E-04	3.42E-03	9.03E-03
α_4			7.34E-06	2.37E-05	5.05E-04
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 23-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.94E-01	9.88E-01	9.80E-01	9.57E-01	9.43E-01
Beta	6.04E-03	1.24E-02	2.05E-02	4.26E-02	5.74E-02
Gamma		1.41E-02	3.18E-02	8.07E-02	1.66E-01
Delta			1.12E-02	6.90E-03	5.30E-02
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 23-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	9.87	14.81	19.74	24.68	29.62
N_1	3.8668	5.5038	6.9656	7.5881	8.1013
N_2	0.0834	0.2519	0.5422	1.3199	1.9157
N_3		0.0036	0.0176	0.1151	0.3612
N_4			0.0002	0.0008	0.0202
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 27
Total Number of Common-Cause Failure Events: 15

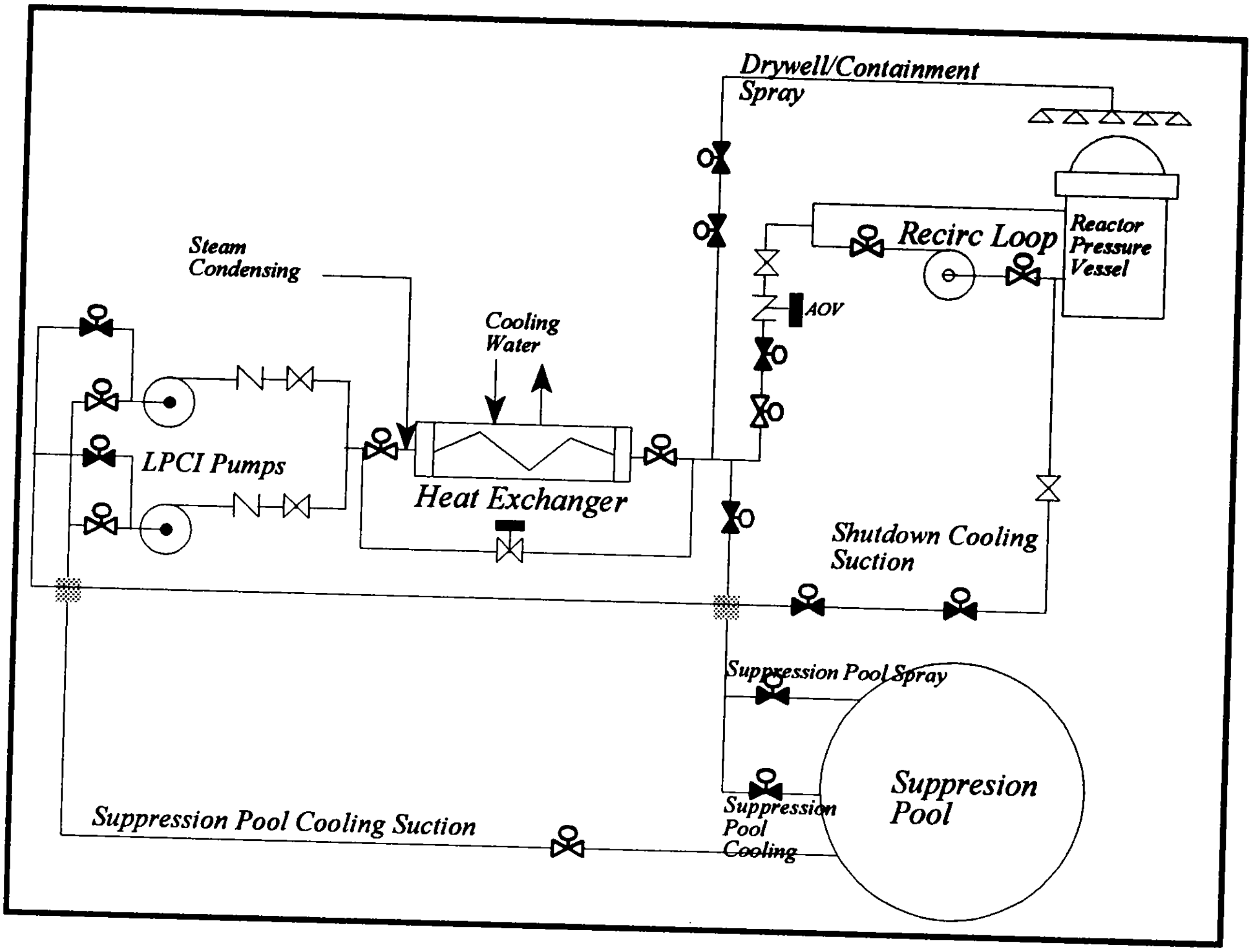

Figure 23-1. BWR low pressure coolant injection system.

3. COMPONENT BOUNDARIES

The main component of a check valve is the valve itself. This component is operated by system pressure overcoming gravity. Typically, there is no capability to manual open, close, or isolate these valves, however, some check valves have manual hand wheels on them (stop-check) and can be manually closed. Other check valves are "air-testable." This should not affect component operation and in some cases the air supply is turned off during operation as a precaution. No power is required for valve operation. Check valves are installed in LPCI systems in the following areas:

- Pump discharge,
- Suppression pool suction, and
- Loop injection.

The function of the check valve is to form a conditional boundary (i.e., one direction) between high pressure and low pressure sections of a system during static conditions. By design, the valve will open to allow flow when the low pressure section has experienced a pressure increase (e.g., pump start). For the purposes of this study, the boundaries will encompass the valve body including internals (e.g. disk, spring), and operators in the cases of air assisted check valves.

4. FAILURE EVENT DEFINITION

Check valve malfunctions are considered to be failures to open or close on demand and failure to stay closed which includes excessive leakage through the valve. Failure modes used to analyze check valve data are:

CC Failure to Open. Examples are:
- Check valve sticks closed,
- Check valve partially opens.

OO Failure to Close. Examples are:
- Check valve sticks closed,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed. In cases where the check valve has been closed for a substantial period of time and is then discovered leaking the failure will be coded as VR.

LPCI check valve failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the LPCI check valves. Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of check valve demand. The exception to this is if a licensee reported that the check valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the check valve from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second LPCI check valve would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another LPCI check valve, the event was identified as a CCF. If, however, the report did not clearly identify that another check valve would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another LPCI check valve operation demand (e.g. the condition was found during inspection, and no check valve demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 23-10 through 23-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of check valve. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
BWR Low Pressure Coolant Injection Check Valves

Table 23-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8218398	0.9404952	0.9585151	0.9974291	0.9172037	1.4454E+01	9.1450E-01
α_2	2.57E-03	5.95E-02	4.15E-02	1.78E-01	8.28E-02	9.1450E-01	1.4454E+01

Table 23-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8087754	0.9172755	0.9290977	0.9852185	0.8447060	2.1294E+01	1.9204E+00
α_2	7.83E-03	6.42E-02	5.20E-02	1.62E-01	1.53E-01	1.4896E+00	2.1725E+01
α_3	3.21E-05	1.86E-02	7.51E-03	7.46E-02	2.50E-03	4.3080E-01	2.2784E+01

Table 23-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8347592	0.9200380	0.9278971	0.9783907	0.8367443	3.2525E+01	2.8268E+00
α_2	3.79E-03	3.80E-02	2.96E-02	1.01E-01	8.44E-02	1.3429E+00	3.4090E+01
α_3	1.49E-03	2.83E-02	2.00E-02	8.35E-02	7.89E-02	1.0030E+00	3.4352E+01
α_4	4.59E-05	1.37E-02	6.15E-03	5.29E-02	0.00E+00	4.8360E-01	3.4868E+01

Table 23-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8599099	0.9272214	0.9327633	0.9755721	0.8411186	4.7357E+01	3.7171E+00
α_2	3.04E-03	2.78E-02	2.19E-02	7.28E-02	6.25E-02	1.4197E+00	4.9654E+01
α_3	1.16E-03	2.03E-02	1.44E-02	5.94E-02	5.63E-02	1.0354E+00	5.0390E+01
α_4	2.08E-04	1.33E-02	7.68E-03	4.54E-02	4.01E-02	6.7800E-01	5.0396E+01
α_5	9.70E-05	1.14E-02	5.97E-03	4.13E-02	0.00E+00	5.8400E-01	5.0490E+01

Table 23-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8724920	0.9300385	0.9343442	0.9728645	0.8410325	6.1625E+01	4.6357E+00
α_2	2.33E-03	2.14E-02	1.68E-02	5.63E-02	4.83E-02	1.4191E+00	6.4842E+01
α_3	1.15E-03	1.69E-02	1.23E-02	4.82E-02	4.37E-02	1.1198E+00	6.5141E+01
α_4	9.33E-05	9.19E-03	4.94E-03	3.28E-02	2.23E-02	6.0900E-01	6.5652E+01
α_5	1.19E-04	9.64E-03	5.34E-03	3.37E-02	2.98E-02	6.3840E-01	6.5622E+01
α_6	4.28E-04	1.28E-02	8.36E-03	4.04E-02	1.49E-02	8.4940E-01	6.5411E+01

ALPHA FACTOR DISTRIBUTIONS
BWR Low Pressure Coolant Injection Check Valves

Table 23-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9155855	0.9754694	0.9859473	0.9996539	0.9888835	2.6094E+01	6.5620E-01
α_2	3.44E-04	2.45E-02	1.41E-02	8.44E-02	1.11E-02	6.5620E-01	2.6094E+01

Table 23-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9152772	0.9687070	0.9760014	0.9971712	0.9807538	3.9568E+01	1.2782E+00
α_2	6.59E-04	2.05E-02	1.33E-02	6.47E-02	1.81E-02	8.3690E-01	4.0090E+01
α_3	2.13E-05	1.08E-02	4.43E-03	4.32E-02	1.15E-03	4.4130E-01	4.0405E+01

Table 23-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9151908	0.9625278	0.9676478	0.9923273	0.9724399	5.6654E+01	2.2056E+00
α_2	2.30E-03	2.30E-02	1.79E-02	6.14E-02	2.44E-02	1.3545E+00	5.7505E+01
α_3	2.89E-06	6.08E-03	1.95E-03	2.62E-02	2.91E-03	3.5810E-01	5.8502E+01
α_4	3.10E-05	8.38E-03	3.80E-03	3.22E-02	2.86E-04	4.9300E-01	5.8367E+01

Table 23-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9182928	0.9594845	0.9632253	0.9878636	0.9677596	7.7454E+01	3.2706E+00
α_2	3.31E-03	2.18E-02	1.80E-02	5.33E-02	2.53E-02	1.7580E+00	7.8967E+01
α_3	1.28E-04	8.36E-03	4.80E-03	2.87E-02	6.46E-03	6.7510E-01	8.0500E+01
α_4	6.03E-08	3.13E-03	5.64E-04	1.51E-02	4.72E-04	2.5280E-01	8.0472E+01
α_5	6.15E-05	7.24E-03	3.77E-03	2.62E-02	1.72E-05	5.8470E-01	8.0140E+01

Table 23-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9215372	0.9583249	0.9613026	0.9849258	0.9648915	9.7320E+01	4.2322E+00
α_2	3.37E-03	1.93E-02	1.62E-02	4.56E-02	2.42E-02	1.9546E+00	9.9598E+01
α_3	5.13E-04	9.87E-03	6.89E-03	2.94E-02	9.50E-03	1.0180E+00	1.0550E+02
α_4	2.56E-06	3.71E-03	1.26E-03	1.57E-02	1.32E-03	3.7690E-01	1.0118E+02
α_5	3.59E-08	2.43E-03	4.17E-04	1.18E-02	7.42E-05	2.4690E-01	1.0131E+02
α_6	8.59E-05	6.42E-03	3.60E-03	2.24E-02	2.06E-06	6.5200E-01	1.0900E+02

ALPHA FACTOR DISTRIBUTIONS
BWR Low Pressure Coolant Injection Check Valves

Table 23-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9148859	0.9767678	0.9881761	0.9998454	0.9939654	2.3267E+01	5.5340E-01
α_2	1.57E-04	2.32E-02	1.18E-02	8.51E-02	6.04E-03	5.5340E-01	2.3267E+01

Table 23-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9164147	0.9711372	0.9792045	0.9982621	0.9875786	3.5514E+01	1.0555E+00
α_2	2.19E-04	1.75E-02	9.78E-03	6.09E-02	1.23E-02	6.3910E-01	3.5930E+01
α_3	1.57E-05	1.14E-02	4.40E-03	4.65E-02	1.75E-04	4.1640E-01	3.6153E+01

Table 23-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9165734	0.9650809	0.9707358	0.9942185	0.9794613	5.1406E+01	1.860E+00
α_2	1.34E-03	2.06E-02	1.50E-02	5.91E-02	1.99E-02	1.0960E+00	5.2170E+01
α_3	2.98E-07	5.26E-03	1.16E-03	2.46E-02	6.46E-04	2.8020E-01	5.2986E+01
α_4	3.03E-05	9.08E-03	4.06E-03	3.52E-02	7.34E-06	4.8380E-01	5.2782E+01

Table 23-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9082788	0.9539587	0.9580131	0.9857574	0.9573996	7.0310E+01	3.3934E+00
α_2	5.18E-03	2.78E-02	2.36E-02	6.46E-02	3.92E-02	2.0479E+00	7.1656E+01
α_3	3.73E-05	7.15E-03	3.43E-03	2.69E-02	3.42E-03	5.2710E-01	7.3176E+01
α_4	2.57E-08	3.18E-03	4.89E-04	1.57E-02	2.37E-05	2.3440E-01	7.3469E+01
α_5	6.69E-05	7.92E-03	4.12E-03	2.87E-02	0.00E+00	5.840E-01	7.3119E+01

Table 23-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9058092	0.9481314	0.9513183	0.9795517	0.9425989	8.8193E+01	4.8247E+00
α_2	7.27E-03	2.90E-02	2.57E-02	6.20E-02	4.79E-02	2.6948E+00	9.0323E+01
α_3	3.83E-04	9.70E-03	6.48E-03	3.00E-02	9.03E-03	9.0180E-01	9.2116E+01
α_4	9.52E-07	3.58E-03	1.03E-03	1.58E-02	5.05E-04	3.3290E-01	9.2685E+01
α_5	3.27E-08	2.62E-03	4.35E-04	1.28E-02	0.00E+00	2.4330E-01	9.2774E+01
α_6	9.37E-05	7.01E-03	3.93E-03	2.44E-02	0.00E+00	6.5190E-01	9.2366E+01

24. PWR Low Pressure Safety Injection Check Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving check valves in low pressure safety injection (LPSI) systems at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failures. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified one common-cause failure to open event, four common-cause failure to close events, and 16 common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 24-1 and 24-2, respectively. Table 24-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 24-4 through 24-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of low pressure safety injection check valves is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 24-10 through 24-24.

2. SYSTEM DESCRIPTION

The low pressure safety injection system (LPSI) is a subsystem of the emergency core cooling (ECCS) that provides emergency coolant injection to maintain reactor coolant inventory and provide adequate long term decay heat removal following a Loss of Coolant Accident (LOCA). The low pressure safety injection function is performed over a relatively long time interval after initiation of the LOCA. The LPSI pumps feed a common header that injects directly into the loop cold legs and can be realigned to inject into the hot legs. The initial suction source for the LPSI pumps is the refueling water storage tank (RWST) which contains enough highly borated water to satisfy the injection needs of the core. During the recirculation phase the pumps can take a suction from the containment sump and supply flow to the loops or to the suction of the safety injection pumps. These pumps also provide a shutdown cooling function. Figure 24-1 illustrates the typical flow path for the LPSI system. The system typically contains two high capacity high pressure centrifugal pumps. The pumps receive power from the IE emergency power system which is backed up by the emergency diesel generators.

The LPSI system is normally in standby. The LPSI pumps are started by the engineered safety features actuation system (ESFAS) or may be manually actuated. A safety injection (SI) signal starts the pumps, aligns the pump suction to the RWST, and completes additional valve lineup changes. The injection phase ends when the RWST reaches the low level setpoint and the system is manually realigned for the recirculation phase.

ALPHA FACTOR AND MGL PARAMETERS
PWR Low Pressure Safety Injection Check Valves

Table 24-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.7930678	0.6800000	0.6451613	0.7142857	0.7500000
α_2	2.07E-01	2.40E-01	1.29E-01	0.00E+0	0.00E+0
α_3		8.00E-02	1.72E-01	1.91E-01	0.00E+0
α_4			5.39E-02	9.51E-02	2.50E-01
α_5				0.00E+0	0.00E+00
α_6					0.00E+00

Table 24-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	7.93E-01	6.80E-01	6.45E-01	7.14E-01	7.50E-01
Beta	2.07E-01	3.20E-01	3.55E-01	2.86E-01	2.50E-01
Gamma		2.50E-01	6.36E-01	1.00E+00	1.00E+00
Delta			2.39E-01	3.33E-01	1.00E+00
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 24-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	1.00	1.50	2.00	2.50	3.00
N_1	0.5330	0.2000	0.0000	0.0000	0.0000
N_2	0.4000	0.6000	0.4000	0.0000	0.0000
N_3		0.2000	0.5330	0.6670	0.0000
N_4			0.1670	0.3330	1.0000
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 3
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
PWR Low Pressure Safety Injection Check Valves

Table 24-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9289102	0.8940886	0.8779394	0.8787685	0.8790286
α_2	7.11E-02	8.04E-02	7.81E-02	5.79E-02	5.36E-02
α_3		2.55E-02	3.07E-02	3.52E-02	2.55E-02
α_4			1.33E-02	2.00E-02	2.29E-02
α_5				8.12E-03	1.38E-02
α_6					5.16E-03

Table 24-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.29E-01	8.94E-01	8.78E-01	8.79E-01	8.79E-01
Beta	7.11E-02	1.06E-01	1.22E-01	1.21E-01	1.21E-01
Gamma		2.41E-01	3.60E-01	5.23E-01	5.57E-01
Delta			3.02E-01	4.44E-01	6.22E-01
Epsilon				2.88E-01	4.53E-01
Mu					2.72E-01

Table 24-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	9.00	13.50	18.00	22.50	27.00
N_1	2.2034	1.8608	1.3245	0.9676	0.5041
N_2	0.8574	1.3818	1.7186	1.5458	1.6776
N_3		0.4378	0.6758	0.9401	0.7974
N_4			0.2923	0.5349	0.7170
N_5				0.2167	0.4318
N_6					0.1613

Total Number of Independent Failure Events: 18
Total Number of Common-Cause Failure Events: 4

ALPHA FACTOR AND MGL PARAMETERS
PWR Low Pressure Safety Injection Check Valves

Table 24-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9547287	0.9126781	0.8715604	0.8576585	0.8461376
α_2	4.53E-02	8.42E-02	1.19E-01	1.03E-01	9.95E-02
α_3		3.09E-03	9.33E-03	3.67E-02	4.01E-02
α_4			1.43E-04	2.19E-03	1.36E-02
α_5				8.19E-06	6.58E-04
α_6					0.00E+00

Table 24-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.55E-01	9.13E-01	8.72E-01	8.58E-01	8.46E-01
Beta	4.53E-02	8.73E-02	1.28E-01	1.42E-01	1.54E-01
Gamma		3.53E-02	7.37E-02	2.74E-01	3.53E-01
Delta			1.51E-02	5.65E-02	2.62E-01
Epsilon				3.72E-03	4.62E-02
Mu					0.00E+00

Table 24-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	5.91	8.87	11.83	14.78	17.74
N_1	4.6050	5.5630	5.8123	6.1557	6.3228
N_2	0.4986	1.3321	2.4082	2.5244	2.8296
N_3		0.0488	0.1888	0.8965	1.1412
N_4			0.0029	0.0535	0.3861
N_5				0.0002	0.0187
N_6					0.0000

Total Number of Independent Failure Events: 17
Total Number of Common-Cause Failure Events: 16

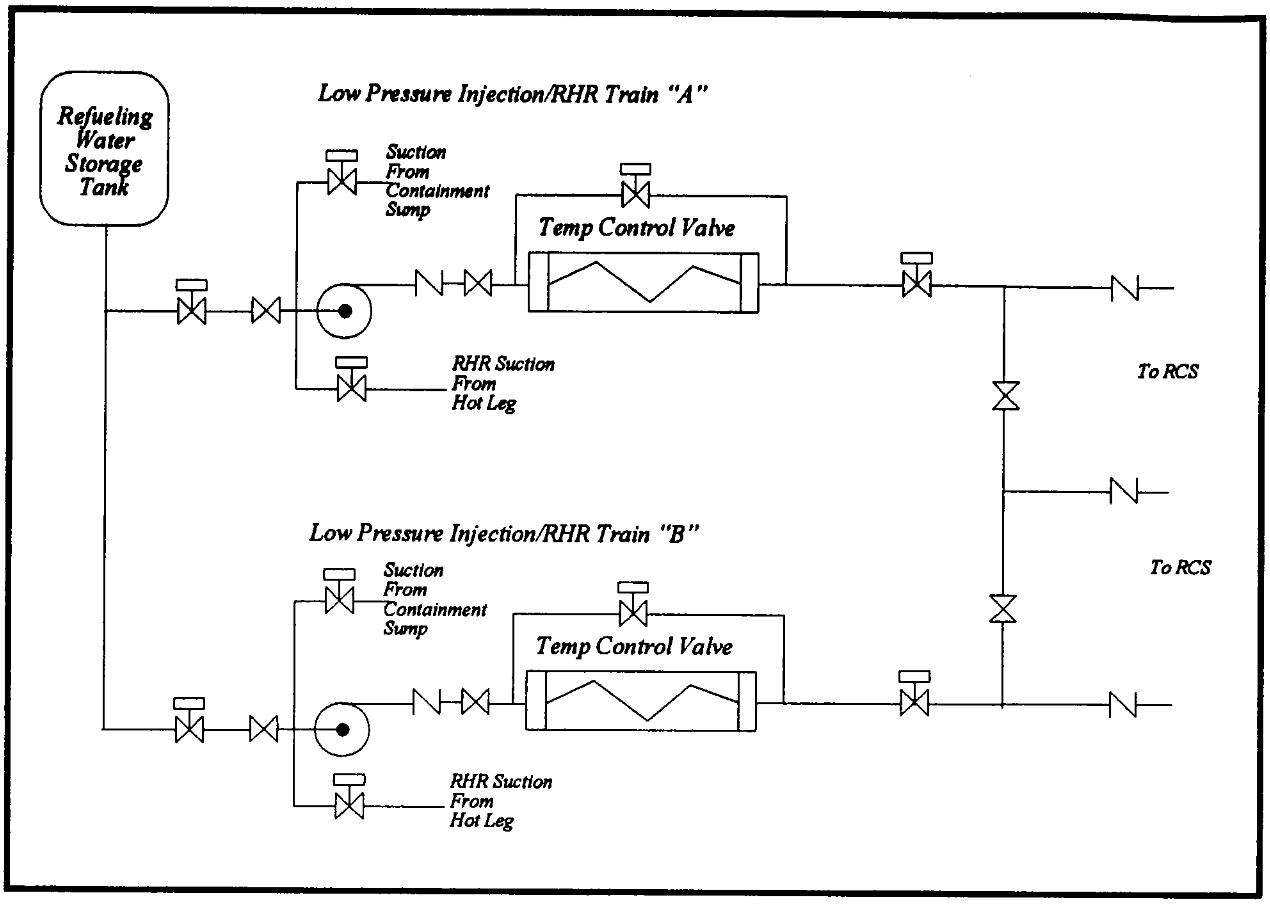

Figure 24-1. PWR low pressure safety injection/residual heat removal.

3. COMPONENT BOUNDARIES

The main component of a check valve is the valve itself. This component is operated by system pressure overcoming gravity. Typically, there is no capability to manually open, close, or isolate these valves, however, some check valves have manual hand wheels or levers (stop-check) and can be manually closed. Other check valves are "air-testable"; which should not affect normal component operation and in some cases the air supply is turned off during operation as a precaution. No power is required for valve operation. Check valves are installed in LPSI systems in the following areas:

- Pump discharge,
- Pump suction,
- Loop injection, and
- System inter- or cross-connection.

The function of the check valve is to form a conditional boundary (i.e., one direction) between high pressure and low pressure sections of a system during static conditions. By design, the valve will open to allow flow when the low pressure section has experienced a pressure increase (e.g., pump start). For the purposes of this study, the boundaries will encompass the valve body including internals (e.g. disk, spring) and operators in the cases of air assisted check valves.

4. FAILURE EVENT DEFINITION

Check valve malfunctions are considered to be failures to open or close on demand and, failure to stay closed which includes excessive leakage through the valve. Examples of the consequences of this failure are increased containment leak rate, interfacing systems LOCA, and system drainage. Failure modes used to analyze check valve data are:

CC Failure to Open. Examples are:
- Check valve sticks closed,
- Check valve partially opens.

OO Failure to Close. Examples are:
- Check valve sticks closed,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed. In cases where the check valve has been closed for a substantial period of time and is then discovered leaking the failure will be coded as VR.

LPSI check valves failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the LPSI check valves. Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of check valve demand. The exception to this is if a licensee reported that the check valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the check valve from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second LPSI check valve would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another LPSI check valve, the event was identified as a CCF. If, however, the report did not clearly identify that another check valve would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another LPSI check valve operation demand (e.g. the condition was found during inspection, and no check valve demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 24-10 through 24-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of check valve. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
PWR Low Pressure Safety Injection Check Valves

Table 24-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7796135	0.9270929	0.9496681	0.9972110	0.7930678	1.1063E+01	8.7000E-01
α_2	2.79E-03	7.29E-02	5.03E-02	2.20E-01	2.07E-01	8.7000E-01	1.1063E+01

Table 24-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7887526	0.9135135	0.9281658	0.9879695	0.6800000	1.690E+01	1.600E+00
α_2	2.80E-03	5.34E-02	3.81E-02	1.56E-01	2.40E-01	9.8720E-01	1.7513E+01
α_3	3.57E-04	3.31E-02	1.83E-02	1.16E-01	8.00E-02	6.1280E-01	1.7887E+01

Table 24-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8216223	0.9175258	0.9270002	0.9809549	0.6451613	2.6700E+01	2.4000E+00
α_2	1.54E-03	3.28E-02	2.28E-02	9.82E-02	1.29E-01	9.5380E-01	2.8146E+01
α_3	7.59E-04	2.73E-02	1.75E-02	8.76E-02	1.72E-01	7.9560E-01	2.8304E+01
α_4	3.03E-04	2.24E-02	1.27E-02	7.73E-02	5.39E-02	6.5060E-01	2.8449E+01

Table 24-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8605568	0.9320086	0.9385659	0.9810034	0.7142857	4.0542E+01	2.9576E+00
α_2	3.41E-04	1.67E-02	1.01E-02	5.57E-02	0.00E+00	7.2800E-01	4.2772E+01
α_3	1.56E-03	2.48E-02	1.80E-02	7.14E-02	1.91E-01	1.0790E+00	4.2421E+01
α_4	9.66E-05	1.30E-02	6.67E-03	4.76E-02	9.51E-02	5.6660E-01	4.2933E+01
α_5	1.14E-04	1.34E-02	7.03E-03	4.85E-02	0.00E+00	5.8400E-01	4.2916E+01

Table 24-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8787236	0.9381118	0.9431881	0.9801221	0.7500000	5.3472E+01	3.5276E+00
α_2	3.49E-04	1.37E-02	8.55E-03	4.45E-02	0.00E+00	7.7910E-01	5.6221E+01
α_3	5.61E-05	9.48E-03	4.66E-03	3.53E-02	0.00E+00	5.4060E-01	5.6459E+01
α_4	2.18E-03	2.30E-02	1.77E-02	6.21E-02	2.50E-01	1.3127E+00	5.5687E+01
α_5	5.36E-08	4.27E-03	7.12E-04	2.08E-02	0.00E+00	2.4330E-01	5.6756E+01
α_6	1.54E-04	1.14E-02	6.44E-03	3.97E-02	0.00E+00	6.5190E-01	5.6348E+01

ALPHA FACTOR DISTRIBUTIONS
PWR Low Pressure Safety Injection Check Valves

Table 24-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.8415788	0.9398288	0.9526759	0.9940046	0.9289102	2.0733E+01	1.3274E+00
α_2	5.99E-03	6.02E-02	4.73E-02	1.58E-01	7.11E-02	1.3274E+00	2.0733E+01

Table 24-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.8332334	0.9210503	0.9294337	0.9801377	0.8940886	3.0561E+01	2.6196E+00
α_2	8.36E-03	5.33E-02	4.46E-02	1.28E-01	8.04E-02	1.7690E+00	3.1412E+01
α_3	8.71E-04	2.56E-02	1.69E-02	8.03E-02	2.55E-02	8.5060E-01	3.2330E+01

Table 24-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.8436157	0.9169640	0.9227250	0.9705844	0.8779394	4.4025E+01	3.9867E+00
α_2	1.01E-02	4.73E-02	4.12E-02	1.06E-01	7.81E-02	2.2724E+00	4.5739E+01
α_3	8.68E-04	1.96E-02	1.34E-02	5.93E-02	3.07E-02	9.3840E-01	4.7073E+01
α_4	4.08E-04	1.62E-02	1.01E-02	5.26E-02	1.33E-02	7.7590E-01	4.7236E+01

Table 24-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.8622430	0.9221184	0.9263194	0.9676232	0.8787685	6.1510E+01	5.1951E+00
α_2	7.21E-03	3.41E-02	2.95E-02	7.66E-02	5.79E-02	2.2738E+00	6.4431E+01
α_3	2.02E-03	2.03E-02	1.57E-02	5.41E-02	3.52E-02	1.3521E+00	6.5353E+01
α_4	2.81E-04	1.15E-02	7.14E-03	3.77E-02	2.00E-02	7.6850E-01	6.5937E+01
α_5	3.34E-04	1.20E-02	7.60E-03	3.87E-02	8.12E-03	8.0700E-01	6.5904E+01

Table 24-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.8731394	0.9251062	0.9284559	0.9656163	0.8790286	7.7976E+01	6.3127E+00
α_2	6.67E-03	2.92E-02	2.55E-02	6.41E-02	5.36E-02	2.4567E+00	8.1832E+01
α_3	1.55E-03	1.59E-02	1.22E-02	4.27E-02	2.55E-02	1.3380E+00	8.2951E+01
α_4	6.81E-04	1.22E-02	8.63E-03	3.60E-02	2.29E-02	1.0297E+00	8.3259E+01
α_5	1.23E-04	8.01E-03	4.60E-03	2.75E-02	1.38E-02	6.7510E-01	8.3614E+01
α_6	2.81E-04	9.65E-03	6.14E-03	3.10E-02	5.16E-03	8.1320E-01	8.3476E+01

ALPHA FACTOR DISTRIBUTIONS
PWR Low Pressure Safety Injection Check Valves

Table 24-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8637156	0.9539061	0.9674533	0.9977174	0.9547287	2.045E+01	9.6860E-01
α_2	2.29E-03	4.61E-02	3.26E-02	1.36E-01	4.53E-02	9.6860E-01	2.045E+01

Table 24-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8464995	0.9314482	0.9403577	0.9858633	0.9126781	2.9633E+01	2.1809E+00
α_2	8.15E-03	5.40E-02	4.49E-02	1.31E-01	8.42E-02	1.7193E+00	3.0950E+01
α_3	3.76E-05	1.45E-02	6.25E-03	5.70E-02	3.09E-03	4.6160E-01	3.1352E+01

Table 24-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8403530	0.9156631	0.9216262	0.9705513	0.8715604	4.2342E+01	3.8999E+00
α_2	1.79E-02	6.41E-02	5.78E-02	1.32E-01	1.19E-01	2.9620E+00	4.3280E+01
α_3	2.20E-05	9.76E-03	4.09E-03	3.87E-02	9.33E-03	4.5140E-01	4.5791E+01
α_4	3.63E-05	1.05E-02	4.74E-03	4.06E-02	1.43E-04	4.8650E-01	4.5755E+01

Table 24-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8526741	0.9156624	0.9199499	0.9639828	0.8576585	5.8978E+01	5.4322E+00
α_2	1.51E-02	5.05E-02	4.59E-02	1.02E-01	1.03E-01	3.2524E+00	6.1158E+01
α_3	1.90E-03	2.03E-02	1.56E-02	5.49E-02	3.67E-02	1.3085E+00	6.3102E+01
α_4	3.19E-07	4.46E-03	1.02E-03	2.07E-02	2.19E-03	2.8710E-01	6.4123E+01
α_5	7.68E-05	9.07E-03	4.73E-03	3.28E-02	8.19E-06	5.8420E-01	6.3826E+01

Table 24-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8595857	0.9152339	0.9186235	0.9592854	0.8461376	7.4535E+01	6.9032E+00
α_2	1.44E-02	4.43E-02	4.06E-02	8.69E-02	9.95E-02	3.6087E+00	7.7830E+01
α_3	2.94E-03	2.07E-02	1.69E-02	5.13E-02	4.01E-02	1.6818E+00	7.9756E+01
α_4	1.50E-04	8.58E-03	5.03E-03	2.91E-02	1.36E-02	6.9880E-01	8.0739E+01
α_5	9.11E-08	3.22E-03	6.21E-04	1.54E-02	6.58E-04	2.6200E-01	8.1176E+01
α_6	1.07E-04	8.01E-03	4.49E-03	2.79E-02	0.00E+00	6.5190E-01	8.0786E+01

25. PWR Auxiliary Feedwater Check Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving check valves in auxiliary feedwater (AFW) systems at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified five common-cause failure to open events, fifteen common-cause failure to close events, and 39 common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 25-1 and 25-2, respectively. Table 25-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 25-4 through 25-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of PWR auxiliary feedwater check valves is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1\text{-}\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 25-10 through 25-24.

2. SYSTEM DESCRIPTION

The auxiliary feedwater system provides a source of feedwater to the steam generators to remove decay heat from the reactor coolant system (RCS) when: (a) the main feedwater system is not available, and (b) RCS pressure is too high to permit heat removal by the residual heat removal (RHR) system. The AFW system is comprised of two, three, or four flow trains, each with an AFP, including the associated pump driver. The combinations of pump-driver sets range from all motor-driven to all turbine-driven AFW pumps and, in a few cases, diesel-driven pumps. Most of the designs incorporate a combination of two full-capacity motor-driven and one double capacity turbine-driven pump. There are no plants with more than one diesel-driven AFP, so CCF analysis of diesel-driven pumps is not applicable. The motor-driven pumps are supplied power from the IE class power system with backup power available from the IE emergency diesel generators (EDG). The water supply for the system is from the condensate storage tank (CST) with a backup source of water (untreated) available from the service water system.

The AFW system is normally in standby. The motor-driven pumps start on one of the following conditions: a safety injection (SI) signal, a low-low level in any steam generator, loss of both main feedwater pumps (MFP), a loss of off-site power (LOSP) or manual initiation. The turbine-driven pump will start on either a low-low level in more than one steam generator or a loss of off-site power. Feedwater flow to the steam generators is controlled from the main control room by air, motor, or hydraulically operated valves. Motor-driven pump run out is controlled by an air or hydraulically controlled regulator valve on the pump discharge. The turbine-driven pump steam supply is controlled by air or hydraulically operated valves. Figure 25-1 shows a typical auxiliary feedwater system.

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Check Valves

Table 25-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
α_1	0.8245484	0.8524372	0.8582592	0.8796748	0.9230306
α_2	1.76E-01	3.30E-02	5.17E-02	2.74E-02	1.95E-02
α_3		1.15E-01	1.62E-04	1.88E-02	1.68E-02
α_4			8.99E-02	1.48E-05	8.18E-03
α_5				7.41E-02	3.26E-06
α_6					3.26E-02

Table 25-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
1-Beta	8.25E-01	8.52E-011	8.58E-01	8.80E-01	9.23E-01
Beta	1.76E-01	1.48E-01	1.42E-01	1.20E-01	7.70E-02
Gamma		7.76E-01	6.36E-01	7.72E-01	7.47E-01
Delta			9.98E-01	7.97E-01	7.09E-01
Epsilon				1.00E+01	7.99E-01
Mu					1.00E+01

Table 25-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
Adj. Ind. Events	9.17	13.75	18.33	22.92	27.50
N_1	1.1404	1.1431	0.7582	0.8277	0.8543
N_2	2.1939	0.5771	1.1487	0.7397	0.5984
N_3		2.0010	0.0036	0.5082	0.5146
N_4			2.0001	0.0004	0.2513
N_5				2.0000	0.0001
N_6					1.0000

Total Number of Independent Failure Events: 22
Total Number of Common-Cause Failure Events: 5

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Check Valves

Table 25-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9297050	0.9182645	0.9095029	0.9083575	0.9064307
α_2	7.03E-02	4.97E-02	5.07E-02	4.72E-02	4.74E-02
α_3		3.21E-02	1.78E-02	2.21E-02	1.70E-02
α_4			2.21E-02	7.19E-03	1.54E-02
α_5				1.52E-02	1.17E-03
α_6					1.27E-02

Table 25-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.30E-01	9.18E-01	9.10E-01	9.08E-01	9.06E-01
Beta	7.03E-02	8.17E-02	9.05E-02	9.16E-02	9.36E-02
Gamma		3.92E-01	4.40E-01	4.85E-01	4.94E-01
Delta			5.53E-01	5.03E-01	6.33E-01
Epsilon				6.78E-01	4.73E-01
Mu					9.15E-01

Table 25-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	22.67	34.00	45.33	56.67	68.00
N_1	5.0750	5.4570	5.3907	5.1103	4.6419
N_2	2.0978	2.1347	2.8252	3.2095	3.7955
N_3		1.3774	0.9921	1.5028	1.3593
N_4			1.2295	0.4893	1.2345
N_5				1.0313	0.0938
N_6					1.0156

Total Number of Independent Failure Events: 68
Total Number of Common-Cause Failure Events: 15

ALPHA FACTOR AND MGL PARAMETERS
PWR Auxiliary Feedwater Check Valves

Table 25-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9808694	0.9675906	0.9569199	0.9507171	0.9465537
α_2	1.91E-02	2.95E-02	3.53E-02	3.67E-02	3.60E-02
α_3		2.90E-03	7.03E-03	1.08E-02	1.37E-02
α_4			7.81E-04	1.75E-03	3.22E-03
α_5				9.24E-05	5.22E-04
α_6					1.17E-05

Table 25-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.81E-01	9.68E-01	9.57E-01	9.51E-01	9.47E-01
Beta	1.91E-02	3.24E-02	4.31E-02	4.93E-02	5.35E-02
Gamma		8.94E-02	1.81E-01	2.56E-01	3.27E-01
Delta			9.99E-02	1.46E-01	2.15E-01
Epsilon				5.02E-02	1.42E-01
Mu					2.20E-02

Table 25-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	36.54	54.81	73.08	91.35	109.63
N_1	10.4562	13.5644	15.9036	17.7253	19.3742
N_2	0.9166	2.0855	3.2795	4.2088	4.9013
N_3		0.2047	0.6539	1.2343	1.8716
N_4			0.0726	0.2005	0.4384
N_5				0.0106	0.0712
N_6					0.0016

Total Number of Independent Failure Events: 112
Total Number of Common-Cause Failure Events: 39

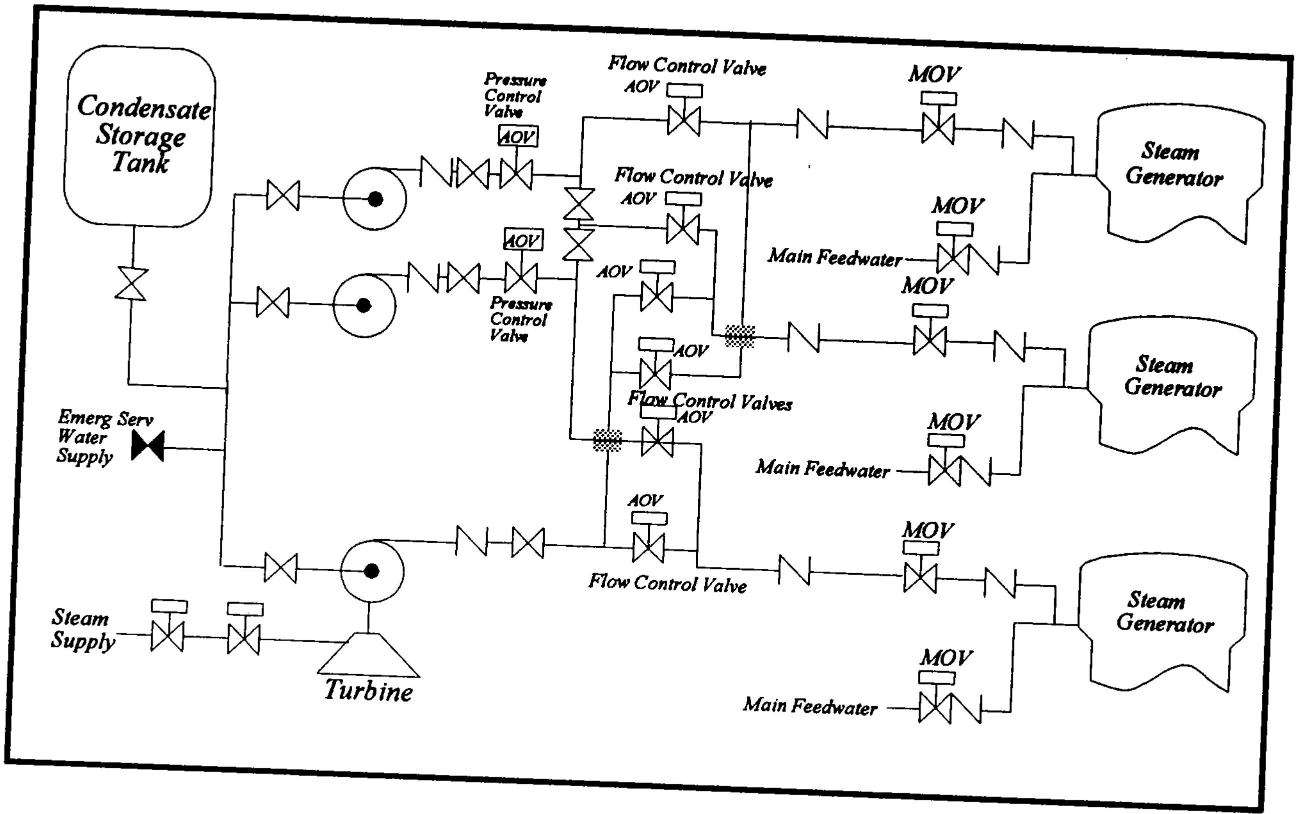

Figure 25-1. Typical auxiliary feedwater system.

3. COMPONENT BOUNDARIES

The main component of a check valve is the valve itself. This component is operated by system pressure overcoming gravity. Typically, there is no capability to manually open, close, or isolate these valves, however, some check valves have manual hand wheels or levers (stop-check) and can be manually closed. Other check valves are "air-testable" which should not affect normal component operation and in some cases the air supply is turned off during operation as a precaution. No power is required for valve operation. Check valves are installed in AFW systems in the following areas:

- Pump discharge,
- Pump suction,
- System inter- or cross-connection, and
- Pump turbine steam inlet.

The function of the check valve is to form a conditional boundary (i.e., one direction) between high pressure and low pressure sections of a system during static conditions. By design, the valve will open to allow flow when the low pressure section has experienced a pressure increase (e.g., pump start). For the purposes of this study, the boundaries will encompass the valve body including internals (e.g. disk, spring) and operators in the cases of air assisted check valves.

4. FAILURE EVENT DEFINITION

Check valve malfunctions are considered to be failures to open or close on demand, and failure to stay closed, including excessive leakage through the valve. Examples of the consequences of these failures are vapor binding AFW pumps, over pressurization of pump suction piping, and system drainage. Failure modes used to analyze check valve data are:

CC Failure to Open. Examples are:
- Check valve sticks closed,
- Check valve partially opens.

OO Failure to Close. Examples are:
- Check valve sticks closed,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed. In cases where the check valve has been closed for a substantial period of time and is then discovered leaking the failure will be coded as VR.

AFW check valve failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the AFW check valves. Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of check valve demand. The exception to this is if a licensee reported that the check valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the check valve from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second AFW check valve would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another AFW check valve, the event was identified as a CCF. If, however, the report did not clearly identify that another check valve would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another AFW check valve operation demand (e.g. the condition was found during inspection, and no check valve demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 25-10 through 25-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of check valve. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Check Valves

Table 25-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7554818	0.8816249	0.8929177	0.9690046	0.8245484	1.9840E+01	2.6639E+00
α_2	3.10E-02	1.18E-01	1.07E-01	2.45E-01	1.76E-01	2.6639E+00	1.9840E+01

Table 25-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8030019	0.8990741	0.9069976	0.9679880	0.8524372	3.093E+01	3.3781E+00
α_2	1.39E-03	2.88E-02	2.01E-02	8.61E-02	3.30E-02	9.6430E-01	3.2507E+01
α_3	1.67E-02	7.21E-02	6.37E-02	1.56E-01	1.15E-01	2.4138E+00	3.1057E+01

Table 25-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8314571	0.9077039	0.9133202	0.9647192	0.8582592	4.3788E+01	4.4524E+00
α_2	5.17E-03	3.53E-02	2.91E-02	8.67E-02	5.17E-02	1.7025E+00	4.6538E+01
α_3	1.86E-07	5.52E-03	1.10E-03	2.62E-02	1.62E-04	2.6620E-01	4.7974E+01
α_4	1.21E-02	5.15E-02	4.54E-02	1.12E-01	8.99E-02	2.4837E+00	4.5757E+01

Table 25-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8626103	0.9222953	0.9264796	0.9676620	0.8796748	6.1790E+01	5.2059E+00
α_2	2.52E-03	2.19E-02	1.74E-02	5.69E-02	2.74E-02	1.4677E+00	6.5528E+01
α_3	5.75E-04	1.37E-02	9.29E-03	4.21E-02	1.88E-02	9.2020E-01	6.6076E+01
α_4	2.77E-08	3.49E-03	5.35E-04	1.73E-02	1.48E-05	2.3400E-01	6.6762E+01
α_5	9.35E-03	3.86E-02	3.41E-02	8.32E-02	7.41E-02	2.5840E+00	6.4412E+01

Table 25-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8944739	0.9415658	0.9450570	0.9767100	0.9230306	7.8826E+01	4.8920E+00
α_2	1.69E-03	1.65E-02	1.28E-02	4.38E-02	1.95E-02	1.3775E+00	8.2341E+01
α_3	7.45E-04	1.26E-02	8.99E-03	3.68E-02	1.68E-02	1.0552E+00	8.2663E+01
α_4	4.85E-05	6.74E-03	3.41E-03	2.47E-02	8.18E-03	5.6400E-01	8.3154E+01
α_5	3.65E-08	2.91E-03	4.84E-04	1.42E-02	3.26E-06	2.4340E-01	8.3475E+01
α_6	2.73E-03	1.97E-02	1.61E-02	4.93E-02	3.26E-02	1.6519E+00	8.2066E+01

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Check Valves

Table 25-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8622159	0.9355517	0.9427487	0.9842367	0.9297050	3.7275E+01	2.5678E+00
α_2	1.58E-02	6.45E-02	5.73E-02	1.38E-01	7.03E-02	2.5678E+00	3.7275E+01

Table 25-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8644844	0.9268752	0.9316775	0.9728483	0.9182645	5.4657E+01	4.3121E+00
α_2	1.01E-02	4.28E-02	3.77E-02	9.28E-02	4.97E-02	2.5219E+00	5.6447E+01
α_3	4.76E-03	3.04E-02	2.52E-02	7.36E-02	3.21E-02	1.7902E+00	5.7179E+01

Table 25-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8687897	0.9223802	0.9258117	0.9642364	0.9095029	7.5421E+01	6.3468E+00
α_2	1.27E-02	4.13E-02	3.76E-02	8.26E-02	5.07E-02	3.3790E+00	7.8389E+01
α_3	1.32E-03	1.53E-02	1.16E-02	4.22E-02	1.78E-02	1.2547E+00	8.0513E+01
α_4	3.07E-03	2.10E-02	1.72E-02	5.17E-02	2.21E-02	1.7131E+00	8.055E+001

Table 25-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8784432	0.9241708	0.9267808	0.9609733	0.9083575	9.9822E+01	8.1905E+00
α_2	1.25E-02	3.65E-02	3.36E-02	7.01E-02	4.72E-02	3.9375E+00	1.0408E+02
α_3	3.02E-003	1.77E-002	1.49E-002	4.23E-002	2.21E-002	1.9148E+00	1.0610E+02
α_4	1.32E-04	6.69E-03	3.99E-03	2.24E-02	7.19E-03	7.2290E-01	1.0729E+02
α_5	2.00E-03	1.50E-02	1.21E-02	3.77E-02	1.52E-02	1.6153E+00	1.0640E+02

Table 25-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8839160	0.9246914	0.9268120	0.9582202	0.9064307	1.2311E+02	1.0260E+01
α_2	1.30E-02	3.44E-02	3.21E-02	6.36E-02	4.74E-02	4.5746E+00	1.2856E+02
α_3	2.40E-03	1.43E-02	1.19E-02	3.42E-02	1.70E-02	1.8999E+00	1.3124E+02
α_4	1.45E-03	1.16E-02	9.28E-03	2.98E-02	1.54E-02	1.5472E+00	1.3159E+02
α_5	7.45E-07	2.53E-03	7.41E-04	1.11E-02	1.17E-03	3.3710E-01	1.3280E+02
α_6	1.75E-03	1.25E-02	1.02E-02	3.13E-02	1.27E-02	1.6675E+00	1.3147E+02

ALPHA FACTOR DISTRIBUTIONS
PWR Auxiliary Feedwater Check Valves

Table 25-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9367023	0.9760571	0.9812937	0.9975002	0.9808694	5.6526E+01	1.3866E+00
α_2	2.50E-03	2.39E-02	1.87E-02	6.33E-02	1.91E-02	1.3866E+00	5.6526E+01

Table 25-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9268172	0.9643428	0.9678577	0.9898356	0.9675906	8.3574E+01	3.0902E+00
α_2	6.57E-03	2.85E-02	2.50E-02	6.26E-02	2.95E-02	2.4727E+00	8.4192E+01
α_3	7.65E-05	7.13E-03	3.85E-03	2.53E-02	2.90E-03	6.1750E-01	8.6047E+01

Table 25-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9206623	0.9554065	0.9579374	0.9814926	0.9569199	1.1368E+02	5.3060E+00
α_2	1.08E-02	3.22E-02	2.96E-02	6.24E-02	3.53E-02	3.8333E+00	1.1515E+02
α_3	3.17E-04	7.70E-03	5.18E-03	2.37E-02	7.03E-03	9.1650E-01	1.1807E+02
α_4	3.15E-05	4.67E-03	2.34E-03	1.73E-02	7.81E-04	5.5620E-01	1.1843E+02

Table 25-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9193650	0.9508065	0.9527382	0.9756430	0.9507171	1.4712E+02	7.6118E+00
α_2	1.26E-02	3.19E-02	2.99E-02	5.80E-02	3.67E-02	4.9368E+00	1.4980E+02
α_3	1.46E-03	1.06E-02	8.62E-03	2.67E-02	1.08E-02	1.6463E+00	1.5309E+02
α_4	4.95E-06	2.81E-03	1.12E-03	1.13E-02	1.75E-03	4.3410E-01	1.5430E+02
α_5	3.49E-05	3.84E-03	2.02E-03	1.39E-02	9.24E-05	5.9460E-01	1.5414E+02

Table 25-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9193082	0.9481663	0.9497370	0.9716516	0.9465537	1.7948E+02	9.8117E+00
α_2	1.29E-02	3.00E-02	2.84E-02	5.28E-02	3.60E-02	5.6804E+00	1.8361E+02
α_3	2.83E-03	1.27E-02	1.11E-02	2.84E-02	1.37E-02	2.4122E+00	1.8688E+02
α_4	8.88E-05	3.97E-03	2.41E-03	1.31E-02	3.22E-03	7.5110E-01	1.8854E+02
α_5	2.72E-07	1.66E-03	4.38E-04	7.48E-03	5.22E-04	3.1450E-01	1.8898E+02
α_6	4.64E-05	3.45E-03	1.93E-03	1.20E-02	1.17E-05	6.5350E-01	1.8864E+02

26. BWR High Pressure Coolant Injection/Reactor Core Isolation Cooling Check Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving check valves in high pressure coolant injection (HPCI) and reactor core isolation cooling (RCIC) systems at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) event reports (LERs) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified one common-cause failure to open events, one common-cause failure to close events, and 13 common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Table 26-1 and 26-2, respectively. Table 26-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 26-4 through 26-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of for high pressure coolant injection check valves is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in tables 26-10 Through 26-24.

2. SYSTEM DESCRIPTION

BWRs can have HPCI and RCIC systems or only a HPCI system (if an Isolation Condenser is present). Both the HPCI and the RCIC are single train systems, and are consequently not subject to CCF events by themselves. This analysis combined the failures of check valves across the system boundaries to identify CCF events.

The HPCI system provides high volume, high pressure makeup water to the reactor pressure vessel (RPV) in the event of a small break LOCA that does not result in a rapid depressurization of the reactor vessel. The HPCI system consists of a turbine driven pump, system piping, valves, and controls. The HPCI system is normally in standby, aligned to take suction from the condensate storage tank (CST), but suction automatically switches from the CST to the suppression pool upon low CST level or high suppression pool water level. The HPCI system automatically starts in response to decreasing RPV water level and is injected into the reactor via the feedwater header. HPCI serves as the primary source of makeup if RCS pressure remains high. Steam to drive the HPCI turbine is routed from main steam. Figure 26-1 shows a typical HPCI System.

The RCIC system provides low volume, high pressure makeup water to the RPV for core cooling when the main steam lines are isolated or the condensate/feedwater system is not available. The RCIC system consists of a turbine driven pump, system piping, valves, and controls. The RCIC system is normally in standby and aligned to take a suction on the CST, but suction automatically switches from the CST to the suppression pool upon low CST level or high suppression pool water level. The RCIC system automatically starts in response to decreasing RPV water level and is injected into the RPV via the feedwater line. Steam to drive the RCIC turbine is routed from main steam. The RCIC system is similar to the HPCI system in terms of components and configuration.

ALPHA FACTOR AND MGL PARAMETERS
BWR High Pressure Coolant Injection/Reactor Core Isolation Cooling Check Valves

Table 26-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9473684	0.9642857	0.9729730	0.9782609	0.9818182
α_2	5.26E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
α_3		3.57E-02	0.00E+00	0.00E+00	0.00E+00
α_4			2.70E-02	0.00E+00	0.00E+00
α_5				2.17E-02	0.00E+00
α_6					1.82E-02

Table 26-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.47E-01	9.64E-01	9.73E-01	9.78E-01	9.82E-01
Beta	5.26E-02	3.57E-02	2.70E-02	2.17E-02	1.82E-02
Gamma		1.00E+00	1.00E+00	1.00E+00	1.00E+00
Delta			1.00E+00	1.00E+00	1.00E+00
Epsilon				1.00E+00	1.00E+00
Mu					1.00E+00

Table 26-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	18.00	27.00	36.00	45.00	54.00
N_1	0.0000	0.0000	0.0000	0.0000	0.0000
N_2	1.0000	0.0000	0.0000	0.0000	0.0000
N_3		1.0000	0.0000	0.0000	0.0000
N_4			1.0000	0.0000	0.0000
N_5				1.0000	0.0000
N_6					1.0000

Total Number of Independent Failure Events: 18
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
BWR High Pressure Coolant Injection/Reactor Core Isolation Cooling Check Valves

Table 26-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9756098	0.9836066	0.9876543	0.9900990	0.9917355
α_2	2.44E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
α_3		1.64E-02	0.00E+00	0.00E+00	0.00E+00
α_4			1.24E-02	0.00E+00	0.00E+00
α_5				9.90E-03	0.00E+00
α_6					8.26E-03

Table 26-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.76E-01	9.84E-01	9.88E-01	9.90E-01	9.92E-01
Beta	2.44E-02	1.64E-02	1.24E-02	9.90E-03	8.26E-03
Gamma		1.00E+00	1.00E+00	1.00E+00	1.00E+00
Delta			1.00E+00	1.00E+00	1.00E+00
Epsilon				1.00E+00	1.00E+00
Mu					1.00E+00

Table 26-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	40.00	60.00	80.00	100.00	120.00
N_1	0.0000	0.0000	0.0000	0.0000	0.0000
N_2	1.0000	0.0000	0.0000	0.0000	0.0000
N_3		1.0000	0.0000	0.0000	0.0000
N_4			1.0000	0.0000	0.0000
N_5				1.0000	0.0000
N_6					1.0000

Total Number of Independent Failure Events: 40
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
BWR High Pressure Coolant Injection/Reactor Core Isolation Cooling Check Valves

Table 26-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9334588	0.8831130	0.8611957	0.8537604	0.8536341
α_2	6.65E-02	9.56E-02	8.99E-02	7.57E-02	6.16E-02
α_3		2.13E-02	4.09E-02	4.82E-02	4.71E-02
α_4			8.02E-03	1.92E-02	2.69E-02
α_5				3.28E-03	9.40E-03
α_6					1.39E-03

Table 26-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.34E-01	8.83E-01	8.61E-01	8.54E-01	8.54E-01
Beta	6.65E-02	1.17E-01	1.39E-01	1.46E-01	1.46E-01
Gamma		1.82E-01	3.52E-01	4.83E-01	5.79E-01
Delta			1.64E-01	3.18E-01	4.45E-01
Epsilon				1.46E-01	2.86E-01
Mu					1.29E-01

Table 26-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	10.30	15.45	20.60	25.75	30.89
N_1	4.3806	4.2330	3.8608	3.4936	3.1910
N_2	1.0465	2.1304	2.5536	2.5917	2.4588
N_3		0.4748	1.1610	1.6491	1.8803
N_4			0.2279	0.6560	1.0739
N_5				0.1123	0.3752
N_6					0.0554

Total Number of Independent Failure Events: 19
Total Number of Common-Cause Failure Events: 13

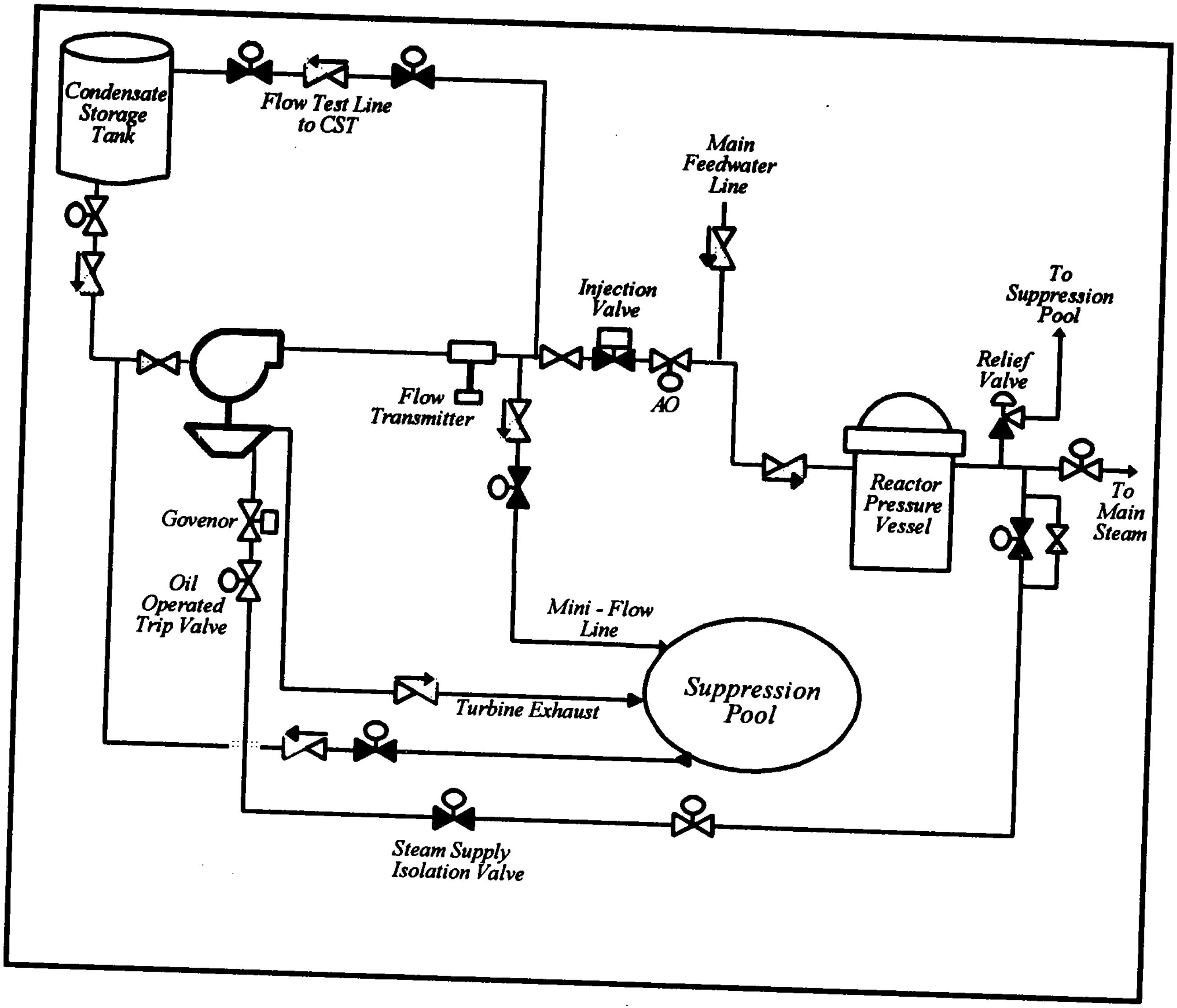

Figure 26-1. High pressure coolant injection/reactor core isolation cooling system.

3. COMPONENT BOUNDARIES

The main component of a check valve is the valve itself. This component is operated by system pressure overcoming gravity. Typically, there is no capability to manually open, close, or isolate these valves however, some check valves have manual hand wheels or levers (stop-check) and can be manually closed. Other check valves are "air-testable" which should not affect normal component operation and in some cases the air supply is turned off during operation as a precaution. No power is required for valve operation. Check valves are installed in HPCI/RCIC systems in the following areas:

- Pump discharge,
- Pump suction,
- Loop injection,
- System inter- or cross-connection, and
- Pump turbine steam inlet.

The function of the check valve is to form a conditional boundary (i.e., one direction) between high pressure and low pressure sections of a system during static conditions. By design, the valve will open to allow flow when the low pressure section has experienced a pressure increase (e.g., pump start). For the purposes of this study, the boundaries will encompass the valve body including internals (e.g. disk, springs) and operators in the cases of air assisted check valves.

4. FAILURE EVENT DEFINITION

Check valve malfunctions are considered to be failures to open or close on demand and failure to stay closed which includes excessive leakage through the valve. Failure modes used to analyze check valve data are:

CC Failure to Open - Examples are:
- Check valve sticks closed,
- Check valve partially opens.

OO Failure to Close - Examples are:
- Check valve sticks closed,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed - In cases where the check valve has been closed for a substantial period of time and is then discovered leaking the failure will be coded as VR.

HPCI/RCIC check valve failures that occurred during testing are included with the failures that occurred during plant transients requiring operation of the HPCI/RCIC check valves. Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of check valve demand. The exception to this is if a licensee reported that the check valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the check valve from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second HPCI/RCIC check valve would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another HPCI/RCIC check valve, the event was identified as a CCF. If, however, the report did not clearly identify that another check valve would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another HPCI/RCIC check valve operation demand (e.g. the condition was found during inspection, and no check valve demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 26-10 through 26-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of check valves. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
BWR High Pressure Coolant Injection/Reactor Core Isolation Cooling Check Valves

Table 26-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8703398	0.9493104	0.9593096	0.9940119	0.9473684	2.7530E+01	1.4700E+00
α_2	5.99E-03	5.07E-02	4.07E-02	1.30E-01	5.26E-02	1.4700E+00	2.7530E+01

Table 26-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9015232	0.9590909	0.9658571	0.9934920	0.9642857	4.2200E+01	1.8000E+00
α_2	7.42E-06	8.80E-03	3.12E-03	3.69E-02	0.00E+00	3.8720E-01	4.3613E+01
α_3	3.49E-03	3.21E-02	2.53E-02	8.40E-02	3.57E-02	1.4128E+00	4.2587E+01

Table 26-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9183807	0.9634920	0.9682943	0.9921767	0.9729730	6.0700E+01	2.3000E+00
α_2	5.83E-05	8.79E-03	4.40E-03	3.24E-02	0.00E+00	5.5380E-01	6.2446E+01
α_3	1.21E-07	4.17E-03	8.10E-04	1.99E-02	0.00E+00	2.6260E-01	6.2737E+01
α_4	2.76E-03	2.36E-02	1.87E-02	6.09E-02	2.70E-02	1.4836E+00	6.1516E+01

Table 26-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9284992	0.9656091	0.9691633	0.9905682	0.9782609	8.3042E+01	2.9576E+00
α_2	1.71E-04	8.47E-03	5.08E-03	2.83E-02	0.00E+00	7.2800E-01	8.5272E+01
α_3	6.09E-06	4.79E-03	1.81E-03	1.97E-02	0.00E+00	4.1200E-01	8.5588E+01
α_4	2.11E-08	2.72E-03	4.14E-04	1.34E-02	0.00E+00	2.3360E-01	8.5766E+01
α_5	2.39E-03	1.84E-02	1.48E-02	4.67E-02	2.17E-02	1.5840E+00	8.4416E+01

Table 26-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9352785	0.9673363	0.9701802	0.9896582	0.9818182	1.0447E+02	3.5276E+00
α_2	1.83E-04	7.21E-03	4.49E-03	2.35E-02	0.00E+00	7.7910E-01	1.0722E+02
α_3	2.94E-05	5.01E-03	2.45E-03	1.87E-02	0.00E+00	5.4060E-01	1.0746E+02
α_4	4.52E-07	2.90E-03	7.58E-04	1.31E-02	0.00E+00	3.1270E-01	1.0769E+02
α_5	2.81E-08	2.25E-03	3.74E-04	1.10E-02	0.00E+00	2.4330E-01	1.0775E+02
α_6	2.11E-03	1.53E-02	1.24E-02	3.83E-02	1.82E-02	1.6519E+00	1.0635E+02

ALPHA FACTOR DISTRIBUTIONS
BWR High Pressure Coolant Injection/Reactor Core Isolation Cooling Check Valves

Table 26-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9254542	0.9711765	0.9770915	0.9966590	0.9756098	4.9530E+01	1.4700E+00
α_2	3.34E-03	2.88E-02	2.29E-02	7.46E-02	2.44E-02	1.4700E+00	4.9530E+01

Table 26-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9432585	0.9766234	0.9806176	0.9963292	0.9836066	7.5200E+01	1.8000E+00
α_2	4.21E-06	5.03E-03	1.77E-03	2.11E-02	0.00E+00	3.8720E-01	7.6613E+01
α_3	1.97E-03	1.84E-02	1.44E-02	4.83E-02	1.64E-02	1.4128E+00	7.5587E+01

Table 26-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9516272	0.9785047	0.9814149	0.9954382	0.9876543	1.0470E+02	2.3000E+00
α_2	3.42E-05	5.18E-03	2.58E-03	1.91E-02	0.00E+00	5.5380E-01	1.0645E+02
α_3	7.11E-08	2.45E-03	4.75E-04	1.17E-02	0.00E+00	2.6260E-01	1.0674E+02
α_4	1.61E-03	1.39E-02	1.10E-02	3.60E-02	1.24E-02	1.4836E+00	1.0552E+02

Table 26-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9561561	0.9790238	0.9812448	0.9942881	0.9900990	1.3804E+02	2.9576E+00
α_2	1.04E-04	5.16E-03	3.09E-03	1.73E-02	0.00E+00	7.2800E-01	1.4027E+02
α_3	3.70E-06	2.92E-03	1.10E-03	1.20E-02	0.00E+00	4.1200E-01	1.4059E+02
α_4	1.28E-08	1.66E-03	2.52E-04	8.18E-03	0.00E+00	2.3360E-01	1.4076E+02
α_5	1.45E-03	1.12E-02	9.02E-03	2.86E-02	9.90E-03	1.5840E+00	1.3941E+02

Table 26-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9596477	0.9797261	0.9815341	0.9936199	0.9917355	1.7047E+02	3.5276E+00
α_2	1.13E-04	4.48E-03	2.78E-03	1.46E-02	0.00E+00	7.7910E-01	1.7322E+02
α_3	1.82E-05	3.11E-03	1.52E-03	1.16E-02	0.00E+00	5.4060E-01	1.7346E+02
α_4	2.80E-07	1.80E-03	4.70E-04	8.11E-03	0.00E+00	3.1270E-01	1.7369E+02
α_5	1.74E-08	1.40E-03	2.32E-04	6.82E-03	0.00E+00	2.4330E-01	1.7375E+02
α_6	1.31E-03	9.49E-03	7.69E-03	2.39E-02	8.26E-03	1.6519E+00	1.7235E+02

ALPHA FACTOR DISTRIBUTIONS
BWR High Pressure Coolant Injection/Reactor Core Isolation Cooling Check Valves

Table 26-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8513890	0.9410553	0.9521613	0.9926238	0.9334588	2.4211E+01	1.5165E+00
α_2	7.37E-03	5.89E-02	4.78E-02	1.49E-01	6.65E-02	1.5165E+00	2.4211E+01

Table 26-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8259289	0.9110640	0.9181849	0.9718003	0.8831130	3.4883E+01	3.4052E+00
α_2	1.58E-02	6.58E-02	5.83E-02	1.41E-01	9.56E-02	2.5176E+00	3.5771E+01
α_3	8.88E-04	2.32E-02	1.55E-02	7.16E-02	2.13E-02	8.8760E-01	3.7401E+01

Table 26-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8309564	0.9036367	0.9085718	0.9594243	0.8611957	4.9161E+01	5.2425E+00
α_2	1.65E-02	5.71E-02	5.18E-02	1.16E-01	8.99E-02	3.1074E+00	5.1296E+01
α_3	2.87E-03	2.62E-02	2.06E-02	6.85E-02	4.09E-02	1.4236E+00	5.2980E+01
α_4	2.45E-04	1.31E-02	7.78E-03	4.40E-02	8.02E-03	7.1150E-01	5.3692E+01

Table 26-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8452952	0.9061758	0.9098151	0.9546047	0.8537604	6.7286E+01	6.9667E+00
α_2	1.36E-02	4.47E-02	4.07E-02	8.97E-02	7.57E-02	3.3197E+00	7.0933E+01
α_3	5.21E-03	2.78E-02	2.36E-02	6.44E-02	4.82E-02	2.0611E+00	7.2192E+01
α_4	4.56E-04	1.20E-02	7.97E-03	3.72E-02	1.92E-02	8.8960E-01	7.3363E+01
α_5	1.62E-04	9.38E-03	5.49E-03	3.18E-02	3.28E-03	6.9630E-01	7.3556E+01

Table 26-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8567748	0.9099137	0.9128480	0.9530188	0.8536341	8.4553E+01	8.3712E+00
α_2	1.03E-02	3.48E-02	3.16E-02	7.06E-02	6.16E-02	3.2379E+00	8.9686E+01
α_3	5.86E-03	2.61E-02	2.27E-02	5.76E-02	4.71E-02	2.4209E+00	9.0503E+01
α_4	1.55E-03	1.49E-02	1.16E-02	3.96E-02	2.69E-02	1.3866E+00	9.1538E+01
α_5	7.19E-05	6.66E-03	3.60E-03	2.36E-02	9.40E-03	6.1850E-01	9.2306E+01
α_6	1.39E-04	7.61E-03	4.49E-03	2.57E-02	1.39E-03	7.0730E-01	9.2217E+01

27. PWR High Pressure Safety Injection Check Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving check valves in high pressure safety injection (HPSI) systems at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified five common-cause failure to open events, one common-cause failure to close event, and 15 common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 27-1 and 27-2, respectively. Table 27-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 27-4 through 27-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of high pressure safety injection systems check valves is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 27-10 through 27-24.

2. SYSTEM DESCRIPTION

The high pressure safety injection (HPSI) system is a subsystem of the emergency core cooling system (ECCS) that functions to provide emergency coolant injection to maintain reactor coolant inventory and provide adequate decay heat removal following a loss of coolant accident (LOCA). The injection function is performed in a relatively short time interval after initiation of the LOCA. The system is typically comprised of two safety injection (SI) pumps and two or three high pressure centrifugal charging pumps (CCP); one CCP is an installed spare which can be manually aligned to either train.

Both the charging and the SI pumps inject directly into the primary loop cold legs, and the SI pumps can be realigned to inject into the hot legs. The suction source for the HPSI pumps is the refueling water storage tank (RWST) which contains enough highly borated water to satisfy the injection needs of the core. Figure 27-1 illustrates the typical flow path for the HPSI system. All pumps and motor operated valves receive power from the 1E emergency power system backed up by the emergency diesel generators.

The HPSI pumps are normally in standby, and are started by the engineered safety features actuation system, or may be manually actuated. A HPSI signal starts the charging and SI pumps, shifts the charging pump suction to the RWST, isolates normal charging and letdown flow and completes additional valve lineup changes. The injection phase ends when the RWST reaches the low level setpoint and the system is realigned for the recirculation phase which takes suction from the containment sump through the RHR system.

ALPHA FACTOR AND MGL PARAMETERS
PWR High Pressure Safety Injection Check Valves

Table 27-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.8410201	0.8358037	0.8549101	0.8643100	0.8688148
α_2	1.59E-01	7.43E-02	3.19E-02	3.92E-02	4.55E-02
α_3		8.99E-02	5.66E-02	1.46E-02	7.50E-03
α_4			5.66E-02	3.51E-02	1.56E-02
α_5				4.68E-02	2.25E-02
α_6					4.00E-02

Table 27-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	8.41E-01	8.36E-01	8.55E-01	8.64E-01	8.69E-01
Beta	1.59E-01	1.64E-01	1.45E-01	1.36E-01	1.31E-01
Gamma		5.48E-01	7.80E-01	7.12E-01	6.53E-01
Delta			5.00E-01	8.49E-01	9.12E-01
Epsilon				5.71E-01	8.00E-01
Mu					6.40E-01

Table 27-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	6.79	10.18	13.57	16.96	20.36
N_1	1.6456	1.4360	1.5378	1.5046	1.3509
N_2	1.5946	1.0320	0.5640	0.8363	1.1376
N_3		1.2500	1.0000	0.3125	0.1875
N_4			1.0000	0.7500	0.3906
N_5				1.0000	0.5625
N_6					1.0000

Total Number of Independent Failure Events: 19
Total Number of Common-Cause Failure Events: 5

ALPHA FACTOR AND MGL PARAMETERS
PWR High Pressure Safety Injection Check Valves

Table 27-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9936584	0.9872612	0.9807692	0.9845560	0.9870968
α_2	6.34E-03	1.27E-02	1.92E-02	7.72E-03	3.23E-03
α_3		0.00E+00	0.00E+00	7.72E-03	6.45E-03
α_4			0.00E+00	0.00E+00	3.23E-03
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 27-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.94E-01	9.87E-01	9.81E-01	9.85E-01	9.87E-01
Beta	6.34E-03	1.27E-02	1.92E-02	1.54E-02	1.29E-02
Gamma		0.00E+00	0.00E+00	5.00E-01	7.50E-01
Delta			0.00E+00	0.00E+00	3.33E-01
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 27-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	25.50	38.25	51.00	63.75	76.50
N_1	0.6670	0.5000	0.0000	0.0000	0.0000
N_2	0.1670	0.5000	1.0000	0.5000	0.2500
N_3		0.0000	0.0000	0.5000	0.5000
N_4			0.0000	0.0000	0.2500
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 51
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
PWR High Pressure Safety Injection Check Valves

Table 27-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
α_1	0.9869072	0.9803322	0.9766072	0.9747465	0.9737559
α_2	1.31E-02	1.63E-02	1.70E-02	1.60E-02	1.53E-02
α_3		3.36E-03	5.09E-03	6.16E-03	6.05E-03
α_4			1.27E-03	2.55E-03	3.42E-03
α_5				5.10E-04	1.28E-03
α_6					2.13E-04

Table 27-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
1-Beta	9.87E-01	9.80E-01	9.77E-01	9.75E-01	9.74E-01
Beta	1.31E-02	1.97E-02	2.34E-02	2.53E-02	2.62E-02
Gamma		1.71E-01	2.72E-01	3.65E-01	4.18E-01
Delta			1.99E-01	3.32E-01	4.48E-01
Epsilon				1.67E-01	3.04E-01
Mu					1.43E-01

Table 27-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
Adj. Ind. Events	22.29	33.43	44.58	55.72	66.87
N_1	2.5094	3.1558	3.6474	4.0651	4.4325
N_2	0.3290	0.6086	0.8415	0.9833	1.1192
N_3		0.1254	0.2512	0.3779	0.4429
N_4			0.0625	0.1564	0.2502
N_5				0.0313	0.0938
N_6					0.0156

Total Number of Independent Failure Events: 75
Total Number of Common-Cause Failure Events: 15

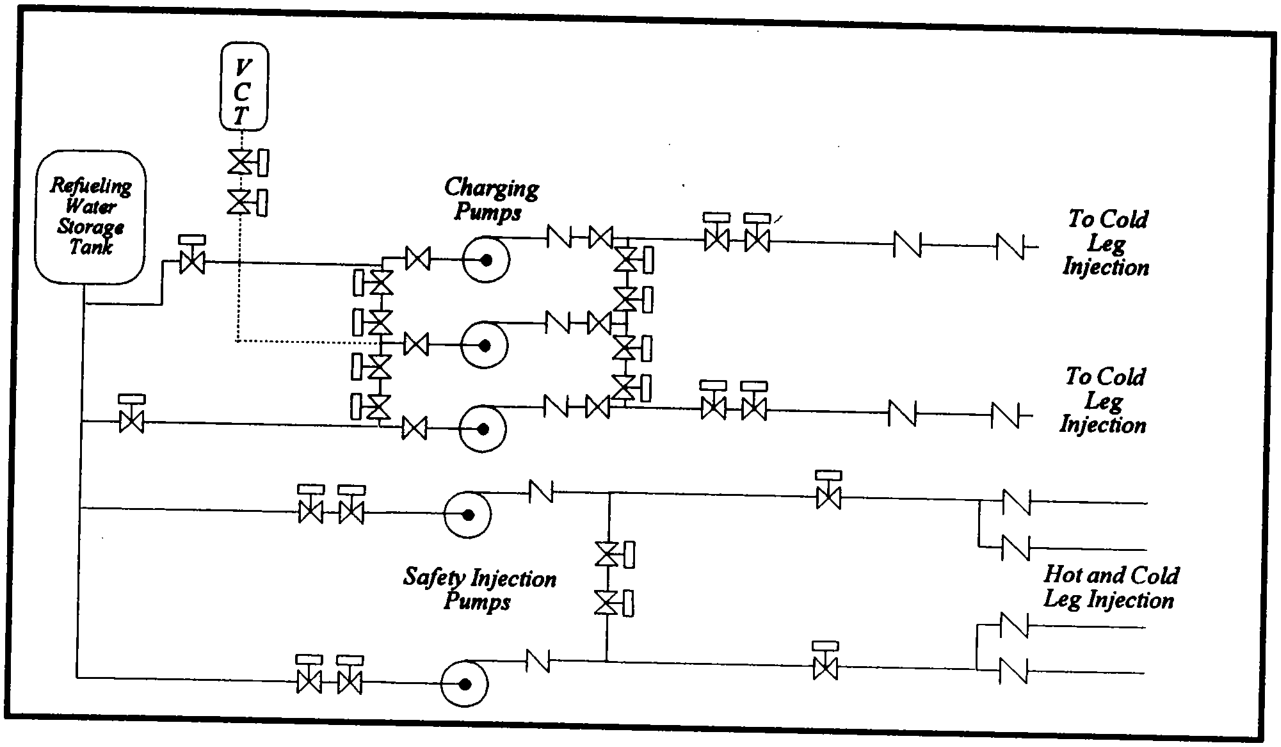

Figure 27-1. PWR high pressure safety injection system.

3. COMPONENT BOUNDARIES

The main component of a check valve is the valve itself. This component is operated by system pressure overcoming gravity. Typically, there is no capability to manual open, close, or isolate these valves, however, some valves have manual hand wheels or levers (stop-check) and can be manually closed. Other valves are "air-testable" which should not affect normal component operation and in some cases the air supply is turned off during operation as a precaution. No power is required for valve operation. Valves are installed in HPSI systems in the following areas:

- Pump discharge,
- Pump suction,
- Loop injection, and
- System inter- or cross-connection.

The function of the check valve is to form a conditional boundary (i.e., one direction) between high pressure and low pressure sections of a system during static conditions. By design, the valve will open to allow flow when the low pressure section has experienced a pressure increase (e.g., pump start). For the purposes of this study, the boundaries will encompass the valve body including internals (e.g. disk, springs) and operators in the cases of air assisted valves.

4. FAILURE EVENT DEFINITION

Check valve malfunctions are considered to be failures to open or close on demand, and failure to stay closed, including excessive leakage through the valve. Examples of the consequences of this failure an increase in containment leak rate, system drainage, and interfacing system LOCA. Failure modes used to analyze check valve data are:

CC Failure to Open. Examples are:

- Check valve sticks closed, and
- Check valve partially opens.

OO Failure to Close. Examples are:

- Check valve sticks open,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed. In cases where the check valve has been closed for a substantial period of time and is then discovered leaking the failure will be coded as VR.

HPSI check valve failures that occurred during testing are included with failures that occurred during plant transients requiring operation of the HPSI check valves. Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of check valve demand. The exception to this is if a licensee reported that the check valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the check valve from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that failure of a second HPSI check valve would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another HPSI check valve, the event was identified as a CCF. If, however, the report did not clearly identify that another check valve would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before another HPSI check valve operation demand (e.g. the condition was found during inspection, and no check valve demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 27-10 through 27-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of check valve. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
PWR High Pressure Safety Injection Check Valves

Table 27-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7692310	0.8969277	0.9100508	0.9795710	0.8410201	1.7966E+01	2.0646E+00
α_2	2.04E-02	1.03E-01	9.00E-02	2.31E-01	1.59E-01	2.0646E+00	1.7966E+01

Table 27-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.7940009	0.8969162	0.9057374	0.9695810	0.8358037	2.6816E+01	3.0820E+00
α_2	5.27E-03	4.75E-02	3.77E-02	1.23E-01	7.43E-02	1.4192E+00	2.8479E+01
α_3	8.00E-03	5.56E-02	4.60E-02	1.36E-01	8.99E-02	1.6628E+00	2.8235E+01

Table 27-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8323817	0.9115223	0.9177768	0.9692400	0.8549101	3.9808E+01	3.8640E+00
α_2	1.75E-03	2.56E-02	1.88E-02	7.28E-02	3.19E-02	1.1178E+00	4.2554E+01
α_3	2.55E-03	2.89E-02	2.21E-02	7.87E-02	5.66E-02	1.2626E+00	4.2409E+01
α_4	4.02E-03	3.40E-02	2.71E-02	8.74E-02	5.66E-02	1.4836E+00	4.2188E+01

Table 27-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8578237	0.9208584	0.9254106	0.9683179	0.8643100	5.6507E+01	4.8564E+00
α_2	3.26E-03	2.55E-02	2.05E-02	6.47E-02	3.92E-02	1.5643E+00	5.9799E+01
α_3	2.35E-04	1.18E-02	7.09E-03	3.95E-02	1.46E-02	7.2450E-01	6.0639E+01
α_4	8.01E-04	1.60E-02	1.12E-02	4.79E-02	3.51E-02	9.8360E-01	6.0380E+01
α_5	3.37E-03	2.58E-02	2.09E-02	6.52E-02	4.68E-02	1.5840E+00	5.9779E+01

Table 27-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8715048	0.9255560	0.9291788	0.9672148	0.8688148	7.2183E+01	5.8058E+00
α_2	4.21E-03	2.46E-02	2.06E-02	5.84E-02	4.55E-02	1.9167E+00	7.6072E+01
α_3	1.89E-04	9.34E-03	5.61E-03	3.12E-02	7.50E-03	7.2810E-01	7.7261E+01
α_4	1.61E-04	9.02E-03	5.31E-03	3.05E-02	1.56E-02	7.0330E-01	7.7286E+01
α_5	2.93E-04	1.03E-02	6.55E-03	3.33E-02	2.25E-02	8.0580E-01	7.7183E+01
α_6	2.94E-03	2.12E-02	1.72E-02	5.29E-02	4.00E-02	1.6519E+00	7.6337E+01

ALPHA FACTOR DISTRIBUTIONS
PWR High Pressure Safety Injection Check Valves

Table 27-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9387921	0.9824682	0.9902105	0.9997852	0.9936584	3.5697E+01	6.3700E-01
α_2	2.17E-04	1.75E-02	9.79E-03	6.12E-02	6.34E-03	6.3700E-01	3.5697E+01

Table 27-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9364069	0.9764706	0.9819416	0.9978132	0.9872612	5.3950E+01	1.3000E+00
α_2	6.09E-04	1.61E-02	1.07E-02	4.98E-02	1.27E-02	8.8720E-01	5.4363E+01
α_3	9.66E-06	7.47E-03	2.84E-03	3.06E-02	0.00E+00	4.1280E-01	5.4837E+01

Table 27-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9338719	0.9705128	0.9744440	0.9937044	0.9807692	7.5700E+01	2.3000E+00
α_2	2.51E-03	1.99E-02	1.60E-02	5.08E-02	1.92E-02	1.5538E+00	7.6446E+01
α_3	9.77E-08	3.37E-03	6.53E-04	1.61E-02	0.00E+00	2.6260E-01	7.7737E+01
α_4	2.06E-05	6.20E-03	2.76E-03	2.40E-02	0.00E+00	4.8360E-01	7.7516E+01

Table 27-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9411519	0.9717645	0.9747173	0.9922861	0.9845560	1.0179E+02	2.9576E+00
α_2	9.64E-04	1.17E-02	8.79E-03	3.25E-02	7.72E-03	1.2280E+00	1.0352E+02
α_3	3.54E-04	8.71E-03	5.84E-03	2.68E-02	7.72E-03	9.1200E-01	1.0384E+02
α_4	1.73E-08	2.23E-03	3.39E-04	1.10E-02	0.00E+00	2.3360E-01	1.0451E+02
α_5	4.69E-05	5.58E-03	2.89E-03	2.02E-02	0.00E+00	5.8400E-01	1.0416E+02

Table 27-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9463253	0.9729681	0.9753522	0.9914653	0.9870968	1.2697E+02	3.5276E+00
α_2	4.37E-04	7.89E-03	5.56E-03	2.33E-02	3.23E-03	1.0291E+00	1.2947E+02
α_3	4.54E-04	7.97E-03	5.64E-03	2.35E-02	6.45E-03	1.0406E+00	1.2946E+02
α_4	3.06E-05	4.31E-03	2.17E-03	1.59E-02	3.23E-03	5.6270E-01	1.2994E+02
α_5	2.33E-08	1.86E-03	3.09E-04	9.10E-03	0.00E+00	2.4330E-01	1.3025E+02
α_6	6.67E-05	5.00E-03	2.80E-03	1.74E-02	0.00E+00	6.5190E-01	1.2985E+02

ALPHA FACTOR DISTRIBUTIONS
PWR High Pressure Safety Injection Check Valves

Table 27-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9270462	0.9772546	0.9854888	0.9993609	0.9869072	3.4329E+01	7.9900E-01
α_2	6.36E-04	2.28E-02	1.45E-02	7.30E-02	1.31E-02	7.9900E-01	3.4329E+01

Table 27-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9266294	0.9712303	0.9769009	0.9964243	0.9803322	5.1786E+01	1.5340E+00
α_2	9.66E-04	1.87E-02	1.31E-02	5.55E-02	1.63E-02	9.9580E-01	5.2324E+01
α_3	5.85E-05	1.01E-02	4.95E-03	3.76E-02	3.36E-03	5.3820E-01	5.2782E+01

Table 27-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9284744	0.9674300	0.9714761	0.9925311	0.9766072	7.2927E+01	2.4552E+00
α_2	1.95E-03	1.85E-02	1.45E-02	4.90E-02	1.70E-02	1.3953E+00	7.3987E+01
α_3	3.12E-05	6.82E-03	3.20E-03	2.59E-02	5.09E-03	5.1380E-01	7.4868E+01
α_4	4.49E-05	7.24E-03	3.58E-03	2.69E-02	1.27E-03	5.4610E-01	7.4836E+01

Table 27-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9313735	0.9653965	0.9684200	0.9890836	0.9747465	9.7827E+01	3.5065E+00
α_2	2.46E-03	1.69E-02	1.38E-02	4.18E-02	1.60E-02	1.7113E+00	9.9622E+01
α_3	2.07E-04	7.80E-03	4.88E-03	2.53E-02	6.16E-03	7.8990E-01	1.0540E+02
α_4	3.38E-06	3.85E-03	1.36E-03	1.61E-02	2.55E-03	3.9000E-01	1.0940E+02
α_5	6.41E-05	6.07E-03	3.27E-03	2.16E-02	5.10E-04	6.1530E-01	1.0720E+02

Table 27-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9343194	0.9647495	0.9671823	0.9868689	0.9737559	1.2177E+02	4.4493E+00
α_2	2.52E-03	1.50E-02	1.26E-02	3.60E-02	1.53E-02	1.8983E+00	1.2432E+02
α_3	3.86E-04	7.79E-03	5.39E-03	2.34E-02	6.05E-03	9.8350E-01	1.2524E+02
α_4	3.17E-05	4.46E-03	2.25E-03	1.64E-02	3.42E-03	5.6290E-01	1.2566E+02
α_5	7.86E-07	2.67E-03	7.82E-04	1.18E-02	1.28E-03	3.3710E-01	1.2588E+02
α_6	7.74E-05	5.29E-03	3.01E-03	1.83E-02	2.13E-04	6.6750E-01	1.2555E+02

28. BWR Isolation Condenser Motor-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving motor-operated valves (MOVs) in the isolation condenser (IC) system at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified one common-cause failure-to-open event and one common-cause failure-to-close event. No failure-to-remain-closed CCF events were identified during the data review. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 28-1 and 28-2, respectively. Table 28-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode. Tables 28-4 through 28-6 contain the corresponding information for the failure to close failure mode. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 28-7 through 28-12.

2. SYSTEM DESCRIPTION

The isolation condenser is part of the BWR emergency core cooling system (ECCS) that transfers residual and decay heat from the reactor coolant system to the atmosphere in the event that the main condenser is not available, or when a high reactor pressure condition exists. The IC system may be placed into service either manually or automatically. The IC system operates using natural circulation as the driving head through the isolation condenser tubes, and is available for operation when there is no electrical power. The primary side of the isolation condenser system is a closed loop from the reactor pressure vessel steam space through the tubes in the isolation condenser, with the condensate returning back to the recirculation loops. During normal plant operations, the secondary (shell) side of the isolation condenser contains sufficient water to cover the primary side tubes. The water in the shell side transfers the heat from the primary side by boiling off and venting directly to the atmosphere. Makeup to the secondary side is provided through the fire water system or through an alternate makeup source, such as the condensate transfer system.

Only five BWR plants have an IC system; those that don't have the IC have reactor core isolation cooling, which is a pump driven system. Some plants have two ICs, and other plants have one IC that contains two sets of steam cooling tubes. Figure 8-1 shows a typical isolation condenser system.

ALPHA FACTOR AND MGL PARAMETERS
Isolation Condenser Motor-Operated Valves

Table 28-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9989552	0.9979123	0.9968652
α_2	1.05E-03	2.09E-03	3.14E-03
α_3		0.00E+00	0.00E+00
α_4			0.00E+00

Table 28-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.99E-01	9.98E-01	9.97E-01
Beta	1.05E-03	2.09E-03	3.14E-03
Gamma		0.00E+00	0.00E+00
Delta			0.00E+00

Table 28-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	15.00	22.50	30.00
N_1	0.9667	1.4000	1.8000
N_2	0.0167	0.0500	0.1000
N_3		0.0000	0.0000
N_4			0.0000

Total Number of Independent Failure Events: 30
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
Isolation Condenser Motor-Operated Valves

Table 28-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9874756	0.9746835	0.9615385
α_2	1.25E-02	2.53E-02	3.85E-02
α_3		0.00E+00	0.00E+00
α_4			0.00E+00

Table 28-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.88E-01	9.75E-01	9.62E-01
Beta	1.25E-02	2.53E-02	3.85E-02
Gamma		0.00E+00	0.00E+00
Delta			0.00E+00

Table 28-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	6.00	9.00	12.00
N_1	0.5835	0.6250	0.5000
N_2	0.0835	0.2500	0.5000
N_3		0.0000	0.0000
N_4			0.0000

Total Number of Independent Failure Events: 12
Total Number of Common-Cause Failure Events: 1

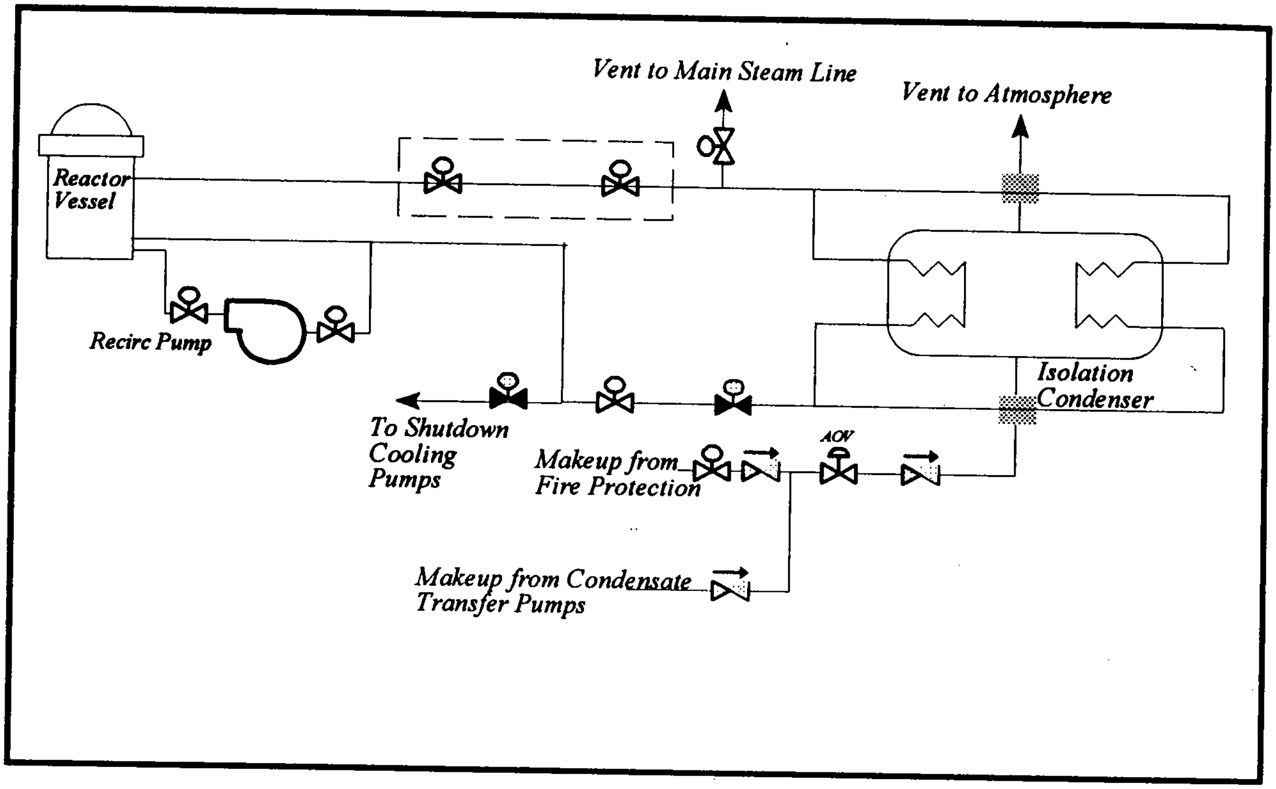

Figure 28-1. Typical isolation condenser system.

3. COMPONENT BOUNDARIES

The main components of a motor-operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual hand wheels, and can be manually operated. AC or DC power is required for valve operation.

The MOVs in the isolation condenser system are used in the following applications:

- Admitting steam to the isolation condenser from the reactor,
- Supplying condensate from the isolation condenser back to the reactor recirculation loop, and
- Supplying cooling water to the isolation condenser from either the condensate system or the fire water system.

4. FAILURE EVENT DEFINITION

The function of the primary side MOVs is to allow primary coolant flow to the isolation condenser. The function of the secondary side MOV is to allow condensing medium makeup flow into the isolation condenser shell. All valves serve as a system containment boundary and would need to close to isolate leaks. The failure modes used in evaluating the isolation condenser MOV data are:

CC Fail to Open: The valve must be in the fully open position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: In cases where the motor-operated valve has been closed for a substantial period of time and is then discovered leaking, the failure is coded as VR. If the discovery is made soon after a system configuration change (i.e., pump operation), then the failure is coded as OO.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure.

These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC".

Many LERs reported only one actual failure, but the report information indicated that failure of a second MOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure is certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 28-7 through 28-12 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of MOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Isolation Condenser Motor-Operated Valves

Table 28-7: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9279471	0.9812690	0.9914733	0.9999312	0.9989552	2.5497E+01	4.8670E-01
α_2	6.56E-05	1.87E-02	8.53E-03	7.21E-02	1.05E-03	4.8670E-01	2.5497E+01

Table 28-8: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9332039	0.9787234	0.9860351	0.9992794	0.9979123	3.910E+01	8.5000E-01
α_2	2.04E-05	1.09E-02	4.45E-03	4.39E-02	2.09E-03	4.3720E-01	3.9513E+01
α_3	1.34E-05	1.03E-02	3.95E-03	4.23E-02	0.00E+00	4.1280E-01	3.9537E+01

Table 28-9: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9362904	0.9758204	0.9810590	0.9974318	0.9968652	5.6500E+01	1.4000E+00
α_2	1.54E-04	1.13E-02	6.37E-03	3.92E-02	3.14E-03	6.5380E-01	5.7246E+01
α_3	1.32E-07	4.54E-03	8.82E-04	2.16E-02	0.00E+00	2.6260E-01	5.7637E+01
α_4	2.78E-05	8.35E-03	3.73E-03	3.24E-02	0.00E+00	4.8360E-01	5.7416E+01

ALPHA FACTOR DISTRIBUTIONS
Isolation Condenser Motor-Operated Valves

Table 28-10: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8789790	0.9667916	0.9829012	0.9997697	0.9874756	1.6114E+01	5.5350E-01
α_2	2.28E-04	3.32E-02	1.71E-02	1.21E-01	1.25E-02	5.5350E-01	1.6114E+01

Table 28-11: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8830041	0.9594203	0.9705938	0.9975603	0.9746835	2.4825E+01	1.0500E+00
α_2	3.08E-04	2.46E-02	1.39E-02	8.57E-02	2.53E-02	6.3720E-01	2.5238E+01
α_3	2.09E-05	1.60E-02	6.15E-03	6.52E-02	0.00E+00	4.1280E-01	2.5462E+01

Table 28-12: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8891726	0.9538462	0.9614052	0.9926291	0.9615385	3.7200E+01	1.8000E+00
α_2	1.62E-03	2.70E-02	1.94E-02	7.84E-02	3.85E-02	1.0538E+00	3.7946E+01
α_3	1.97E-07	6.73E-03	1.32E-03	3.21E-02	0.00E+00	2.6260E-01	3.8737E+01
α_4	4.16E-05	1.24E-02	5.56E-03	4.80E-02	0.00E+00	4.8360E-01	3.8516E+01

29. BWR High Pressure Coolant Injection and Reactor Core Isolation Cooling Motor-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving motor-operated valves (MOVs) in the high pressure coolant injection (HPCI) and reactor core isolation cooling (RCIC) system at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified three common-cause failure-to-open events and two common-cause failure-to-close event for the injection valves, two common-cause failure-to-remain-closed events for the pump turbine steam supply valves, five failure-to-open common-cause events and four common-cause failure-to-close events that affect both types of MOVs. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for the injection valve failure to open failure mode are shown in Tables 29-1 and 29-2, respectively. Table 29-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 29-4 through 29-15 contain the corresponding information for the failure to close and failure to remain closed failure modes for the injection, steam supply, and both types of MOVs. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 29-29-16 through 29-38.

2. SYSTEM DESCRIPTION

BWRs can have HPCI and RCIC systems or only a HPCI system (if an isolation condenser is present). Both the HPCI and the RCIC are single train systems, and are not consequently subject to CCF events by themselves. This analysis combined the failures of MOVs across the system boundaries to identify CCF events.

The HPCI system supplies high volume, high pressure make-up water to the reactor pressure vessel (RPV) in the event of a small break LOCA which does not result in a rapid depressurization of the reactor vessel. The HPCI system consists of a turbine driven pump, system piping, valves and controls. The HPCI system is normally in standby, isolates on low pressure, and is aligned to take a suction from the condensate storage tank (CST) but suction is automatically switched from the CST to the suppression pool upon low CST level or high suppression pool water level. The HPCI system is automatically started in response to decreasing RPV water level and is injected into the reactor via the feedwater system. HPCI serves as the primary source of makeup if RCS pressure remains high. Steam to drive the HPCI turbine is routed from main steam.

The RCIC system provides low volume, high pressure makeup water to the RPV for core cooling when the main steam lines are isolated or the condensate and feedwater system is not available. The RCIC system consists of a turbine driven pump, system piping, valves and controls. The RCIC system is normally in standby, and is aligned to take a suction from the CST, but suction is automatically switched from the CST to the suppression pool upon low CST level or high suppression pool water level. The RCIC system is automatically started in response to decreasing RPV water level and is injected into the reactor via the feedwater line. Steam for the RCIC turbine-driven pump is routed from mail steam. Figure 29-1 shows a typical HPCI system; the configuration of the RCIC system is similar.

ALPHA FACTOR AND MGL PARAMETERS
HPCI/RCIC Injection Motor-Operated Valves

Table 29-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9536339	0.9675266	0.9743904	0.9784509	0.9811204
α_2	4.64E-02	1.59E-03	2.08E-03	2.39E-03	2.57E-03
α_3		3.09E-02	2.24E-04	3.93E-04	5.71E-04
α_4			2.33E-02	2.90E-05	6.35E-05
α_5				1.87E-02	3.92E-06
α_6					1.57E-02

Table 29-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.54E-01	9.68E-01	9.74E-01	9.79E-01	9.81E-01
Beta	4.64E-02	3.25E-02	2.56E-02	2.16E-02	1.89E-02
Gamma		9.51E-01	9.19E-01	8.89E-01	8.64E-01
Delta			9.91E-01	9.80E-01	9.65E-01
Epsilon				9.99E-01	9.96E-01
Mu					1.00E+01

Table 29-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	41.54	62.31	83.08	103.85	124.63
N_1	0.4197	0.5265	0.5833	0.6011	0.5905
N_2	2.0401	0.1035	0.1782	0.2553	0.3281
N_3		2.0055	0.0192	0.0419	0.0729
N_4			2.0015	0.0031	0.0081
N_5				2.0001	0.0005
N_6					2.0000

Total Number of Independent Failure Events: 97
Total Number of Common-Cause Failure Events: 3

ALPHA FACTOR AND MGL PARAMETERS
HPCI/RCIC Injection Motor-Operated Valves

Table 29-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9973117	0.9951217	0.9933549	0.9900165	0.9883734
α_2	2.69E-03	4.63E-03	5.96E-03	7.90E-03	7.76E-03
α_3		2.53E-04	6.57E-04	1.90E-03	3.19E-03
α_4			2.43E-05	1.85E-04	6.19E-04
α_5				5.85E-06	5.38E-05
α_6					1.63E-06

Table 29-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.97E-01	9.95E-01	9.93E-01	9.90E-01	9.88E-01
Beta	2.69E-03	4.88E-03	6.65E-03	9.98E-03	1.16E-02
Gamma		5.18E-02	1.03E-01	2.09E-01	3.33E-01
Delta			3.57E-02	9.16E-02	1.75E-01
Epsilon				3.06E-02	8.21E-02
Mu					2.94E-02

Table 29-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	20.00	30.00	40.00	50.00	60.00
N_1	0.5894	0.7412	0.8247	0.7330	0.6375
N_2	0.0555	0.1429	0.2451	0.4046	0.4760
N_3		0.0078	0.0270	0.0972	0.1959
N_4			0.0010	0.0095	0.0380
N_5				0.0003	0.0033
N_6					0.0001

Total Number of Independent Failure Events: 60
Total Number of Common-Cause Failure Events: 2

ALPHA FACTOR AND MGL PARAMETERS
HPCI/RCIC Turbine Steam Supply Motor-Operated Valves

Table 29-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9999871	0.9999770	0.9999677
α_2	1.29E-05	2.30E-05	3.23E-05
α_3		0.00E+00	0.00E+00
α_4			0.00E+00

Table 29-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	1.00E+00	1.00E+00	1.00E+00
Beta	1.29E-05	2.30E-05	3.23E-05
Gamma		0.00E+00	0.00E+00
Delta			0.00E+00

Table 29-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	23.00	34.50	46.00
N_1	0.1995	0.2985	0.3970
N_2	0.0003	0.0008	0.0015
N_3		0.0000	0.0000
N_4			0.0000

Total Number of Independent Failure Events: 46
Total Number of Common-Cause Failure Events: 2

ALPHA FACTOR AND MGL PARAMETERS
HPCI/RCIC Motor-Operated Valves, both Injection and Turbine Steam Supply

Table 29-10: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9712123	0.9798879	0.9841097	0.9865718	0.9881654
α_2	2.88E-02	1.09E-03	1.44E-03	1.69E-03	1.86E-03
α_3		1.90E-02	1.37E-04	2.41E-04	3.50E-04
α_4			1.43E-02	1.78E-05	3.88E-05
α_5				1.15E-02	2.40E-06
α_6					9.59E-03

Table 29-11: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.71E-01	9.80E-01	9.84E-01	9.87E-01	9.88E-01
Beta	2.88E-02	2.01E-02	1.59E-02	1.34E-02	1.18E-02
Gamma		9.46E-01	9.09E-01	8.74E-01	8.43E-01
Delta			9.91E-01	9.80E-01	9.65E-01
Epsilon				9.99E-01	9.96E-01
Mu					1.00E+01

Table 29-12: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	68.00	102.00	136.00	170.00	204.00
N_1	0.9619	1.3280	1.6361	1.8976	2.1227
N_2	2.0441	0.1153	0.2017	0.2946	0.3871
N_3		2.0055	0.0192	0.0419	0.0729
N_4			2.0015	0.0031	0.0081
N_5				2.0001	0.0005
N_6					2.0000

Total Number of Independent Failure Events: 204
Total Number of Common-Cause Failure Events: 5

ALPHA FACTOR AND MGL PARAMETERS
HPCI/RCIC Motor-Operated Valves, both Injection and Turbine Steam Supply

Table 29-13: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
α_1	0.9972286	0.9947832	0.9925857	0.9893969	0.9872568
α_2	2.77E-03	5.06E-03	6.99E-03	9.30E-03	1.03E-02
α_3		1.57E-04	4.09E-04	1.18E-03	1.99E-03
α_4			1.52E-05	1.16E-04	3.86E-04
α_5				3.65E-06	3.35E-05
α_6					1.02E-06

Table 29-14: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
1-Beta	9.97E-01	9.95E-01	9.93E-01	9.89E-01	9.87E-01
Beta	2.77E-03	5.22E-03	7.41E-03	1.06E-02	1.27E-02
Gamma		3.01E-02	5.72E-02	1.23E-01	1.89E-01
Delta			3.57E-02	9.16E-02	1.75E-01
Epsilon				3.06E-02	8.21E-02
Mu					2.94E-02

Table 29-15: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
Adj. Ind. Events	32.00	48.00	64.00	80.00	96.00
N_1	1.0677	1.3501	1.4914	1.3869	1.2058
N_2	0.0919	0.2510	0.4612	0.7652	1.0174
N_3		0.0078	0.0270	0.0972	0.1959
N_4			0.0010	0.0095	0.0380
N_5				0.0003	0.0033
N_6					0.0001

Total Number of Independent Failure Events: 112
Total Number of Common-Cause Failure Events: 4

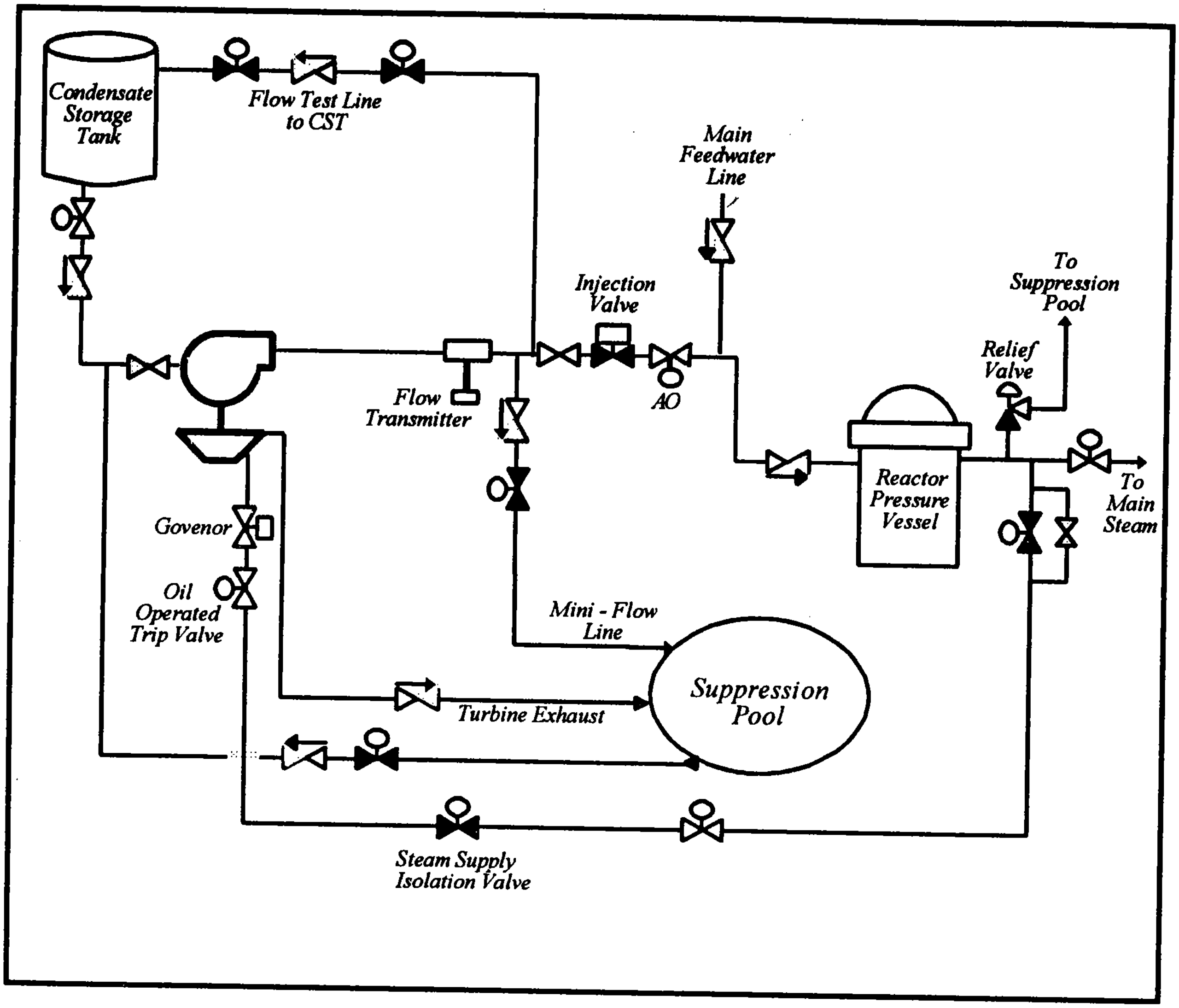

Figure 29-1. BWR high pressure coolant injection system.

3. COMPONENT BOUNDARIES

The main components of a motor-operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual hand wheels, and can be manually operated. AC or DC power is required for valve operation.

MOVs are used in the HPCI/RCIC system in the following applications:

- Pump discharge,
- Pump suction,
- Loop injection,
- System inter- or cross-connection, and
- Steam supply.

4. FAILURE EVENT DEFINITION

The function of the injection MOVs is to allow injection flow to the primary system through the reactor vessel. During normal plant operations, most of the MOVs remain closed to isolate the high pressure and low pressure portions of the system. All valves serve as a system containment boundary and would need to close to isolate leaks. The failure modes used in evaluating the isolation condenser MOV data are:

CC Fail to Open: The valve must be in the fully open position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: Leakage through the valve following a successful closure. This is intended to capture leakage events that affect the operation of the system or the plant, and not minor leakage resulting in failure of local leak rate tests.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure. These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC."

Many LERs reported only one actual failure, but the report information indicated that failure of a second MOV would have occurred from the same cause if a operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 29-16 through 29-38 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of MOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
HPCI/RCIC Injection Motor-Operated Valves

Table 29-16: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8991799	0.9535168	0.9590234	0.9890106	0.9536339	5.1490E+01	2.5101E+00
α_2	1.10E-02	4.65E-02	4.10E-02	1.01E-01	4.64E-02	2.5101E+00	5.1490E+01

Table 29-17: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9249820	0.9640625	0.9678196	0.9902796	0.9675266	7.8037E+01	2.9090E+00
α_2	2.18E-05	6.06E-03	2.73E-03	2.34E-02	1.59E-03	4.9070E-01	8.0455E+01
α_3	6.73E-03	2.99E-02	2.61E-02	6.60E-02	3.09E-02	2.4183E+00	7.8528E+01

Table 29-18: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9378518	0.9687204	0.9714726	0.9901649	0.9743904	1.0836E+02	3.4989E+00
α_2	1.34E-04	6.54E-03	3.93E-03	2.19E-02	2.08E-03	7.3200E-01	1.1113E+02
α_3	1.50E-07	2.52E-03	5.55E-04	1.18E-02	2.24E-04	2.8180E-01	1.1158E+02
α_4	5.13E-03	2.22E-02	1.94E-02	4.88E-02	2.33E-02	2.4851E+00	1.0937E+02

Table 29-19: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9452170	0.9709843	0.9731016	0.9895223	0.9784509	1.4249E+02	4.2580E+00
α_2	3.32E-04	6.70E-03	4.63E-03	2.01E-02	2.39E-03	9.8330E-01	1.4577E+02
α_3	7.13E-06	3.09E-03	1.29E-03	1.23E-02	3.93E-04	4.5390E-01	1.4629E+02
α_4	1.46E-08	1.61E-03	2.52E-04	7.94E-03	2.90E-05	2.3670E-01	1.4651E+02
α_5	4.22E-03	1.76E-02	1.55E-02	3.83E-02	1.87E-02	2.5841E+00	1.4416E+02

Table 29-20: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9502438	0.9726664	0.9743961	0.9891877	0.9811204	1.7569E+02	4.9372E+00
α_2	4.02E-04	6.13E-03	4.43E-03	1.77E-02	2.57E-03	1.1072E+00	1.7952E+02
α_3	3.53E-05	3.40E-03	1.82E-03	1.21E-02	5.71E-04	6.1350E-01	1.8010E+02
α_4	3.45E-07	1.78E-03	4.83E-04	7.95E-03	6.35E-05	3.2080E-01	1.8031E+02
α_5	1.72E-08	1.35E-03	2.25E-04	6.58E-03	3.92E-06	2.4380E-01	1.8038E+02
α_6	3.60E-03	1.47E-02	1.29E-02	3.18E-02	1.57E-02	2.6519E+00	1.7798E+02

ALPHA FACTOR DISTRIBUTIONS
HPCI/RCIC Injection Motor-Operated Valves

Table 29-21: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9357905	0.9828517	0.9916825	0.9999140	0.9973117	3.0119E+01	5.2550E-01
α_2	8.93E-05	1.72E-02	8.32E-03	6.42E-02	2.69E-03	5.2550E-01	3.0119E+01

Table 29-22: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9388026	0.9797256	0.9860416	0.9990647	0.9951217	4.5941E+01	9.5070E-01
α_2	6.09E-05	1.13E-02	5.48E-03	4.23E-02	4.63E-03	5.3010E-01	4.6362E+01
α_3	1.31E-05	8.97E-03	3.49E-03	3.65E-02	2.53E-04	4.2060E-01	4.6471E+01

Table 29-23: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9405549	0.9765552	0.9811102	0.9969800	0.9933549	6.5525E+01	1.5731E+00
α_2	3.29E-04	1.19E-02	7.53E-03	3.84E-02	5.96E-03	7.9890E-01	6.6299E+01
α_3	3.35E-07	4.32E-03	1.00E-03	2.00E-02	6.57E-04	2.8960E-01	6.6809E+01
α_4	2.43E-05	7.22E-03	3.23E-03	2.80E-02	2.43E-05	4.8460E-01	6.6614E+01

Table 29-24: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9405291	0.9729385	0.9763218	0.9937824	0.9900165	8.8775E+01	2.4692E+00
α_2	8.62E-04	1.24E-02	9.08E-03	3.54E-02	7.90E-03	1.1326E+00	9.0112E+01
α_3	2.43E-05	5.58E-03	2.60E-03	2.13E-02	1.90E-03	5.0920E-01	9.0735E+01
α_4	3.30E-08	2.66E-03	4.42E-04	1.30E-02	1.85E-04	2.4310E-01	9.1001E+01
α_5	5.41E-05	6.40E-03	3.33E-03	2.32E-02	5.85E-06	5.8430E-01	9.0660E+01

Table 29-25: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9424303	0.9716583	0.9743675	0.9916310	0.9883734	1.1111E+02	3.2409E+00
α_2	9.42E-04	1.10E-02	8.29E-03	3.02E-02	7.76E-03	1.2551E+00	1.1310E+02
α_3	1.35E-04	6.44E-03	3.88E-03	2.15E-02	3.19E-03	7.3650E-01	1.1361E+02
α_4	1.24E-06	3.07E-03	9.49E-04	1.33E-02	6.19E-04	3.5070E-01	1.1400E+02
α_5	3.14E-08	2.16E-03	3.68E-04	1.05E-02	5.38E-05	2.4660E-01	1.1410E+02
α_6	7.62E-05	5.70E-03	3.19E-03	1.99E-02	1.63E-06	6.520E-01	1.1370E+02

ALPHA FACTOR DISTRIBUTIONS
HPCI/RCIC Turbine Steam Supply Motor-Operated Valves

Table 29-26: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9447164	0.9858345	0.9937925	0.9999562	0.9999871	3.2730E+01	4.7030E-01
α_2	4.08E-05	1.42E-02	6.21E-03	5.53E-02	1.29E-05	4.7030E-01	3.2730E+01

Table 29-27: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9492929	0.9842362	0.9899859	0.9995570	0.9999770	4.9999E+01	8.080E-01
α_2	6.52E-06	7.64E-03	2.71E-03	3.20E-02	2.30E-05	3.8800E-01	5.0412E+01
α_3	1.05E-05	8.13E-03	3.09E-03	3.33E-02	0.00E+00	4.1280E-01	5.0387E+01

Table 29-28: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9513015	0.9820231	0.9862377	0.9983386	0.9999677	7.1097E+01	1.3015E+00
α_2	5.14E-05	7.67E-03	3.84E-03	2.83E-02	3.23E-05	5.5530E-01	7.1843E+01
α_3	1.05E-07	3.63E-03	7.04E-04	1.73E-02	0.00E+00	2.6260E-01	7.2136E+01
α_4	2.22E-05	6.68E-03	2.98E-03	2.59E-02	0.00E+00	4.8360E-01	7.1915E+01

ALPHA FACTOR DISTRIBUTIONS
HPCI/RCIC Motor-Operated Valves, both Injection and Turbine Steam Supply

Table 29-29: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.9322727	0.9689640	0.9727469	0.9927144	0.9712123	7.8492E+01	2.5141E+00
α_2	7.28E-03	3.10E-02	2.73E-02	6.77E-02	2.88E-02	2.5141E+00	7.8492E+01

Table 29-30: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.9496141	0.9759508	0.9785184	0.9935182	0.9798879	1.1853E+02	2.9208E+00
α_2	1.68E-05	4.14E-03	1.90E-03	1.58E-02	1.09E-03	5.0250E-01	1.2095E+02
α_3	4.46E-03	1.99E-02	1.73E-02	4.42E-02	1.90E-02	2.4183E+00	1.1903E+02

Table 29-31: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.9577290	0.9787631	0.9806564	0.9933203	0.9841097	1.6234E+02	3.5224E+00
α_2	1.04E-04	4.56E-03	2.78E-03	1.51E-02	1.44E-03	7.5550E-01	1.6511E+02
α_3	1.01E-07	1.70E-03	3.74E-04	7.93E-03	1.37E-04	2.8180E-01	1.6558E+02
α_4	3.44E-03	1.50E-02	1.31E-02	3.30E-02	1.43E-02	2.4851E+00	1.6338E+02

Table 29-32: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.9621018	0.9799414	0.9814146	0.9927455	0.9865718	2.0994E+02	4.2973E+00
α_2	2.60E-04	4.77E-03	3.35E-03	1.42E-02	1.69E-03	1.0226E+00	2.1322E+02
α_3	4.88E-06	2.12E-03	8.83E-04	8.42E-03	2.41E-04	4.5390E-01	2.1378E+02
α_4	9.98E-09	1.11E-03	1.73E-04	5.44E-03	1.78E-05	2.3670E-01	2.1400E+02
α_5	2.88E-03	1.21E-02	1.06E-02	2.63E-02	1.15E-02	2.5841E+00	2.1165E+02

Table 29-33: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	**5th%**	**Mean**	**Median**	**95th%**	**MLE**	**a**	**b**
α_1	0.9652425	0.9809011	0.9821116	0.9924212	0.9881654	2.5660E+02	4.9962E+00
α_2	3.27E-04	4.46E-03	3.28E-03	1.26E-02	1.86E-03	1.1662E+00	2.6043E+02
α_3	2.43E-05	2.35E-03	1.26E-03	8.36E-03	3.50E-04	6.1350E-01	2.6098E+02
α_4	2.38E-07	1.23E-03	3.33E-04	5.49E-03	3.88E-05	3.2080E-01	2.6128E+02
α_5	1.19E-08	9.32E-04	1.55E-04	4.55E-03	2.40E-06	2.4380E-01	2.6135E+02
α_6	2.48E-03	1.01E-02	8.92E-03	2.20E-02	9.59E-03	2.6519E+00	2.5894E+02

ALPHA FACTOR DISTRIBUTIONS
HPCI/RCIC Motor-Operated Valves, both Injection and Turbine Steam Supply

Table 29-34: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9523236	0.9869810	0.9933807	0.9999036	0.9972286	4.2598E+01	5.6190E-01
α_2	9.30E-05	1.30E-02	6.62E-03	4.77E-02	2.77E-03	5.6190E-01	4.2598E+01

Table 29-35: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9530013	0.9838619	0.9884480	0.9990323	0.9947832	6.4550E+01	1.0588E+00
α_2	1.20E-04	9.73E-03	5.39E-03	3.41E-02	5.06E-03	6.3820E-01	6.4971E+01
α_3	9.33E-06	6.41E-03	2.48E-03	2.61E-02	1.57E-04	4.2060E-01	6.5188E+01

Table 29-36: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9526069	0.9805480	0.9839147	0.9969793	0.9925857	9.0191E+01	1.7892E+00
α_2	5.94E-04	1.10E-02	7.75E-03	3.27E-02	6.99E-03	1.0150E+00	9.0965E+01
α_3	2.44E-07	3.15E-03	7.29E-04	1.46E-02	4.09E-04	2.8960E-01	9.1691E+01
α_4	1.77E-05	5.27E-03	2.35E-03	2.04E-02	1.52E-05	4.8460E-01	9.1496E+01

Table 29-37: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9510468	0.9768542	0.9794076	0.9939408	0.9893969	1.1943E+02	2.8298E+00
α_2	1.44E-03	1.22E-02	9.67E-03	3.17E-02	9.30E-03	1.4932E+00	1.2077E+02
α_3	1.81E-05	4.17E-03	1.94E-03	1.59E-02	1.18E-03	5.0920E-01	1.2175E+02
α_4	2.46E-08	1.99E-03	3.29E-04	9.71E-03	1.16E-04	2.4310E-01	1.2202E+02
α_5	4.03E-05	4.78E-03	2.48E-03	1.73E-02	3.65E-06	5.8430E-01	1.2168E+02

Table 29-38: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9513028	0.9750281	0.9770935	0.9917097	0.9872568	1.4768E+02	3.7823E+00
α_2	1.84E-03	1.19E-02	9.79E-03	2.90E-02	1.03E-02	1.7965E+00	1.4967E+02
α_3	1.02E-04	4.86E-03	2.93E-03	1.62E-02	1.99E-03	7.3650E-01	1.5073E+02
α_4	9.31E-07	2.32E-03	7.15E-04	1.01E-02	3.86E-04	3.5070E-01	1.5111E+02
α_5	2.37E-08	1.63E-03	2.78E-04	7.91E-03	3.35E-05	2.4660E-01	1.5122E+02
α_6	5.74E-05	4.31E-03	2.41E-03	1.50E-02	1.02E-06	6.5200E-01	1.5081E+02

30. BWR Residual Heat Removal Motor-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving motor-operated valves (MOVs) in the residual heat removal (RHR) system and low pressure coolant injection (LPCI) system at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified 23 common-cause failure-to-open events, 24 common-cause failure-to-close events, and 14 common-cause failure-to-remain-closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 30-1 and 30-2, respectively. Table 30-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 30-4 through 30-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 30-10 through 30-24.

2. SYSTEM DESCRIPTION

The RHR system and LPCI system in BWR plants is a part of the emergency core cooling system (ECCS) that serves several functions by operating in different modes:

- Low pressure coolant injection (LPCI) mode - to provide low pressure makeup water to the reactor vessel for core cooling under loss of coolant accident (LOCA) conditions,
- Containment spray mode - to reduce primary containment pressure and temperature following a LOCA,
- Shutdown cooling and head spray mode - to remove decay heat from the reactor core following a reactor shutdown and to reduce reactor vessel dome pressure during normal cooldown,
- Suppression pool cooling mode - to remove heat from the suppression pool,
- Steam condensing mode - to provide a means of removing decay heat with main steam isolation valves closed,
- Containment flooding mode - to provide a means of flooding primary containment, and
- Fuel pool cooling assist mode - to provide a means to augment the fuel pool cooling and cleanup system.

Under accident conditions, the LPCI mode is automatically initiated. All other modes require manual system alignment for proper operation. In the LPCI mode, the pumps takes suction from the suppression pool and discharge to the recirculation loops. The RHR heat exchangers are bypassed in this mode. The containment spray mode protects the containment structure from possible over pressurization from steam which might bypass the suppression pool, including system breaks within the containment volume. In this mode water is pumped from the suppression pool through heat exchangers to spray nozzles located high in the containment space. The suppression pool cooling mode is designed to

ALPHA FACTOR AND MGL PARAMETERS
BWR Residual Heat Removal Motor-Operated Valves

Table 30-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9747769	0.9720205	0.9664169	0.9654873	0.9656303
α_2	2.52E-02	1.66E-02	2.30E-02	1.84E-02	1.53E-02
α_3		1.14E-02	2.45E-03	8.71E-03	9.32E-03
α_4			8.17E-03	8.52E-04	3.84E-03
α_5				6.56E-03	4.32E-04
α_6					5.49E-03

Table 30-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.75E-01	9.72E-01	9.66E-01	9.66E-01	9.66E-01
Beta	2.52E-02	2.80E-02	3.36E-02	3.45E-02	3.44E-02
Gamma		4.08E-01	3.16E-01	4.67E-01	5.55E-01
Delta			7.69E-01	4.60E-01	5.12E-01
Epsilon				8.85E-01	6.06E-01
Mu					9.27E-01

Table 30-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	113.37	170.05	226.74	283.42	340.11
N_1	10.5529	12.4522	12.7760	12.9310	13.4675
N_2	3.2066	3.1084	5.6924	5.6472	5.5963
N_3		2.1449	0.6072	2.6729	3.4142
N_4			2.0236	0.2614	1.4068
N_5				2.0120	0.1582
N_6					2.0094

Total Number of Independent Failure Events: 318
Total Number of Common-Cause Failure Events: 23

ALPHA FACTOR AND MGL PARAMETERS

BWR Residual Heat Removal Motor-Operated Valves

Table 30-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
α_1	0.9722298	0.9635205	0.9579754	0.9561519	0.9562972
α_2	2.78E-002	2.44E-02	2.77E-02	2.49E-02	2.06E-02
α_3		1.21E-02	6.17E-03	1.08E-02	1.35E-02
α_4			8.19E-03	1.76E-03	3.51E-03
α_5				6.40E-03	6.88E-04
α_6					5.34E-03

Table 30-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
1-Beta	9.72E-01	9.64E-01	9.58E-01	9.56E-01	9.56E-01
Beta	2.78E-02	3.65E-02	4.20E-02	4.39E-02	4.37E-02
Gamma		3.32E-01	3.42E-01	4.32E-01	5.28E-01
Delta			5.70E-01	4.31E-01	4.13E-01
Epsilon				7.84E-01	6.32E-01
Mu					8.86E-01

Table 30-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
Adj. Ind. Events	55.58	83.36	111.15	138.94	166.72
N_1	8.8765	10.7351	11.8845	12.8798	13.9079
N_2	1.8411	2.3814	3.5540	3.9561	3.8944
N_3		1.1811	0.7920	1.7100	2.5577
N_4			1.0513	0.2796	0.6634
N_5				1.0166	0.1300
N_6					1.0092

Total Number of Independent Failure Events: 162
Total Number of Common-Cause Failure Events: 24

ALPHA FACTOR AND MGL PARAMETERS

BWR Residual Heat Removal Motor-Operated Valves

Table 30-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9887587	0.9773790	0.9656687	0.9430002	0.9286212
α_2	1.12E-02	2.26E-02	3.43E-02	5.23E-02	5.89E-02
α_3		0.00E+00	0.00E+00	4.75E-03	1.10E-02
α_4			0.00E+00	0.00E+00	1.50E-03
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 30-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.89E-01	9.77E-01	9.66E-01	9.43E-01	9.29E-01
Beta	1.12E-02	2.26E-02	3.43E-02	5.70E-02	7.14E-02
Gamma		0.00E+00	0.00E+00	8.34E-02	1.76E-01
Delta			0.00E+00	0.00E+00	1.20E-01
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 30-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	5.37	8.05	10.73	13.41	16.10
N_1	2.7485	3.8491	4.7657	5.2350	5.6315
N_2	0.0923	0.2754	0.5509	1.0330	1.3771
N_3		0.0000	0.0000	0.0940	0.2581
N_4			0.0000	0.0000	0.0352
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 18
Total Number of Common-Cause Failure Events: 14

limit the long term bulk temperature rise of the suppression pool water following a design basis LOCA. A closed path from the suppression pool through the RHR loops to the reactor vessel and back to the suppression pool through the break can be maintained for decay heat removal from the core.

The shutdown cooling and head spray mode takes suction from the recirculation system loop and discharges back into the condensate and feedwater system lines. The water passes through the heat exchangers where it is cooled by the service water system. Following isolation of the reactor from its primary heat sink, the RHR steam condensing mode is used in conjunction with the reactor core isolation cooling system to remove decay heat, via the heat exchangers, and minimize the makeup water requirements. Containment flooding is accomplished by the standby coolant supply mode by cross connecting the service water system and pumping service water into the reactor vessel. The fuel pool assist mode allows the RHR system to provide additional cooling to the spent fuel in the fuel pool.

A simplified schematic drawing of a typical BWR RHR system configuration in presented in Figure 30-1.

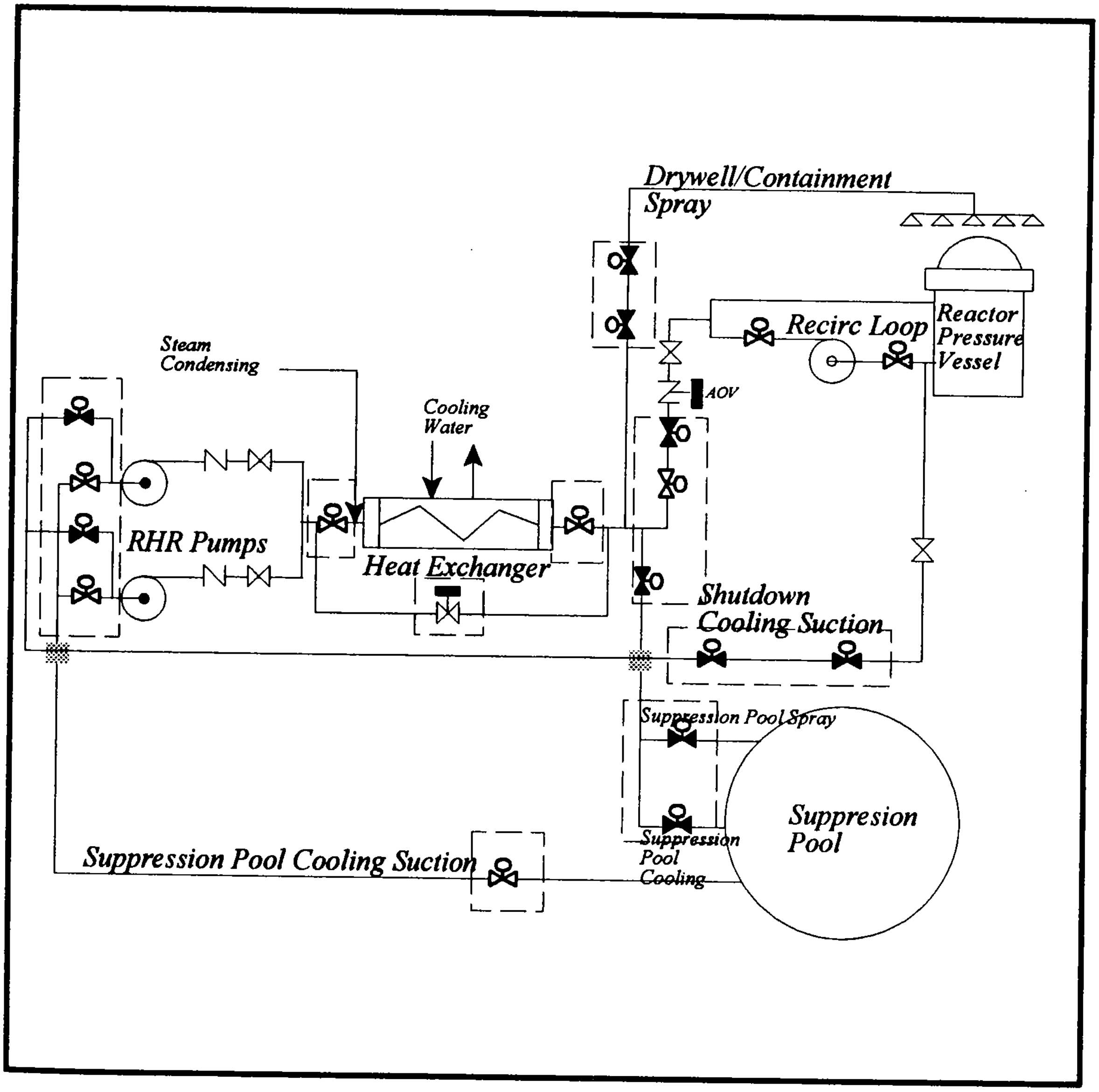

Figure 30-1. BWR residual heat removal system.

3. COMPONENT BOUNDARIES

The main components of a motor-operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual hand wheels, and can be manually operated. AC or DC power is required for valve operation.

MOVs are used in the RHR system in the following applications:

- Pump discharge,
- Pump suction,
- Loop injection, and
- System inter- or cross-connection.

4. FAILURE EVENT DEFINITION

The function of the injection MOVs is to allow injection flow to the reactor vessel. During normal plant operations, most of the MOVs remain closed to isolate the high pressure and low pressure portions of the system. The failure modes used in evaluating the RHR MOV data are:

CC	Fail to Open: A successful operation of the valve is the valve is in the fully open position. Anything less than fully open is considered a failure to open.
OO	Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.
VR	Fail to Remain Closed: Leakage through the valve following a successful closure. This is intended to capture leakage events that affect the operation of the system or the plant, and not minor leakage resulting in failure of local leak rate tests.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure. These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC."

Many LERs reported only one actual failure, but the report information indicated that failure of a second MOV would have occurred from the same cause if a operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 30-10 through 30-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of MOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
BWR Residual Heat Removal Motor-Operated Valves

Table 30-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9473482	0.9731883	0.9754598	0.9912686	0.9747769	1.3345E+02	3.6766E+00
α_2	8.73E-03	2.68E-02	2.45E-02	5.27E-02	2.52E-02	3.6766E+00	1.3345E+02

Table 30-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9485072	0.9702910	0.9718152	0.9868635	0.9720205	1.9770E+02	6.0533E+00
α_2	5.35E-03	1.72E-02	1.56E-02	3.43E-02	1.66E-02	3.4956E+00	2.026E+02
α_3	2.97E-03	1.26E-02	1.10E-02	2.75E-02	1.14E-02	2.5577E+00	2.0120E+02

Table 30-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9448602	0.9648587	0.9659872	0.9810100	0.9664169	2.6422E+02	9.6232E+00
α_2	1.02E-02	2.28E-02	2.17E-02	3.93E-02	2.30E-02	6.2462E+00	2.6760E+02
α_3	1.12E-04	3.18E-03	2.08E-03	9.98E-03	2.45E-03	8.6980E-01	2.7297E+02
α_4	2.12E-03	9.16E-03	7.99E-03	2.02E-02	8.17E-03	2.5072E+00	2.7134E+02

Table 30-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9459783	0.9638236	0.9647136	0.9786397	0.9654873	3.3439E+02	1.2551E+01
α_2	8.30E-03	1.84E-02	1.75E-02	3.16E-02	1.84E-02	6.3752E+00	3.4057E+02
α_3	2.50E-03	8.89E-03	7.97E-03	1.85E-02	8.71E-03	3.0849E+00	3.4386E+02
α_4	5.33E-06	1.43E-03	6.45E-04	5.50E-03	8.52E-04	4.9500E-01	3.4645E+02
α_5	1.79E-03	7.48E-03	6.56E-03	1.63E-02	6.56E-03	2.5960E+00	3.4435E+02

Table 30-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9478310	0.9639460	0.9646846	0.9775496	0.9656303	4.0405E+02	1.5113E+01
α_2	6.87E-03	1.52E-02	1.45E-02	2.62E-02	1.53E-02	6.3754E+00	4.1279E+02
α_3	3.21E-03	9.44E-03	8.67E-03	1.83E-02	9.32E-03	3.9548E+00	4.1521E+02
α_4	5.96E-04	4.10E-03	3.35E-03	1.02E-02	3.84E-03	1.7195E+00	4.1744E+02
α_5	1.02E-06	9.58E-04	3.49E-04	3.97E-03	4.32E-04	4.0150E-01	4.1876E+02
α_6	1.55E-03	6.35E-03	5.58E-03	1.38E-02	5.49E-03	2.6613E+00	4.1650E+02

ALPHA FACTOR DISTRIBUTIONS
BWR Residual Heat Removal Motor-Operated Valves

Table 30-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9321933	0.9697096	0.9737228	0.9935002	0.9722298	7.3987E+01	2.3111E+00
α_2	6.50E-03	3.03E-02	2.63E-02	6.78E-02	2.78E-02	2.3111E+00	7.3987E+01

Table 30-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9282071	0.9616188	0.9642975	0.9858619	0.9635205	1.0930E+02	4.3625E+00
α_2	6.26E-03	2.44E-02	2.16E-02	5.18E-02	2.44E-02	2.7686E+00	1.1089E+02
α_3	1.83E-03	1.40E-02	1.13E-02	3.56E-02	1.21E-02	1.5939E+00	1.1207E+02

Table 30-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9268079	0.9566314	0.9585934	0.9797550	0.9579754	1.4773E+02	6.6973E+00
α_2	9.37E-03	2.66E-02	2.46E-02	5.07E-02	2.77E-02	4.1078E+00	1.5032E+02
α_3	4.01E-04	6.83E-03	4.85E-03	2.00E-02	6.17E-03	1.0546E+00	1.5337E+02
α_4	1.22E-03	9.94E-03	7.92E-03	2.56E-02	8.19E-03	1.5349E+00	1.5289E+02

Table 30-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9287053	0.9551268	0.9566451	0.9763528	0.9561519	1.8986E+02	8.9199E+00
α_2	9.02E-03	2.36E-02	2.20E-02	4.35E-02	2.49E-02	4.6841E+00	1.9410E+02
α_3	2.05E-03	1.07E-02	9.08E-03	2.47E-02	1.08E-02	2.1220E+00	1.9666E+02
α_4	1.17E-05	2.58E-03	1.21E-03	9.82E-03	1.76E-03	5.1320E-01	1.9827E+02
α_5	1.05E-03	8.05E-03	6.47E-03	2.05E-02	6.40E-03	1.6060E+00	1.9718E+02

Table 30-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9317061	0.9554234	0.9566721	0.9748693	0.9562972	2.3110E+02	1.0782E+01
α_2	7.37E-03	1.93E-02	1.80E-02	3.58E-02	2.06E-02	4.6735E+00	2.3721E+02
α_3	3.62E-03	1.28E-02	1.15E-02	2.65E-02	1.35E-02	3.0983E+00	2.3878E+02
α_4	1.96E-04	4.04E-03	2.78E-03	1.22E-02	3.51E-03	9.7610E-01	2.4091E+02
α_5	9.90E-07	1.54E-03	5.16E-04	6.56E-03	6.88E-04	3.7330E-01	2.4151E+02
α_6	9.50E-04	6.87E-03	5.56E-03	1.72E-02	5.34E-03	1.6611E+00	2.4022E+02

ALPHA FACTOR DISTRIBUTIONS
BWR Residual Heat Removal Motor-Operated Valves

Table 30-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8879870	0.9691235	0.9839587	0.9997701	0.9887587	1.7649E+01	5.6230E-01
α_2	2.27E-04	3.09E-02	1.60E-02	1.12E-01	1.12E-02	5.6230E-01	1.7649E+01

Table 30-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8907270	0.9618306	0.9721523	0.9975799	0.9773790	2.7099E+01	1.0754E+00
α_2	3.42E-04	2.35E-02	1.35E-02	8.07E-02	2.26E-02	6.6260E-01	2.7512E+01
α_3	1.92E-05	1.47E-02	5.63E-03	5.99E-02	0.00E+00	4.1280E-01	2.7762E+01

Table 30-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8951225	0.9559801	0.9630261	0.9927108	0.9656687	4.0196E+01	1.8509E+00
α_2	1.75E-03	2.63E-02	1.92E-02	7.50E-02	3.43E-02	1.1047E+00	4.0942E+01
α_3	1.83E-07	6.25E-03	1.22E-03	2.98E-02	0.00E+00	2.6260E-01	4.1784E+01
α_4	3.85E-05	1.15E-02	5.16E-03	4.45E-02	0.00E+00	4.8360E-01	4.1563E+01

Table 30-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8946908	0.9483936	0.9533358	0.9851853	0.9430002	5.6687E+01	3.0846E+00
α_2	4.51E-03	2.95E-02	2.44E-02	7.18E-02	5.23E-02	1.7610E+00	5.8011E+01
α_3	3.59E-05	8.47E-03	3.93E-03	3.23E-02	4.75E-03	5.0600E-01	5.9266E+01
α_4	3.04E-08	3.91E-03	5.97E-04	1.93E-02	0.00E+00	2.3360E-01	5.9538E+01
α_5	8.27E-05	9.77E-03	5.10E-03	3.53E-02	0.00E+00	5.8400E-01	5.9188E+01

Table 30-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8968199	0.9450538	0.9489041	0.9801115	0.9286212	7.2204E+01	4.1980E+00
α_2	5.60E-03	2.82E-02	2.42E-02	6.46E-02	5.89E-02	2.1562E+00	7.4246E+01
α_3	2.88E-04	1.05E-02	6.60E-03	3.38E-02	1.10E-02	7.9870E-01	7.5603E+01
α_4	1.73E-06	4.55E-03	1.40E-03	1.98E-02	1.50E-03	3.4790E-01	7.6054E+01
α_5	3.98E-08	3.18E-03	5.30E-04	1.55E-02	0.00E+00	2.4330E-01	7.6159E+01
α_6	1.14E-04	8.53E-03	4.79E-03	2.97E-02	0.00E+00	6.5190E-01	7.5750E+01

31. PWR High Pressure Safety Injection Motor-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving motor-operated valves (MOVs) in the high pressure safety injection system (HPSI) system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified 23 common-cause failure-to-open events, 11 common-cause failure-to-close, and six failure-to-remain closed CCF events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 31-1 and 31-2, respectively. Table 31-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 31-4 through 31-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 31-10 through 31-24.

2. SYSTEM DESCRIPTION

The high pressure safety injection (HPSI) system is a subsystem of the emergency core cooling system (ECCS) that functions to provide emergency coolant injection to maintain reactor coolant inventory and provide adequate decay heat removal following a loss of coolant accident (LOCA). The coolant injection function is performed in a relatively short time interval after initiation of the LOCA. The system is typically comprised of two safety injection (SI) pumps and two or three high pressure centrifugal charging pumps (CCP); one CCP is an installed spare which can be manually aligned to either train. The HPSI pumps inject directly into the primary loop cold legs, and the SI pumps can be realigned to inject into the hot legs. The suction source for the HPSI MOVs is the refueling water storage tank (RWST) and contains enough highly borated water to satisfy the injection needs of the core. Figure 31-1 illustrates the typical flow path for the HPSI system. All pumps and most motor-operated valves receive power from the 1E emergency power system and are backed up by the emergency diesel generators.

The system is normally aligned and in the standby mode. The HPSI pumps are started by the engineered safety features actuation system (ESFAS) or may be manually actuated. A HPSI signal starts the charging and SI pumps, shifts the charging pump suction to the RWST, isolates normal charging and letdown flow and completes additional valve lineup changes. The injection phase ends when the RWST reaches the low level setpoint and the system is realigned for the recirculation phase. The number of HPSI MOVs at a plant is usually at least 12, but due to the diversity of the system functions, most CCF events only affect about six MOVs.

ALPHA FACTOR AND MGL PARAMETERS
High Pressure Safety Injection Motor-Operated Valves

Table 31-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9213610	0.9355827	0.9386097	0.9412263	0.9430793
α_2	7.86E-02	1.57E-02	2.32E-02	2.25E-02	2.22E-02
α_3		4.87E-02	1.28E-03	6.00E-03	7.04E-03
α_4			3.69E-02	3.06E-04	2.33E-03
α_5				3.00E-02	8.83E-05
α_6					2.52E-02

Table 31-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.21E-01	9.36E-01	9.39E-01	9.41E-01	9.43E-01
Beta	7.86E-02	6.44E-02	6.14E-02	5.88E-02	5.69E-02
Gamma		7.56E-01	6.22E-01	6.17E-01	6.09E-01
Delta			9.66E-01	8.35E-01	7.97E-01
Epsilon				9.90E-01	9.16E-01
Mu					9.97E-01

Table 31-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	71.81	107.72	143.63	179.53	215.44
N_1	7.1499	8.6794	9.0664	9.0046	8.8002
N_2	6.7393	1.9575	3.7738	4.5094	5.2865
N_3		6.0569	0.2089	1.2016	1.6735
N_4			6.0045	0.0612	0.5533
N_5				6.0006	0.0210
N_6					6.0000

Total Number of Independent Failure Events: 200
Total Number of Common-Cause Failure Events: 23

ALPHA FACTOR AND MGL PARAMETERS
High Pressure Safety Injection Motor-Operated Valves

Table 31-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9859859	0.9780496	0.9727823	0.9685667	0.9647397
α_2	1.40E-02	1.88E-02	2.12E-02	2.36E-02	2.66E-02
α_3		3.16E-03	4.82E-03	4.92E-03	4.23E-03
α_4			1.19E-03	2.40E-03	3.03E-03
α_5				4.79E-04	1.21E-03
α_6					2.01E-04

Table 31-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.86E-01	9.78E-01	9.73E-01	9.69E-01	9.65E-01
Beta	1.40E-02	2.20E-02	2.72E-02	3.14E-02	3.53E-02
Gamma		1.44E-01	2.21E-01	2.48E-01	2.46E-01
Delta			1.98E-01	3.69E-01	5.12E-01
Epsilon				1.66E-01	3.17E-01
Mu					1.43E-01

Table 31-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	23.95	35.92	47.90	59.87	71.85
N_1	2.5323	3.0497	3.3202	3.3776	3.2245
N_2	0.3764	0.7486	1.1168	1.5432	2.0699
N_3		0.1260	0.2537	0.3213	0.3289
N_4			0.0626	0.1568	0.2356
N_5				0.0313	0.0939
N_6					0.0156

Total Number of Independent Failure Events: 74
Total Number of Common-Cause Failure Events: 11

ALPHA FACTOR AND MGL PARAMETERS
High Pressure Safety Injection Motor-Operated Valves

Table 31-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9943181	0.9886125	0.9828025	0.9780968	0.9749604
α_2	5.68E-03	1.14E-02	1.72E-02	1.87E-02	1.90E-02
α_3		0.00E+00	6.25E-06	3.20E-03	5.40E-03
α_4			0.00E+00	0.00E+00	6.57E-04
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 31-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.94E-01	9.89E-01	9.83E-01	9.78E-01	9.75E-01
Beta	5.68E-03	1.14E-02	1.72E-02	2.19E-02	2.50E-02
Gamma		0.00E+00	3.63E-04	1.46E-01	2.42E-01
Delta			0.00E+00	0.00E+00	1.08E-01
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 31-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	7.20	10.80	14.40	18.00	21.60
N_1	0.8499	1.1371	1.3328	1.4653	1.5674
N_2	0.0460	0.1375	0.2752	0.3723	0.4510
N_3		0.0000	0.0001	0.0636	0.1284
N_4			0.0000	0.0000	0.0156
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 18
Total Number of Common-Cause Failure Events: 6

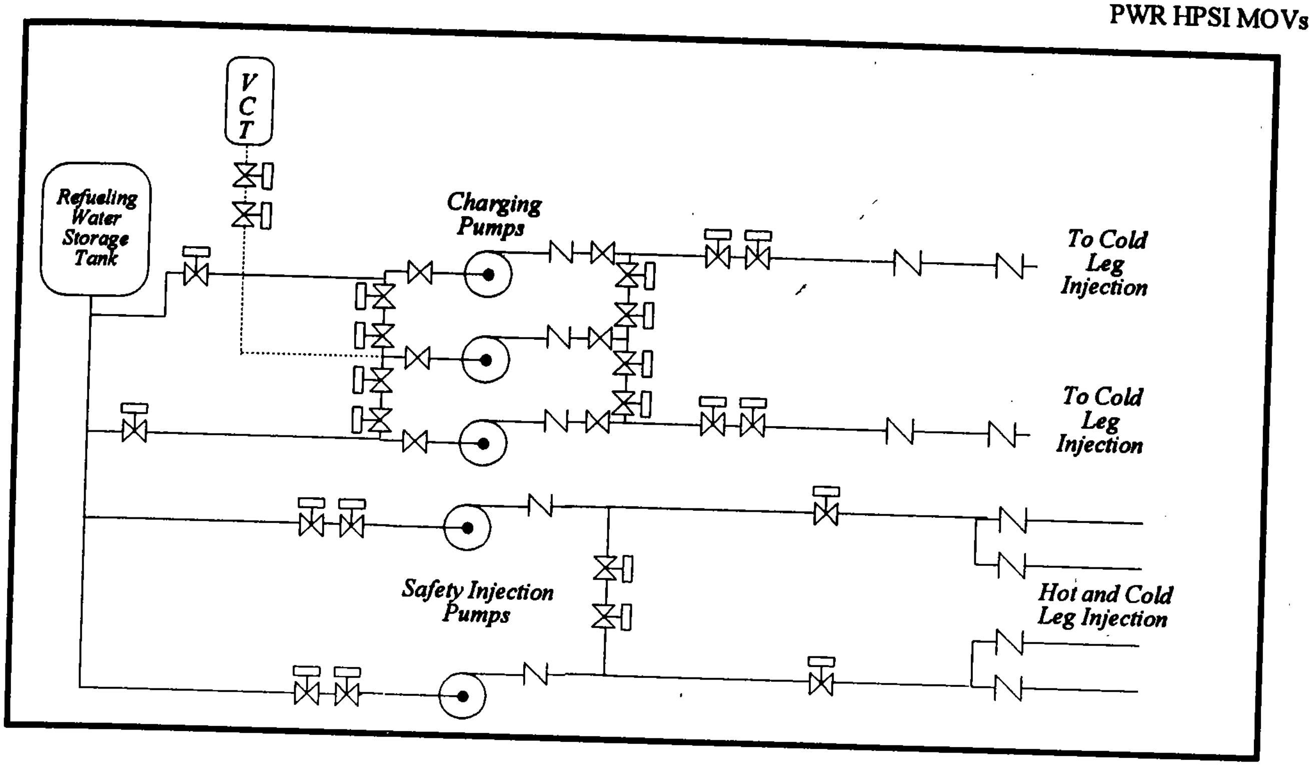

Figure 31-1. PWR high pressure safety injection system.

3. COMPONENT BOUNDARIES

The main components of a motor-operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual hand wheels, and can be manually operated. AC or DC power is required for valve operation.

The MOVs in the HPSI system are used in the following applications:

- Admitting borated water to the suction of the charging pumps and safety injection pumps,
- Shifting charging pump and safety injection pump suction to the containment sump, and
- Aligning discharge of safety injection pumps from cold leg to hot leg injection.

4. FAILURE EVENT DEFINITION

The function of the HPSI MOVs is to allow borated water flow through the HPSI system into the reactor coolant system. All valves serve as a system containment boundary and would need to close to isolate leaks. The failure modes used in evaluating the Safety Injection System MOV data are:

CC Fail to Open: The valve must be in the fully open position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: In cases where the motor-operated valve has been closed for a substantial period of time and is then discovered leaking, the failure will be coded as VR. If the discovery is made soon after a system configuration change (i.e., pump operation), then the failure is coded as OO.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure. These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC."

Many LERs reported only one actual failure, but the report information indicated that failure of a second MOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 31-10 through 31-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of motor operated valves. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
High Pressure Safety Injection Motor-Operated Valves

Table 31-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8760082	0.9246672	0.9276156	0.9632430	0.9213610	8.8490E+01	7.2093E+00
α_2	3.68E-02	7.53E-02	7.24E-02	1.24E-01	7.86E-02	7.2093E+00	8.8490E+01

Table 31-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9004928	0.9372258	0.9392932	0.9668882	0.9355827	1.3160E+02	8.8144E+00
α_2	3.61E-03	1.67E-02	1.45E-02	3.74E-02	1.57E-02	2.3447E+00	1.3807E+02
α_3	2.12E-02	4.61E-02	4.39E-02	7.83E-02	4.87E-02	6.4697E+00	1.3395E+02

Table 31-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9094451	0.9401804	0.9417344	0.9656175	0.9386097	1.7740E+02	1.1287E+01
α_2	8.35E-03	2.29E-02	2.13E-02	4.32E-02	2.32E-02	4.3276E+00	1.8436E+02
α_3	7.16E-06	2.50E-03	1.08E-03	9.79E-03	1.28E-03	4.7150E-01	1.8822E+02
α_4	1.58E-02	3.44E-02	3.28E-02	5.86E-02	3.69E-02	6.4881E+00	1.8220E+02

Table 31-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9163618	0.9428639	0.9440875	0.9651758	0.9412263	2.2658E+02	1.3730E+01
α_2	8.90E-03	2.18E-02	2.05E-02	3.92E-02	2.25E-02	5.2374E+00	2.3507E+02
α_3	8.89E-04	6.72E-03	5.41E-03	1.70E-02	6.00E-03	1.6136E+00	2.3870E+02
α_4	1.12E-07	1.23E-03	2.91E-04	5.64E-03	3.06E-04	2.9480E-01	2.4002E+02
α_5	1.26E-02	2.74E-02	2.61E-02	4.66E-02	3.00E-02	6.5846E+00	2.3373E+02

Table 31-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9211586	0.9447612	0.9457806	0.9648946	0.9430793	2.7471E+02	1.6062E+01
α_2	9.21E-03	2.09E-02	1.98E-02	3.62E-02	2.22E-02	6.0656E+00	2.8471E+02
α_3	1.54E-03	7.62E-03	6.52E-03	1.74E-02	7.04E-03	2.2141E+00	2.8856E+02
α_4	1.04E-04	2.98E-03	1.95E-03	9.38E-03	2.33E-03	8.6600E-01	2.8991E+02
α_5	2.81E-08	9.09E-04	1.78E-04	4.33E-03	8.83E-05	2.6430E-01	2.9051E+02
α_6	1.06E-02	2.29E-02	2.18E-02	3.89E-02	2.52E-02	6.6519E+00	2.8412E+02

ALPHA FACTOR DISTRIBUTIONS
High Pressure Safety Injection Motor-Operated Valves

Table 31-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9278629	0.9770364	0.9849376	0.9992307	0.9859859	3.6012E+01	8.4640E-01
α_2	7.66E-04	2.30E-02	1.51E-02	7.21E-02	1.40E-02	8.4640E-01	3.6012E+01

Table 31-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9257368	0.9700132	0.9754375	0.9957255	0.9780496	5.4170E+01	1.6746E+00
α_2	1.43E-03	2.03E-02	1.50E-02	5.77E-02	1.88E-02	1.1358E+00	5.4709E+01
α_3	5.62E-05	9.65E-03	4.73E-03	3.59E-02	3.16E-03	5.3880E-01	5.5306E+01

Table 31-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9261190	0.9652512	0.9691281	0.9911345	0.9727823	7.5920E+01	2.7331E+00
α_2	3.00E-03	2.12E-02	1.73E-02	5.29E-02	2.12E-02	1.6706E+00	7.6983E+01
α_3	3.08E-05	6.56E-03	3.10E-03	2.49E-02	4.82E-03	5.1630E-01	7.8137E+01
α_4	4.30E-05	6.94E-03	3.43E-03	2.58E-02	1.19E-03	5.4620E-01	7.8107E+01

Table 31-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9272028	0.9619165	0.9648071	0.9867360	0.9685667	1.0129E+02	4.0102E+00
α_2	4.52E-03	2.16E-02	1.86E-02	4.87E-02	2.36E-02	2.2712E+00	1.0303E+02
α_3	1.44E-04	6.96E-03	4.19E-03	2.32E-02	4.92E-03	7.3330E-01	1.0457E+02
α_4	3.28E-06	3.71E-03	1.32E-03	1.55E-02	2.40E-03	3.9040E-01	1.0491E+02
α_5	6.17E-05	5.84E-03	3.15E-03	2.08E-02	4.79E-04	6.1530E-01	1.0469E+02

Table 31-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9280955	0.9597046	0.9620263	0.9833660	0.9647397	1.2555E+02	5.2715E+00
α_2	5.73E-03	2.18E-02	1.94E-02	4.60E-02	2.66E-02	2.8490E+00	1.2797E+02
α_3	2.36E-04	6.65E-03	4.36E-03	2.09E-02	4.23E-03	8.6950E-01	1.2995E+02
α_4	2.63E-05	4.19E-03	2.07E-03	1.56E-02	3.03E-03	5.4830E-01	1.3027E+02
α_5	7.60E-07	2.58E-03	7.54E-04	1.13E-02	1.21E-03	3.3720E-01	1.3048E+02
α_6	7.47E-05	5.10E-03	2.90E-03	1.76E-02	2.01E-04	6.6750E-01	1.3015E+02

ALPHA FACTOR DISTRIBUTIONS
High Pressure Safety Injection Motor-Operated Valves

Table 31-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8931325	0.9714854	0.9861789	0.9998643	0.9943181	1.7580E+01	5.160E-01
α_2	1.38E-04	2.85E-02	1.38E-02	1.07E-01	5.68E-03	5.160E-01	1.7580E+01

Table 31-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8994148	0.9666067	0.9769272	0.9985020	0.9886125	2.7137E+01	9.3750E-01
α_2	9.68E-05	1.87E-02	9.07E-03	7.00E-02	1.14E-02	5.2470E-01	2.7550E+01
α_3	1.93E-05	1.47E-02	5.65E-03	6.01E-02	0.00E+00	4.1280E-01	2.7662E+01

Table 31-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9056076	0.9625003	0.9695904	0.9950997	0.9828025	4.0433E+01	1.5753E+00
α_2	6.17E-04	1.97E-02	1.28E-02	6.26E-02	1.72E-02	8.2900E-01	4.1179E+01
α_3	1.84E-07	6.25E-03	1.22E-03	2.98E-02	6.25E-06	2.6270E-01	4.1746E+01
α_4	3.85E-05	1.15E-02	5.16E-03	4.45E-02	0.00E+00	4.8360E-01	4.1525E+01

Table 31-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9118577	0.9600421	0.9650603	0.9910414	0.9780968	5.7507E+01	2.3935E+00
α_2	1.20E-03	1.84E-02	1.33E-02	5.27E-02	1.87E-02	1.1030E+00	5.8800E+01
α_3	2.41E-05	7.94E-03	3.49E-03	3.10E-02	3.20E-03	4.7560E-01	5.9425E+01
α_4	3.04E-08	3.90E-03	5.96E-04	1.93E-02	0.00E+00	2.3360E-01	5.9667E+01
α_5	8.26E-05	9.75E-03	5.08E-03	3.53E-02	0.00E+00	5.8400E-01	5.9317E+01

Table 31-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9169117	0.9593208	0.9632555	0.9882700	0.9749604	7.3639E+01	3.1226E+00
α_2	1.33E-03	1.60E-02	1.21E-02	4.43E-02	1.90E-02	1.2301E+00	7.5532E+01
α_3	1.29E-04	8.72E-03	4.98E-03	3.00E-02	5.40E-03	6.690E-01	7.6093E+01
α_4	1.02E-06	4.28E-03	1.21E-03	1.90E-02	6.57E-04	3.2830E-01	7.6433E+01
α_5	3.97E-08	3.17E-03	5.28E-04	1.55E-02	0.00E+00	2.4330E-01	7.6518E+01
α_6	1.14E-04	8.49E-03	4.77E-03	2.95E-02	0.00E+00	6.5190E-01	7.6110E+01

32. PWR Low Pressure Safety Injection Motor-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving motor-operated valves (MOVs) in the low pressure safety injection (LPSI) system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified 13 common-cause failure-to-open events, six common-cause failure-to-close, and four failure-to-remain closed CCF events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 32-1 and 32-2, respectively. Table 32-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 32-4 through 32-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 32-10 through 32-24.

2. SYSTEM DESCRIPTION

The low pressure safety injection system (LPSI) is a subsystem of the emergency core cooling system (ECCS) that functions to provide emergency coolant injection to maintain reactor coolant inventory and provide adequate long term decay heat removal following a loss of coolant accident (LOCA). The low pressure safety injection function is performed over a relatively long time interval after initiation of the LOCA. The LPSI pumps inject directly into the primary loop cold legs and can be realigned to inject into the hot legs. The initial suction source for the LPSI pumps is the refueling water storage tank (RWST) which contains enough highly borated water to satisfy the injection needs of the core. During the recirculation phase the pumps take a suction from the containment sump and supply flow to the loops or to the suction of the high pressure safety injection pumps. These pumps also provide for the shutdown cooling function. Figure 32-1 illustrates the typical flow path for the LPSI system. The system is typically comprised of two high capacity centrifugal pumps. The pumps receive power from the 1E emergency power system and are backed up by the emergency diesel generators.

The system is normally aligned and in the standby mode. The LPSI pumps are started by the engineered safety features actuation system or may be manually actuated. A safety injection (SI) signal starts the pumps, aligns the pump suction to the RWST, and completes additional valve lineup changes. The injection phase ends when the RWST reaches the low level setpoint and the system is realigned for the recirculation phase. The number of LPSI MOVs is usually at least eight; some plant designs have multiple MOVs in series on the reactor coolant system (RCS) suction line.

ALPHA FACTOR AND MGL PARAMETERS
PWR Low Pressure Safety Injection Motor-Operated Valves

Table 32-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9910681	0.9863696	0.9851123	0.9839008	0.9826218
α_2	8.93E-03	1.15E-02	9.04E-03	1.05E-02	1.17E-02
α_3		2.17E-03	5.49E-03	2.50E-03	2.10E-03
α_4			3.56E-04	3.02E-03	1.70E-03
α_5				1.04E-04	1.83E-03
α_6					4.34E-05

Table 32-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.91E-01	9.86E-01	9.85E-01	9.84E-01	9.83E-01
Beta	8.93E-03	1.36E-02	1.49E-02	1.61E-02	1.74E-02
Gamma		1.59E-01	3.93E-01	3.49E-01	3.26E-01
Delta			6.09E-02	5.55E-01	6.29E-01
Epsilon				3.34E-02	5.24E-01
Mu					2.32E-02

Table 32-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	115.16	172.74	230.33	287.91	345.49
N_1	5.8514	6.6975	7.4762	7.7578	7.6235
N_2	1.0906	2.0856	2.1821	3.1479	4.2080
N_3		0.3940	1.3258	0.7525	0.7556
N_4			0.0860	0.9062	0.6095
N_5				0.0313	0.6563
N_6					0.0156

Total Number of Independent Failure Events: 319
Total Number of Common-Cause Failure Events: 13

ALPHA FACTOR AND MGL PARAMETERS
PWR Low Pressure Safety Injection Motor-Operated Valves

Table 32-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9947762	0.9895297	0.9842125	0.9846306	0.9846113
α_2	5.22E-03	1.05E-02	1.58E-02	1.08E-02	9.33E-03
α_3		0.00E+00	0.00E+00	4.58E-03	4.25E-03
α_4			0.00E+00	0.00E+00	1.81E-03
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 32-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.95E-01	9.90E-01	9.84E-01	9.85E-01	9.85E-01
Beta	5.22E-03	1.05E-02	1.58E-02	1.54E-02	1.54E-02
Gamma		0.00E+00	0.00E+00	2.98E-01	3.94E-01
Delta			0.00E+00	0.00E+00	2.98E-01
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 32-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	47.66	71.48	95.31	119.14	142.96
N_1	1.9472	2.1420	1.8176	1.8582	1.7819
N_2	0.2605	0.7790	1.5580	1.3262	1.3716
N_3		0.0000	0.0000	0.5625	0.6250
N_4			0.0000	0.0000	0.2656
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 127
Total Number of Common-Cause Failure Events: 6

ALPHA FACTOR AND MGL PARAMETERS
PWR Low Pressure Safety Injection Motor-Operated Valves

Table 32-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9989834	0.9979804	0.9969734	0.9959494	0.9949434
α_2	1.02E-03	2.02E-03	3.03E-03	4.05E-03	5.05E-03
α_3		0.00E+00	0.00E+00	4.69E-06	3.91E-06
α_4			0.00E+00	0.00E+00	0.00E+00
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 32-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.99E-01	9.98E-01	9.97E-01	9.96E-01	9.95E-01
Beta	1.02E-03	2.02E-03	3.03E-03	4.05E-03	5.06E-03
Gamma		0.00E+00	0.00E+00	1.16E-03	7.73E-04
Delta			0.00E+00	0.00E+00	0.00E+00
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 32-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	8.00	12.00	16.00	20.00	24.00
N_1	0.5489	0.7982	1.0303	1.2437	1.4413
N_2	0.0087	0.0259	0.0517	0.0863	0.1292
N_3		0.0000	0.0000	0.0001	0.0001
N_4			0.0000	0.0000	0.0000
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 24
Total Number of Common-Cause Failure Events: 4

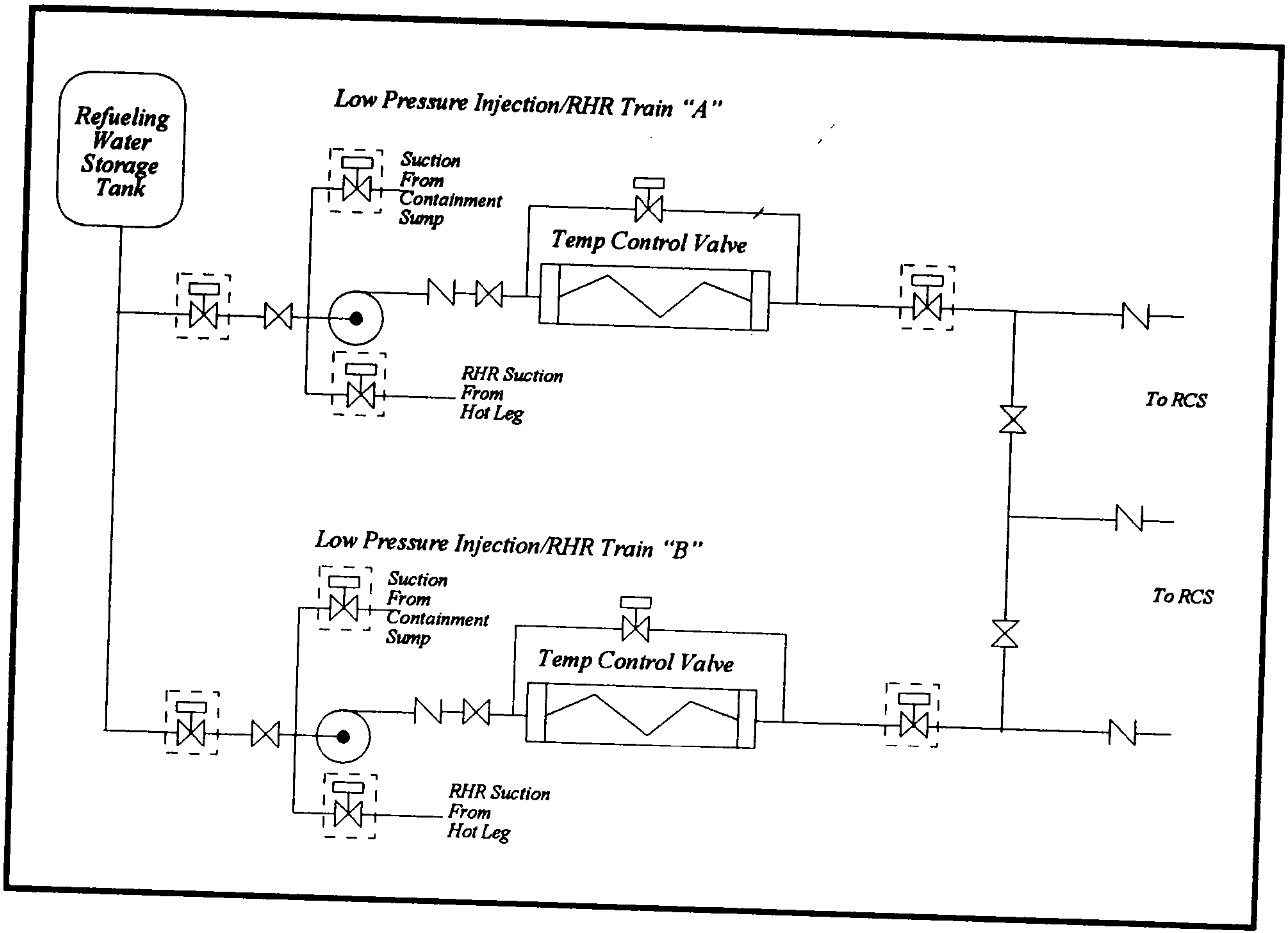

Figure 32-1. PWR low pressure safety injection/residual heat removal system.

3. COMPONENT BOUNDARIES

The main components of a motor-operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual hand wheels, and can be manually operated. AC or DC power is required for valve operation.

The MOVs in the low pressure safety injection system are used in the following applications:

- Provide a suction source from the RWST,
- Allow shifting suction to the containment sump, and
- Allow a suction path from the RCS hot legs for shutdown cooling.

4. FAILURE EVENT DEFINITION

The function of the LPSI MOVs is to provide a suction from the RWST, allow shifting the suction to the containment sump at the end of the injection phase, and provide for a suction from the RCS hot leg. All valves serve as a system containment boundary and would need to close to isolate leaks. The failure modes used in evaluating the low pressure safety injection system MOV data are:

CC Fail to Open: A successful operation of the valve is the valve is in the fully open position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: In cases where the motor-operated valve has been closed for a substantial period of time and is then discovered leaking, the failure will be coded as VR. If the discovery is made soon after a system configuration change (i.e., pump operation), then the failure is coded as OO.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. Stroke time testing failures were not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure. These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC."

Many LERs reported only one actual failure, but the report information indicated that failure of a second MOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 32-10 through 32-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of motor operated valves. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Low Pressure Safety Injection Motor-Operated Valves

Table 32-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9697998	0.9881863	0.9905472	0.9985111	0.9910681	1.3054E+02	1.5606E+00
α_2	1.49E-03	1.18E-02	9.46E-03	3.02E-02	8.93E-03	1.5606E+00	1.3054E+02

Table 32-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9663049	0.9834296	0.9850282	0.9950897	0.9863696	1.9464E+02	3.2796E+00
α_2	2.85E-03	1.25E-02	1.09E-02	2.76E-02	1.15E-02	2.4728E+00	1.9545E+02
α_3	1.15E-04	4.08E-03	2.57E-03	1.32E-02	2.17E-03	8.0680E-01	1.9711E+02

Table 32-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9665105	0.9816985	0.9828842	0.9928278	0.9851123	2.6251E+02	4.8939E+00
α_2	2.58E-03	1.02E-02	9.04E-03	2.20E-02	9.04E-03	2.7359E+00	2.6467E+02
α_3	7.67E-04	5.94E-03	4.76E-03	1.51E-02	5.49E-03	1.5884E+00	2.6582E+02
α_4	1.60E-05	2.13E-03	1.08E-03	7.80E-03	3.56E-04	5.6960E-01	2.6683E+02

Table 32-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9661996	0.9800429	0.9809737	0.9907010	0.9839008	3.3371E+02	6.7955E+00
α_2	3.82E-03	1.14E-02	1.04E-02	2.22E-02	1.05E-02	3.8759E+00	3.3663E+02
α_3	2.50E-04	3.42E-03	2.51E-03	9.70E-03	2.50E-03	1.1645E+00	3.3934E+02
α_4	2.34E-04	3.35E-03	2.44E-03	9.56E-03	3.02E-03	1.1398E+00	3.3937E+02
α_5	1.90E-05	1.81E-03	9.70E-04	6.44E-03	1.04E-04	6.1530E-01	3.3989E+02

Table 32-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9658863	0.9787260	0.9794938	0.9889379	0.9826218	4.0359E+02	8.7726E+00
α_2	4.78E-03	1.21E-02	1.13E-02	2.21E-02	1.17E-02	4.9871E+00	4.0738E+02
α_3	2.85E-04	3.14E-03	2.39E-03	8.59E-03	2.10E-03	1.2962E+00	4.1107E+02
α_4	9.31E-05	2.24E-03	1.50E-03	6.89E-03	1.70E-03	9.2220E-01	4.1144E+02
α_5	8.48E-05	2.18E-03	1.45E-03	6.78E-03	1.83E-03	8.9960E-01	4.1146E+02
α_6	2.36E-05	1.62E-03	9.17E-04	5.60E-03	4.34E-05	6.6750E-01	4.1170E+02

ALPHA FACTOR DISTRIBUTIONS
Low Pressure Safety Injection Motor-Operated Valves

Table 32-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9593499	0.9877980	0.9926426	0.9997523	0.9947762	5.9137E+01	7.3050E-01
α_2	2.51E-04	1.22E-02	7.36E-03	4.07E-02	5.22E-03	7.3050E-01	5.9137E+01

Table 32-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9556364	0.9825334	0.9859504	0.9977471	0.9895297	8.8822E+01	1.5790E+00
α_2	9.54E-04	1.29E-02	9.53E-03	3.64E-02	1.05E-02	1.1662E+00	8.9235E+01
α_3	5.88E-06	4.57E-03	1.73E-03	1.87E-02	0.00E+00	4.1280E-01	8.9988E+01

Table 32-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9516556	0.9770788	0.9795842	0.9939452	0.9842125	1.2183E+02	2.8580E+00
α_2	3.25E-03	1.69E-02	1.44E-02	3.92E-02	1.58E-02	2.1118E+00	1.2258E+02
α_3	6.09E-08	2.11E-03	4.08E-04	1.00E-02	0.00E+00	2.6260E-01	1.2443E+02
α_4	1.28E-05	3.88E-03	1.72E-03	1.51E-02	0.00E+00	4.8360E-01	1.2420E+02

Table 32-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9541340	0.9763866	0.9783132	0.9920707	0.9846306	1.5904E+02	3.8463E+00
α_2	2.34E-03	1.26E-02	1.07E-02	2.95E-02	1.08E-02	2.0542E+00	1.6083E+02
α_3	2.89E-04	5.98E-03	4.12E-03	1.80E-02	4.58E-03	9.7450E-01	1.6191E+02
α_4	1.11E-08	1.43E-03	2.18E-04	7.08E-03	0.00E+00	2.3360E-01	1.6265E+02
α_5	3.01E-05	3.59E-03	1.86E-03	1.30E-02	0.00E+00	5.8400E-01	1.6230E+02

Table 32-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9560295	0.9760510	0.9776241	0.9907131	0.9846113	1.9521E+02	4.7898E+00
α_2	2.10E-03	1.08E-02 ✓	9.17E-03	2.48E-02	9.33E-03	2.1507E+00	1.9785E+02
α_3	4.28E-04	5.83E-03	4.29E-03	1.65E-02	4.25E-03	1.1656E+00	1.9883E+02
α_4	2.32E-05	2.89E-03	1.49E-03	1.05E-02	1.81E-03	5.7830E-01	1.9942E+02
α_5	1.51E-08	1.22E-03	2.02E-04	5.94E-03	0.00E+00	2.4330E-01	1.9976E+02
α_6	4.34E-05	3.26E-03	1.82E-03	1.14E-02	0.00E+00	6.5190E-01	1.9935E+02

ALPHA FACTOR DISTRIBUTIONS
Low Pressure Safety Injection Motor-Operated Valves

Table 32-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9005178	0.9742048	0.9883199	0.9999129	0.9989834	1.8079E+01	4.7870E-01
α_2	8.35E-05	2.58E-02	1.17E-02	9.95E-02	1.02E-03	4.7870E-01	1.8079E+01

Table 32-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9094715	0.9713467	0.9813354	0.9991028	0.9979804	2.7998E+01	8.2590E-01
α_2	1.89E-05	1.43E-02	5.51E-03	5.86E-02	2.02E-03	4.1310E-01	2.8411E+01
α_3	1.87E-05	1.43E-02	5.50E-03	5.86E-02	0.00E+00	4.1280E-01	2.8411E+01

Table 32-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9166504	0.9686247	0.9755631	0.9968513	0.9969734	4.1730E+01	1.3517E+00
α_2	1.40E-04	1.41E-02	7.56E-03	5.01E-02	3.03E-03	6.0550E-01	4.2476E+01
α_3	1.78E-07	6.10E-03	1.19E-03	2.91E-02	0.00E+00	2.6260E-01	4.2819E+01
α_4	3.75E-05	1.12E-02	5.03E-03	4.34E-02	0.00E+00	4.8360E-01	4.2598E+01

Table 32-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9226385	0.9666721	0.9716131	0.9937822	0.9959494	5.9286E+01	2.0440E+00
α_2	3.90E-04	1.33E-02	8.49E-03	4.25E-02	4.05E-03	8.1430E-01	6.0516E+01
α_3	8.58E-06	6.72E-03	2.55E-03	2.76E-02	4.69E-06	4.1210E-01	6.0918E+01
α_4	2.96E-08	3.81E-03	5.82E-04	1.88E-02	0.00E+00	2.3360E-01	6.1096E+01
α_5	8.06E-05	9.52E-03	4.97E-03	3.44E-02	0.00E+00	5.8400E-01	6.0746E+01

Table 32-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9274827	0.9661843	0.9700648	0.9916065	0.9949434	7.5913E+01	2.6569E+00
α_2	4.66E-04	1.16E-02	7.76E-03	3.56E-02	5.05E-03	9.0830E-01	7.7662E+01
α_3	4.06E-05	6.88E-03	3.37E-03	2.56E-02	3.91E-06	5.4070E-01	7.8029E+01
α_4	6.23E-07	3.98E-03	1.05E-03	1.80E-02	0.00E+00	3.1270E-01	7.8257E+01
α_5	3.87E-08	3.10E-03	5.15E-04	1.51E-02	0.00E+00	2.4330E-01	7.8327E+01
α_6	1.11E-04	8.30E-03	4.66E-03	2.89E-02	0.00E+00	6.5190E-01	7.7918E+01

33. PWR Containment Spray Motor Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common cause failure (CCF) parameters of various models using operational data involving motor operated valves (MOVs) in the containment spray system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common cause failure events. Failure modes analyzed are failure to open, failure to close and failure to remain open. The data cover the time period from 1980 through 1995.

The data review identified 12 common cause failure-to-open events, two common cause failure-to-close, and one failure-to-remain closed CCF event. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 33-1 and 33-2, respectively. Table 33-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 33-4 through 33-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 33-10 through 33-24 .

2. SYSTEM DESCRIPTION

The containment spray system (CSS) is a subsystem of the emergency core cooling system (ECCS) that provides for the removal of heat and containment pressure control following a loss of coolant accident (LOCA) or a steamline break inside containment. Initially, water from the refueling water storage tank (RWST), and subsequently, primary coolant from the containment sump is pumped through spray headers in the top of the containment building. The CSS typically consists of two separate and complete trains with a vertically mounted centrifugal pump, valves, and piping connecting the pump suction to the refueling water storage tank (RWST), and valves to allow shifting the CSS pump suction to the containment sump. Power to the CSS pumps and valves is provided from the 1E electrical system, which is backed up by the 1E emergency diesels generators. Some plant designs provide a heat exchanger for cooling, others provide for a sodium hydroxide chemical addition to the CSS to improve the removal of iodine from the containment atmosphere, and some plants have both. The number of MOVs in the PWR containment spray system is typically six or eight , depending on plant-specific designs.

The CSS is normally in standby and is automatically started by the Engineered Safety Features Actuation System on high containment pressure. The CSS can be manually actuated from the main control panel. Figure 33-1 provides an illustration of a typical flow path for the containment spray system.

ALPHA FACTOR AND MGL PARAMETERS
PWR Containment Spray Motor-Operated Valves

Table 33-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9477037	0.9608982	0.9663222	0.9714503	0.9747696
α_2	5.23E-02	5.34E-03	8.05E-03	5.54E-03	4.77E-03
α_3		3.38E-02	3.69E-05	2.39E-03	2.26E-03
α_4			2.56E-02	4.12E-06	9.26E-04
α_5				2.06E-02	6.91E-07
α_6					1.73E-02

Table 33-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.48E-01	9.61E-011	9.66E-01	9.72E-01	9.75E-01
Beta	5.23E-02	3.91E-02	3.37E-02	2.86E-02	2.52E-02
Gamma		8.63E-01	7.61E-01	8.06E-01	8.11E-01
Delta			9.99E-01	8.96E-01	8.89E-01
Epsilon				1.00E+01	9.49E-01
Mu					1.00E+00

Table 33-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	93.14	139.71	186.29	232.86	279.43
N_1	2.3022	2.6610	2.4992	2.6958	2.7775
N_2	5.2667	0.7915	1.5722	1.3429	1.3815
N_3		5.0020	0.0072	0.5788	0.6548
N_4			5.0002	0.0010	0.2680
N_5				5.0000	0.0002
N_6					5.0000

Total Number of Independent Failure Events: 163
Total Number of Common Cause Failure Events: 12

ALPHA FACTOR AND MGL PARAMETERS
PWR Containment Spray Motor-Operated Valves

Table 33-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9530411	0.9680902	0.9757544	0.9803788	0.9834611
α_2	4.70E-02	1.59E-04	2.40E-04	3.22E-04	4.03E-04
α_3		3.18E-02	0.00E+00	0.00E+00	0.00E+00
α_4			2.40E-02	0.00E+00	0.00E+00
α_5				1.93E-02	0.00E+00
α_6					1.61E-02

Table 33-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.53E-01	9.68E-01	9.76E-01	9.80E-01	9.84E-01
Beta	4.70E-02	3.19E-02	2.43E-02	1.96E-02	1.65E-02
Gamma		9.95E-01	9.90E-01	9.84E-01	9.76E-01
Delta			1.00E+00	1.00E+00	1.00E+00
Epsilon				1.00E+00	1.00E+00
Mu					1.00E+00

Table 33-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	20.00	30.00	40.00	50.00	60.00
N_1	0.3297	0.4900	0.6470	0.7997	0.9500
N_2	1.0017	0.0050	0.0100	0.0167	0.0250
N_3		1.0000	0.0000	0.0000	0.0000
N_4			1.0000	0.0000	0.0000
N_5				1.0000	0.0000
N_6					1.0000

Total Number of Independent Failure Events: 50
Total Number of Common Cause Failure Events: 2

ALPHA FACTOR AND MGL PARAMETERS
PWR Containment Spray Motor-Operated Valves

Table 33-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9999303	0.9998677	0.9998096	0.9993864	0.9990451
α_2	6.97E-05	1.29E-04	1.82E-04	5.97E-04	9.03E-04
α_3		3.58E-06	8.04E-06	1.72E-05	5.01E-05
α_4			0.00E+00	0.00E+00	1.79E-06
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 33-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	1.00E+01	1.00E+01	1.00E+01	9.99E-01	9.99E-01
Beta	6.97E-05	1.32E-04	1.90E-04	6.14E-04	9.55E-04
Gamma		2.70E-02	4.23E-02	2.80E-02	5.43E-02
Delta			0.00E+00	0.00E+00	3.45E-02
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 33-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	18.50	27.75	37.00	46.25	55.50
N_1	0.1476	0.2178	0.2858	0.3304	0.3668
N_2	0.0013	0.0036	0.0068	0.0278	0.0505
N_3		0.0001	0.0003	0.0008	0.0028
N_4			0.0000	0.0000	0.0001
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 37
Total Number of Common Cause Failure Events: 1

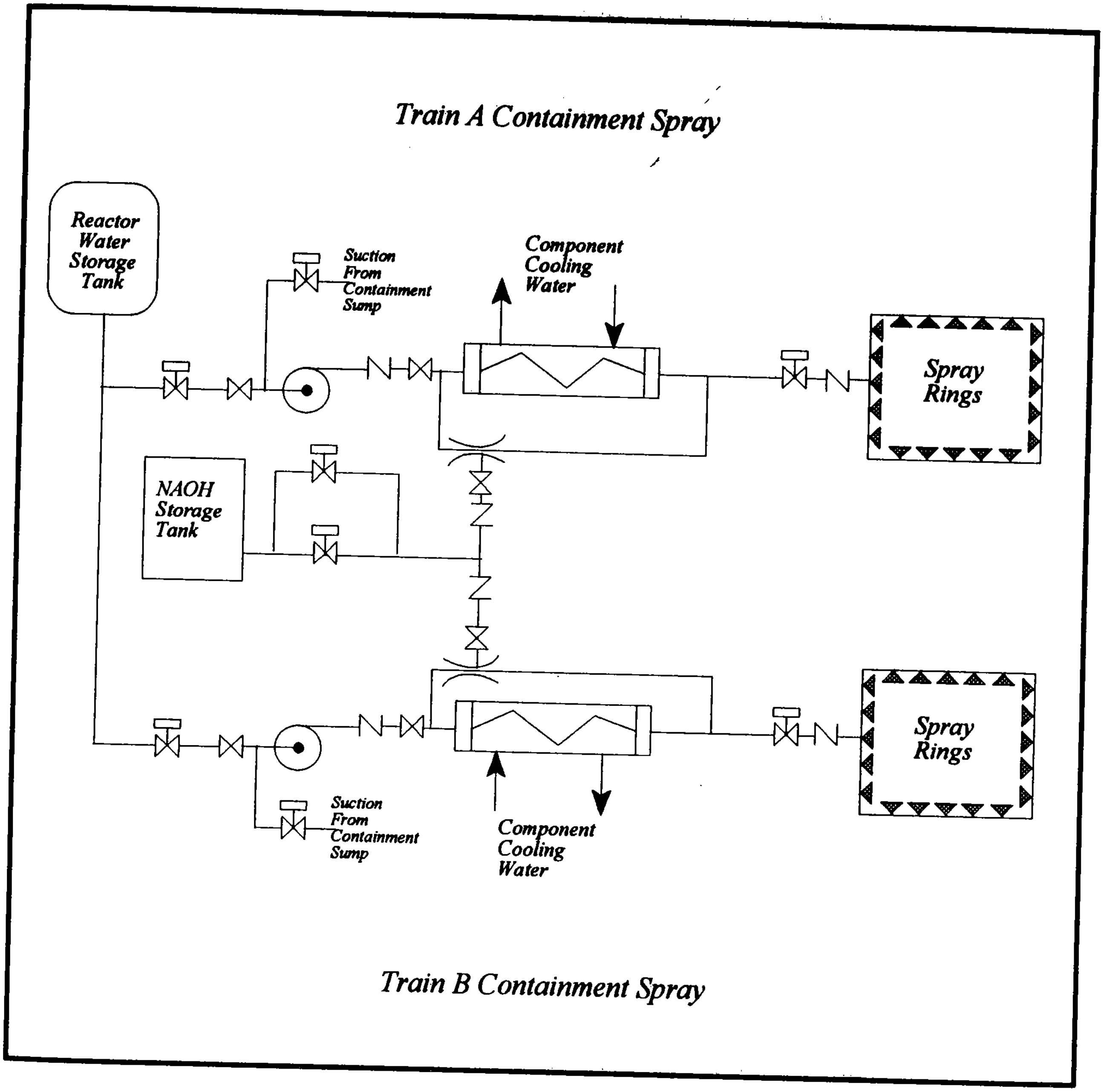

Figure 33-1. PWR containment spray system.

3. COMPONENT BOUNDARIES

The main components of a motor operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual handwheels, and can be manually operated. AC or DC power is required for valve operation.

The MOVs in the containment spray system are used in the following applications:

- admitting borated water to the containment spray system from the RWST ,
- shifting suction of the containment spray pumps from the RWST to the containment sump,
- admitting chemical addition to the containment spray, and
- admitting coolant to the containment spray rings.

4. FAILURE EVENT DEFINITION

The function of the containment spray MOVs is to allow borated water flow to the containment spray system spray rings. Some valves serve as a system containment boundary and would need to close to isolate leaks. The failure modes used in evaluating the containment spray system MOV data are:

CC Fail to Open: The valve must be in the fully open position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Failure to Remain Closed: In cases where the motor operated valve has been closed for a substantial period of time and is then discovered leaking, the failure will be coded as VR. If the discovery is made soon after a system configuration change (i.e., pump operation), then the failure is coded as OO.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure. These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC."

Many LERs reported only one actual failure, but the report information indicated that failure of a second MOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 33-10 through 33-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of MOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
PWR Containment Spray Motor-Operated Valves

Table 33-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9096740	0.9481811	0.9508659	0.9775176	0.9477037	1.0497E+02	5.7367E+00
α_2	2.25E-02	5.18E-02	4.91E-02	9.03E-02	5.23E-02	5.7367E+00	1.0497E+02

Table 33-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9319187	0.9598358	0.9616949	0.9814135	0.9608982	1.5757E+02	6.5935E+00
α_2	5.40E-04	7.18E-03	5.30E-03	2.02E-02	5.34E-03	1.1787E+00	1.6299E+02
α_3	1.38E-02	3.30E-02	3.11E-02	5.86E-02	3.38E-02	5.4148E+00	1.5875E+02

Table 33-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9418620	0.9644052	0.9657984	0.9822022	0.9663222	2.1349E+02	7.8796E+00
α_2	1.85E-03	9.60E-03	8.17E-03	2.23E-02	8.05E-03	2.1260E+00	2.1924E+02
α_3	4.67E-08	1.22E-03	2.48E-04	5.77E-03	3.69E-05	2.6980E-01	2.2110E+02
α_4	1.04E-02	2.48E-02	2.34E-02	4.40E-02	2.56E-02	5.4838E+00	2.1589E+02

Table 33-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9498414	0.9685631	0.9696665	0.9835321	0.9714503	2.7360E+02	8.8803E+00
α_2	1.37E-03	7.33E-03	6.21E-03	1.71E-02	5.54E-03	2.0709E+00	2.8041E+02
α_3	1.76E-04	3.51E-03	2.43E-03	1.05E-02	2.39E-03	9.9080E-01	2.8149E+02
α_4	6.75E-09	8.31E-04	1.27E-04	4.10E-03	4.12E-06	2.3460E-01	2.8225E+02
α_5	8.35E-03	1.98E-02	1.86E-02	3.50E-02	2.06E-02	5.5840E+00	2.7690E+02

Table 33-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9550789	0.9712942	0.9722056	0.9843916	0.9747696	3.3268E+02	9.8321E+00
α_2	1.24E-03	6.31E-03	5.38E-03	1.46E-02	4.77E-03	2.1606E+00	3.4035E+02
α_3	2.70E-04	3.49E-03	2.58E-03	9.81E-03	2.26E-03	1.1954E+00	3.4132E+02
α_4	1.38E-05	1.70E-03	8.73E-04	6.17E-03	9.26E-04	5.8070E-01	3.4193E+02
α_5	8.92E-09	7.11E-04	1.18E-04	3.47E-03	6.91E-07	2.4350E-01	3.4227E+02
α_6	7.01E-03	1.65E-02	1.56E-02	2.92E-02	1.73E-02	5.6519E+00	3.3686E+02

ALPHA FACTOR DISTRIBUTIONS
PWR Containment Spray Motor-Operated Valves

Table 33-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8796665	0.9530284	0.9623470	0.9944572	0.9530411	2.9860E+01	1.4717E+00
α_2	5.54E-03	4.70E-02	3.77E-02	1.20E-01	4.70E-02	1.4717E+00	2.9860E+01

Table 33-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9084668	0.9619960	0.9682995	0.9939442	0.9680902	4.5690E+01	1.8050E+00
α_2	7.60E-06	8.26E-03	2.97E-03	3.45E-02	1.59E-04	3.9220E-01	4.7103E+01
α_3	3.23E-03	2.98E-02	2.34E-02	7.79E-02	3.18E-02	1.4128E+00	4.6082E+01

Table 33-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9236851	0.9658572	0.9703456	0.9926585	0.9757544	6.5347E+01	2.310E+00
α_2	6.00E-05	8.33E-03	4.23E-03	3.06E-02	2.40E-04	5.6380E-01	6.7093E+01
α_3	1.13E-07	3.88E-03	7.54E-04	1.85E-02	0.00E+00	2.6260E-01	6.7394E+01
α_4	2.57E-03	2.19E-02	1.74E-02	5.67E-02	2.40E-02	1.4836E+00	6.6173E+01

Table 33-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9327042	0.9676060	0.9709429	0.9910865	0.9803788	8.8842E+01	2.9743E+00
α_2	1.77E-04	8.11E-03	4.93E-03	2.69E-02	3.22E-04	7.4470E-01	9.1072E+01
α_3	5.70E-06	4.49E-03	1.70E-03	1.84E-02	0.00E+00	4.1200E-01	9.1404E+01
α_4	1.97E-08	2.54E-03	3.87E-04	1.26E-02	0.00E+00	2.3360E-01	9.1583E+01
α_5	2.24E-03	1.73E-02	1.39E-02	4.38E-02	1.93E-02	1.5840E+00	9.0232E+01

Table 33-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9388505	0.9691005	0.9717805	0.9901727	0.9834611	1.1142E+02	3.5526E+00
α_2	1.96E-04	6.99E-03	4.42E-03	2.26E-02	4.03E-04	8.0410E-01	1.1417E+02
α_3	2.76E-05	4.70E-03	2.30E-03	1.75E-02	0.00E+00	5.4060E-01	1.1443E+02
α_4	4.25E-07	2.72E-03	7.12E-04	1.23E-02	0.00E+00	3.1270E-01	1.1466E+02
α_5	2.64E-08	2.12E-03	3.51E-04	1.03E-02	0.00E+00	2.4330E-01	1.1473E+02
α_6	1.98E-03	1.44E-02	1.17E-02	3.60E-02	1.61E-02	1.6519E+00	1.1332E+02

ALPHA FACTOR DISTRIBUTIONS
PWR Containment Spray Motor-Operated Valves

Table 33-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9359135	0.9835494	0.9927546	0.9999487	0.9999303	2.8178E+01	4.7130E-01
α_2	4.81E-05	1.65E-02	7.25E-03	6.41E-02	6.97E-05	4.7130E-01	2.8178E+01

Table 33-21: Alpha Factor Distribution Summary -Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9413607	0.9817224	0.9883440	0.9994792	0.9998677	4.3168E+01	8.0370E-01
α_2	7.99E-06	8.89E-03	3.18E-03	3.71E-02	1.29E-04	3.9080E-01	4.3581E+01
α_3	1.22E-05	9.39E-03	3.58E-03	3.85E-02	3.58E-06	4.1290E-01	4.3559E+01

Table 33-22: Alpha Factor Distribution Summary -Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9442117	0.9793485	0.9841492	0.9980660	0.9998096	6.1986E+01	1.3071E+00
α_2	6.22E-05	8.86E-03	4.48E-03	3.25E-02	1.82E-04	5.6060E-01	6.2733E+01
α_3	1.22E-07	4.15E-03	8.09E-04	1.98E-02	8.04E-06	2.6290E-01	6.3030E+01
α_4	2.54E-05	7.64E-03	3.41E-03	2.96E-02	0.00E+00	4.8360E-01	6.2810E+01

Table 33-23: Alpha Factor Distribution Summary -Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9460345	0.9770668	0.9806347	0.9959015	0.9993864	8.4622E+01	1.9862E+00
α_2	2.00E-04	8.73E-03	5.35E-03	2.88E-02	5.97E-04	7.5580E-01	8.5852E+01
α_3	6.14E-06	4.77E-03	1.81E-03	1.96E-02	1.72E-05	4.1280E-01	8.6195E+01
α_4	2.09E-08	2.70E-03	4.11E-04	1.33E-02	0.00E+00	2.3360E-01	8.6375E+01
α_5	5.69E-05	6.74E-03	3.51E-03	2.44E-02	0.00E+00	5.8400E-01	8.6024E+01

Table 33-24: Alpha Factor Distribution Summary -Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9485313	0.9763039	0.9791602	0.9943121	0.9990451	1.0634E+02	2.5810E+00
α_2	2.35E-04	7.62E-03	4.89E-03	2.43E-02	9.03E-04	8.2960E-01	1.0809E+02
α_3	3.01E-05	4.99E-03	2.45E-03	1.86E-02	5.01E-05	5.4340E-01	1.0838E+02
α_4	4.50E-07	2.87E-03	7.53E-04	1.30E-02	1.79E-06	3.1280E-01	1.0861E+02
α_5	2.79E-08	2.23E-03	3.71E-04	1.09E-02	0.00E+00	2.4330E-01	1.0868E+02
α_6	8.00E-05	5.99E-03	3.35E-03	2.08E-02	0.00E+00	6.5190E-01	1.0827E+02

34. PWR Auxiliary Feedwater Motor-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving motor-operated valves (MOVs) in the auxiliary feedwater (AFW) system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed. The data cover the time period from 1980 through 1995.

The data review identified 12 common-cause failure-to-open events, 11 common-cause failure-to-close events, and four failure-to-remain closed CCF events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 34-1 and 34-2, respectively. Table 34-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 34-4 through 34-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 34-10 through 34-24.

2. SYSTEM DESCRIPTION

The auxiliary feedwater system provides a source of feedwater to the steam generators to remove decay heat from the reactor coolant system (RCS) when: (a) the main feedwater system is not available, and (b) RCS pressure is too high to permit heat removal by the residual heat removal (RHR) system. The AFW system is typically comprised of two motor-driven, full capacity pumps and a steam driven, double capacity pump along with valves and control systems to allow control of steam generator level and feedwater flow rate. The motor-driven pumps are supplied power from the 1E class power system with backup power available from the 1E emergency diesel generators (EDG). The water supply for the system is from the condensate storage tank (CST) with a backup source of water (untreated) available from the service water system.

The AFW system is normally in standby, regardless of whether the plant is at power or shutdown. The motor-driven pumps start on one of the following conditions: a safety injection (SI) signal, a low-low level in any steam generator, loss of both main feedwater pumps (MFP), a loss of off-site power (LOSP) or manual initiation. The turbine-driven pump will start on either a low-low level in more than one steam generator or a loss of off-site power. Flow to the steam generators is a two stage process at some plants. First the pumps start on demand from a steam generator low level signal. Control valves regulate the flow as needed. Feedwater flow to the steam generators is controlled from the main control room by air, motor, or hydraulically operated valves. Motor-driven pump runout is controlled by an air or hydraulically controlled regulator valve on the pump discharge. The turbine-driven pump steam supply is controlled by air or hydraulically operated valves. Figure 34-1 shows a typical auxiliary feedwater system. The number of MOVs in the AFW system ranges from four to eight, depending on the number of steam generators and pump types.

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Motor-Operated Valves

Table 34-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9787183	0.9624049	0.9624494	0.9622645	0.9653305
α_2	2.13E-02	2.84E-02	1.76E-02	1.86E-02	1.31E-02
α_3		9.22E-03	1.40E-02	4.94E-03	8.35E-03
α_4			5.95E-03	9.70E-03	1.93E-03
α_5				4.49E-03	7.67E-03
α_6					3.62E-03

Table 34-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.79E-01	9.62E-01	9.62E-01	9.62E-01	9.65E-01
Beta	2.13E-02	3.76E-02	3.76E-02	3.77E-02	3.47E-02
Gamma		2.45E-01	5.32E-01	5.07E-01	6.22E-01
Delta			2.98E-01	7.42E-01	6.13E-01
Epsilon				3.17E-01	8.54E-01
Mu					3.20E-01

Table 34-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	94.91	142.36	189.82	237.27	284.73
N_1	6.7249	4.7150	3.9251	2.5574	2.0497
N_2	2.2100	4.3369	3.5388	4.6356	3.8931
N_3		1.4084	2.8228	1.2323	2.4790
N_4			1.1975	2.4176	0.5742
N_5				1.1194	2.2789
N_6					1.0744

Total Number of Independent Failure Events: 261
Total Number of Common-Cause Failure Events: 12

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Motor-Operated Valves

Table 34-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9710148	0.9464114	0.9408460	0.9438771	0.9459012
α_2	2.90E-02	4.32E-02	3.53E-02	2.65E-02	2.20E-02
α_3		1.04E-02	1.74E-02	1.31E-02	1.32E-02
α_4			6.51E-03	1.15E-02	5.80E-03
α_5				5.01E-03	8.94E-03
α_6					4.12E-03

Table 34-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.71E-01	9.46E-01	9.41E-01	9.44E-01	9.46E-01
Beta	2.90E-02	5.36E-02	5.92E-02	5.61E-02	5.41E-02
Gamma		1.94E-01	4.04E-01	5.28E-01	5.93E-01
Delta			2.73E-01	5.57E-01	5.88E-01
Epsilon				3.04E-01	6.92E-01
Mu					3.15E-01

Table 34-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	37.94	56.92	75.89	94.86	113.83
N_1	4.9673	4.0853	3.5190	3.2446	2.9712
N_2	1.2808	2.7855	2.9771	2.7547	2.7217
N_3		0.6688	1.4658	1.3655	1.6300
N_4			0.5498	1.1924	0.7165
N_5				0.5207	1.1038
N_6					0.5082

Total Number of Independent Failure Events: 107
Total Number of Common-Cause Failure Events: 11

ALPHA FACTOR AND MGL PARAMETERS
Auxiliary Feedwater Motor-Operated Valves

Table 34-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9996404	0.9992960	0.9989821	0.9986779	0.9983941
α_2	3.60E-04	6.92E-04	9.88E-04	1.27E-03	1.51E-03
α_3		1.18E-05	2.95E-05	5.67E-05	9.05E-05
α_4			0.00E+00	0.00E+00	1.97E-06
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 34-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	1.00E+01	9.99E-01	9.99E-01	9.99E-01	9.98E-01
Beta	3.60E-04	7.04E-04	1.02E-03	1.32E-03	1.61E-03
Gamma		1.68E-02	2.90E-02	4.29E-02	5.76E-02
Delta			0.00E+00	0.00E+00	2.13E-02
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 34-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	16.62	24.92	33.23	41.54	49.85
N_1	0.3376	0.4893	0.6302	0.7604	0.8821
N_2	0.0061	0.0176	0.0335	0.0536	0.0769
N_3		0.0003	0.0010	0.0024	0.0046
N_4			0.0000	0.0000	0.0001
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 54
Total Number of Common-Cause Failure Events: 4

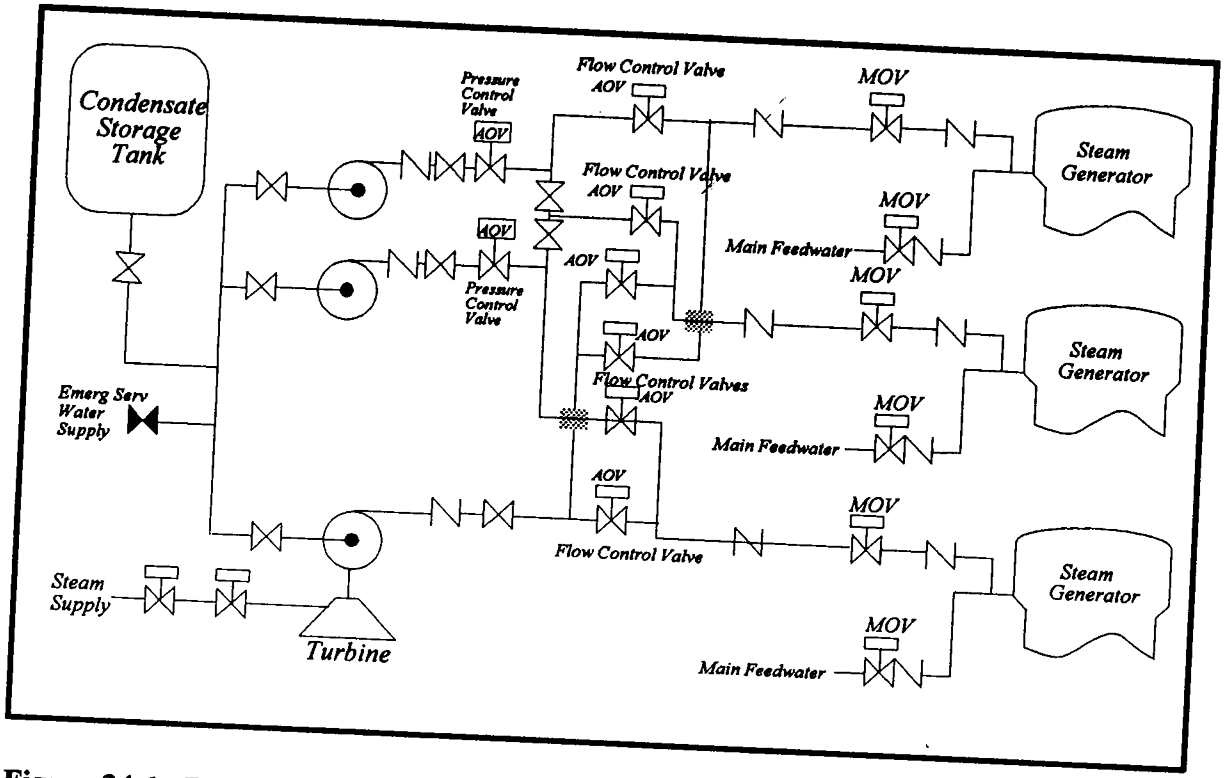

Figure 34-1. PWR auxiliary feedwater system.

3. COMPONENT BOUNDARIES

The main components of a motor-operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual handwheels, and can be manually operated. AC or DC power is required for valve operation.

The MOVs in the auxiliary feedwater system are used in the following applications:

- Supply or isolation of AFW flow to individual steam generators, and
- Supply of condensate to the AFW pumps.

4. FAILURE EVENT DEFINITION

The function of the auxiliary feedwater MOVs is to allow feedwater flow to the steam generators or to isolate flow to individual steam generators. All valves serve as a system containment boundary and would need to close to isolate leaks. The failure modes used in evaluating the auxiliary feedwater MOV data are:

CC Fail to Open: The valve must be in the fully open position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: In cases where the motor-operated valve has been closed for a substantial period of time and is then discovered leaking or unable to pass a surveillance test, the failure will be coded as VR. If the discovery is made soon after a system configuration change (i.e., pump operation), then the failure is coded as OO.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure. These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC."

Many LERs reported only one actual failure, but the report information indicated that failure of a second MOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 34-10 through 34-24 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of AFW MOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Auxiliary Feedwater Motor-Operated Valves

Table 34-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9494295	0.9764603	0.9791964	0.9941394	0.9787183	1.1117E+02	2.680E+00
α_2	5.86E-03	2.35E-02	2.08E-02	5.06E-02	2.13E-02	2.680E+00	1.1117E+02

Table 34-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9341490	0.9612303	0.9630426	0.9821297	0.9624049	1.6228E+02	6.5453E+00
α_2	1.08E-02	2.80E-02	2.61E-02	5.15E-02	2.84E-02	4.7241E+00	1.6410E+02
α_3	1.71E-03	1.08E-02	8.93E-03	2.62E-02	9.22E-03	1.8212E+00	1.6700E+02

Table 34-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9379049	0.9610262	0.9623698	0.9795561	0.9624494	2.1845E+02	8.8591E+00
α_2	6.30E-03	1.80E-02	1.66E-02	3.45E-02	1.76E-02	4.0926E+00	2.2322E+02
α_3	3.82E-03	1.36E-02	1.22E-02	2.81E-02	1.40E-02	3.0854E+00	2.2422E+02
α_4	1.04E-03	7.40E-03	6.01E-03	1.85E-02	5.95E-03	1.6811E+00	2.2563E+02

Table 34-13: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9403213	0.9607150	0.9617755	0.9774994	0.9622645	2.7787E+02	1.1363E+01
α_2	7.66E-03	1.85E-02	1.75E-02	3.32E-02	1.86E-02	5.3636E+00	2.8387E+02
α_3	7.74E-04	5.69E-03	4.59E-03	1.43E-02	4.94E-03	1.6443E+00	2.8759E+02
α_4	2.24E-03	9.17E-03	8.06E-03	1.99E-02	9.70E-03	2.6512E+00	2.8658E+02
α_5	8.45E-04	5.89E-03	4.80E-03	1.47E-02	4.49E-03	1.7034E+00	2.8753E+02

Table 34-14: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9454938	0.9633589	0.9642417	0.9782201	0.9653305	3.3725E+02	1.2827E+01
α_2	5.08E-03	1.34E-02	1.24E-02	2.47E-02	1.31E-02	4.6722E+00	3.4541E+02
α_3	2.38E-03	8.63E-03	7.71E-03	1.80E-02	8.35E-03	3.0196E+00	3.4706E+02
α_4	9.47E-05	2.53E-03	1.67E-03	7.91E-03	1.93E-03	8.8690E-01	3.4919E+02
α_5	1.67E-03	7.21E-03	6.29E-03	1.59E-02	7.67E-03	2.5222E+00	3.4756E+02
α_6	7.21E-04	4.93E-03	4.03E-03	1.22E-02	3.62E-03	1.7263E+00	3.4835E+02

ALPHA FACTOR DISTRIBUTIONS
Auxiliary Feedwater Motor-Operated Valves

Table 34-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9212071	0.9676902	0.9732668	0.9950811	0.9710148	5.2437E+01	1.7508E+00
α_2	4.92E-03	3.23E-02	2.67E-02	7.88E-02	2.90E-02	1.7508E+00	5.2437E+01

Table 34-16: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9009675	0.9471248	0.9508013	0.9807118	0.9464114	7.6205E+01	4.2543E+00
α_2	1.15E-02	3.94E-02	3.57E-02	8.02E-02	4.32E-02	3.1727E+00	7.7287E+01
α_3	8.43E-04	1.34E-02	9.68E-03	3.89E-02	1.04E-02	1.0816E+00	7.9378E+01

Table 34-17: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9028653	0.9430023	0.9456620	0.9740403	0.9408460	1.0411E+02	6.2927E+00
α_2	1.01E-02	3.20E-02	2.92E-02	6.34E-02	3.53E-02	3.5309E+00	1.0687E+02
α_3	2.31E-03	1.57E-02	1.28E-02	3.86E-02	1.74E-02	1.7284E+00	1.0867E+02
α_4	5.25E-04	9.36E-03	6.61E-03	2.76E-02	6.51E-03	1.0334E+00	1.0937E+02

Table 34-18: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9118292	0.9458743	0.9479294	0.9728941	0.9438771	1.3615E+02	7.7909E+00
α_2	7.55E-03	2.42E-02	2.20E-02	4.83E-02	2.65E-02	3.4827E+00	1.4046E+02
α_3	1.89E-03	1.24E-02	1.02E-02	3.03E-02	1.31E-02	1.7775E+00	1.4216E+02
α_4	1.08E-03	9.91E-03	7.75E-03	2.61E-02	1.15E-02	1.4260E+00	1.4252E+02
α_5	5.02E-04	7.68E-03	5.55E-03	2.21E-02	5.01E-03	1.1047E+00	1.4284E+02

Table 34-19: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9177781	0.9478246	0.9495081	0.9721128	0.9459012	1.6727E+02	9.2078E+00
α_2	6.20E-03	1.98E-02	1.81E-02	3.96E-02	2.20E-02	3.5080E+00	1.7298E+02
α_3	2.43E-03	1.23E-02	1.05E-02	2.83E-02	1.32E-02	2.1706E+00	1.7431E+02
α_4	3.23E-04	5.83E-03	4.10E-03	1.72E-02	5.80E-03	1.0292E+00	1.7545E+02
α_5	7.47E-04	7.63E-03	5.87E-03	2.05E-02	8.94E-03	1.3471E+00	1.7513E+02
α_6	4.78E-04	6.57E-03	4.83E-03	1.86E-02	4.12E-03	1.1601E+00	1.7532E+02

ALPHA FACTOR DISTRIBUTIONS
Auxiliary Feedwater Motor-Operated Valves

Table 34-20: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9315031	0.9823432	0.9921322	0.9999420	0.9996404	2.6488E+01	4.7610E-01
α_2	5.47E-05	1.77E-02	7.87E-03	6.85E-02	3.60E-04	4.7610E-01	2.6488E+01

Table 34-21: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9371050	0.9802568	0.9872858	0.9994053	0.9992960	4.0609E+01	8.1790E-01
α_2	1.12E-05	9.77E-03	3.65E-03	4.03E-02	6.92E-04	4.0480E-01	4.1022E+01
α_3	1.30E-05	9.97E-03	3.81E-03	4.08E-02	1.18E-05	4.1310E-01	4.1014E+01

Table 34-22: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9402808	0.9777191	0.9827851	0.9978276	0.9989821	5.8560E+01	1.3345E+00
α_2	8.51E-05	9.81E-03	5.14E-03	3.54E-02	9.88E-04	5.8730E-01	5.9307E+01
α_3	1.33E-07	4.40E-03	8.62E-04	2.10E-02	2.95E-05	2.6360E-01	5.9631E+01
α_4	2.69E-05	8.07E-03	3.60E-03	3.13E-02	0.00E+00	4.8360E-01	5.9411E+01

Table 34-23: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9427507	0.9755499	0.9792933	0.9955501	0.9986779	8.0342E+01	2.0136E+00
α_2	2.44E-04	9.49E-03	5.92E-03	3.09E-02	1.27E-03	7.8160E-01	8.1574E+01
α_3	6.65E-06	5.03E-03	1.91E-03	2.06E-02	5.67E-05	4.1440E-01	8.1941E+01
α_4	2.20E-08	2.84E-03	4.32E-04	1.40E-02	0.00E+00	2.3360E-01	8.2122E+01
α_5	5.98E-05	7.09E-03	3.69E-03	2.57E-02	0.00E+00	5.8400E-01	8.1772E+01

Table 34-24: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9456136	0.9748654	0.9778547	0.9939016	0.9983941	1.0120E+02	2.6092E+00
α_2	2.80E-04	8.25E-03	5.38E-03	2.60E-02	1.51E-03	8.5600E-01	1.0295E+02
α_3	3.22E-05	5.25E-03	2.59E-03	1.95E-02	9.05E-05	5.4520E-01	1.0326E+02
α_4	4.72E-07	3.01E-03	7.90E-04	1.36E-02	1.97E-06	3.1280E-01	1.0350E+02
α_5	2.93E-08	2.34E-03	3.89E-04	1.14E-02	0.00E+00	2.4330E-01	1.0357E+02
α_6	8.39E-05	6.28E-03	3.52E-03	2.19E-02	0.00E+00	6.5190E-01	1.0316E+02

35. Pressurizer PORV Motor-Operated Block Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving the pressurizer relief valve motor-operated block valves (MOVs) in the primary coolant system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open and failure to close. The data cover the time period from 1980 through 1995.

The data review identified one common-cause failure-to-open event and five common-cause failure-to-close, and one common-cause failure-to-remain-closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to close are shown in Tables 35-1 and 35-2, respectively. Table 35-3 contains the average impact vectors (N_1-N_3) and the number of adjusted independent events for this failure mode. Tables 35-4 through 35-9 contain the corresponding information for the failure to close failure mode. The size of the affected population of block MOVs is denoted as CCCG and is either two or three for all plants. The alpha factor model parameters are denoted by α_1-α_3. Beta (β) and gamma (γ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 35-10 through 35-15.

2. SYSTEM DESCRIPTION

The pressurizer power operated relief valves (PORV) automatically actuate to lower pressure in the event of a power mismatch that causes high reactor pressure. The PORVs are not required in order to prevent over pressurization but rather function to increase plant operability. Pressurizer safety valves, with setpoints higher than the PORVs, are used for over pressure protection. The discharge from both the PORVs and the safety valves goes to the pressurizer relief tank (PRT). The PORVs may also be remotely actuated manually. During shutdown conditions the PORVs may provide cold over pressure protection. In order to provide cold over pressure protection, operator action is required to reset the automatic lift setpoints.

Motor operated block valves are located between the pressurizer and the PORV, and function to isolate the PORVs in the event of leakage through the PORVs and, thus, out of the primary coolant system. Figure 35-1 illustrates a typical configuration of pressurizer PORVs, safety valves, and the block MOVs. There are either two or three PORVs on a pressurizer, so each plant will have two or three block MOVs.

ALPHA FACTOR AND MGL PARAMETERS
Pressurizer PORV Block Motor-Operated Valves

Table 35-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3
α_1	0.9814815	0.9875776
α_2	1.85E-02	0.00E+00
α_3		1.24E-02

Table 35-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameters	CCCG=2	CCCG=3
1-Beta	9.82E-01	9.88E-01
Beta	1.85E-02	1.24E-02
Gamma		1.00E+00

Table 35-3: Summary of average Impact Vectors - Fail to Open

Avg. Impact Vectors	CCCG=2	CCCG=3
Adj. Ind. Events	53.00	79.50
N_1	0.0000	0.0000
N_2	1.0000	0.0000
N_3		1.0000

Total Number of Independent Failure Events: 53
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
Pressurizer PORV Block Motor-Operated Valves

Table 35-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	**CCCG=2**	**CCCG=3**
α_1	0.9790023	0.9781485
α_2	2.10E-02	1.05E-02
α_3		1.13E-02

Table 35-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	**CCCG=2**	**CCCG=3**
1-Beta	9.79E-01	9.78E-01
Beta	2.10E-02	2.19E-02
Gamma		5.18E-01

Table 35-6: Summary of average Impact Vectors - Fail to Close

Avg. Impact Vector	**CCCG=2**	**CCCG=3**
Adj. Ind. Events	81.82	122.73
N_1	1.9403	1.4440
N_2	1.7965	1.3360
N_3		1.4380

Total Number of Independent Failure Events: 90
Total Number of Common-Cause Failure Events: 5

ALPHA FACTOR AND MGL PARAMETERS
Pressurizer PORV Block Motor-Operated Valves

Table 35-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3
α_1	0.9991797	0.9984675
α_2	8.20E-04	1.48E-03
α_3		5.47E-05

Table 35-8: Summary of MGL Parameter Estimations -Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3
1-Beta	9.99E-01	9.99E-01
Beta	8.20E-04	1.53E-03
Gamma		3.57E-02

Table 35-9: Summary of average Impact Vectors -Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3
Adj. Ind. Events	12.00	18.00
N_1	0.1800	0.2430
N_2	0.0100	0.0270
N_3		0.0010

Total Number of Independent Failure Events: 12
Total Number of Common-Cause Failure Events: 1

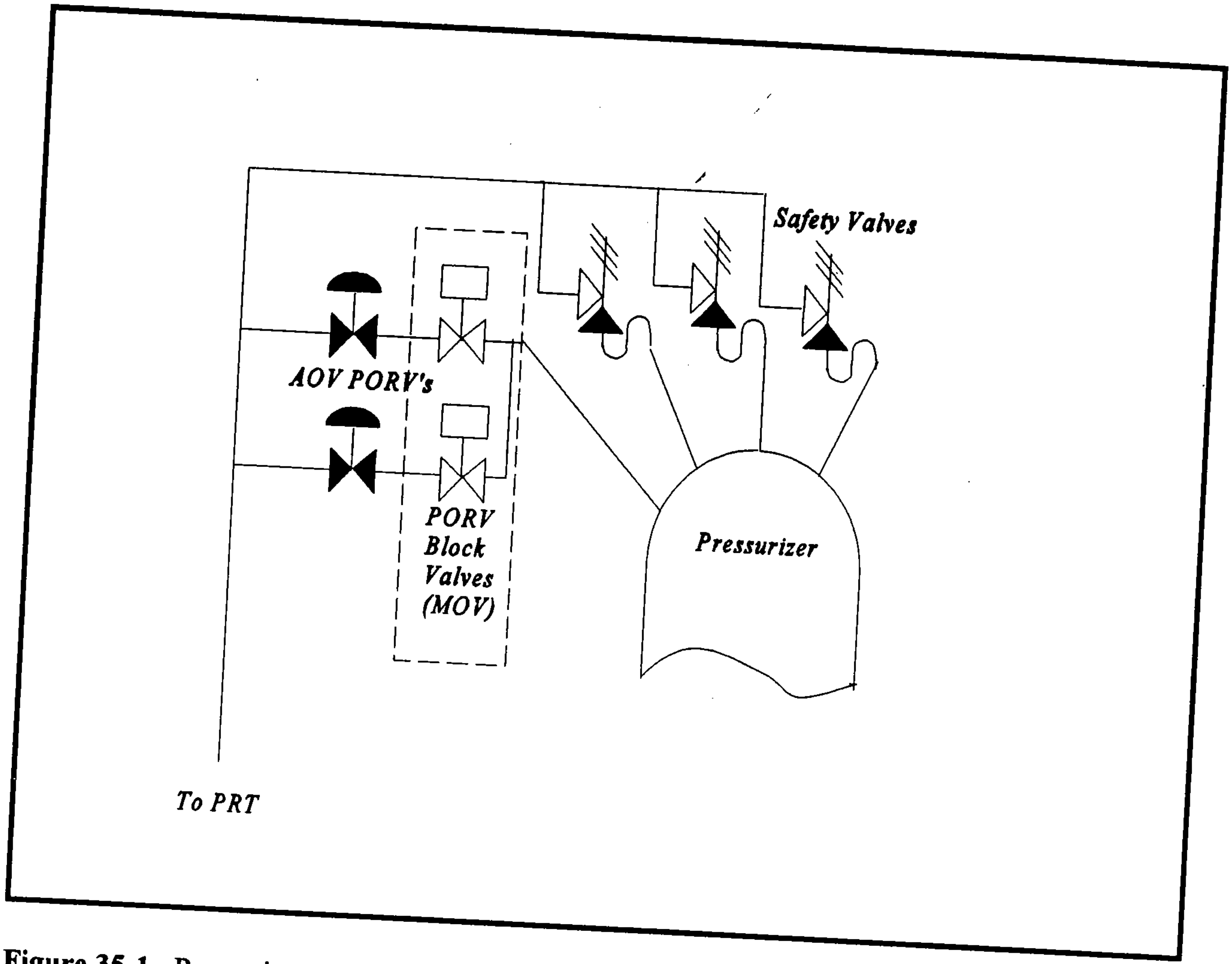

Figure 35-1. Pressurizer safety, relief, and PORV block valves.

3. COMPONENT BOUNDARIES

The main components of a motor-operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual handwheels, and can be manually operated. AC or DC power is required for valve operation.

The PORV block MOVs are used to isolate the PORVs to prevent the loss of primary coolant. They are normally open. The block MOVs would be closed remotely manually if the associated PORV leaks, or doesn't reseat fully following a transient.

4. FAILURE EVENT DEFINITION

The function of the PORV block MOVs is to isolate leakage from the primary coolant system through the PORV. The failure modes used in evaluating the PORV block MOV data are:

CC Fail to Open: The valve must be in the fully open position. Anything less than fully open is considered a failure to open.

OO Fail to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Fail to Remain Closed: In cases where the motor-operated valve has been closed for a substantial period of time and is then discovered leaking, the failure is coded as VR. If the discovery is made soon after a system configuration change (i.e., pump operation), then the failure is coded as OO.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open or closed state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure. These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC."

Many LERs reported only one actual failure, but the report information indicated that failure of a second block MOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another block MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another block MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an block MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 35-10 through 35-15 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of block MOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions that capture plant-to-plant variability will be provided later.

ALPHA FACTOR DISTRIBUTIONS
Pressurizer PORV Block Motor-Operated Valves

Table 35-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9404258	0.9770312	0.9817937	0.9973500	0.9814815	6.2530E+01	1.4700E+00
α_2	2.65E-03	2.30E-02	1.82E-02	5.96E-02	1.85E-02	1.4700E+00	6.2530E+01

Table 35-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9546249	0.9813471	0.9845616	0.9970809	0.9875776	9.4700E+01	1.8000E+00
α_2	3.35E-06	4.01E-03	1.41E-03	1.68E-02	0.00E+00	3.8720E-01	9.6113E+01
α_3	1.57E-03	1.46E-02	1.15E-02	3.86E-02	1.24E-02	1.4128E+00	9.5087E+01

ALPHA FACTOR DISTRIBUTIONS
Pressurizer PORV Block Motor-Operated Valves

Table 35-12: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9464360	0.9762811	0.9795245	0.9950401	0.9790023	9.3290E+01	2.2665E+00
α_2	4.96E-03	2.37E-02	2.05E-02	5.36E-02	2.10E-02	2.2665E+00	9.3290E+01

Table 35-13: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9504925	0.9749972	0.9771835	0.9920397	0.9781485	1.3937E+02	3.5740E+00
α_2	1.77E-03	1.21E-02	9.87E-03	2.98E-02	1.05E-02	1.7232E+00	1.4122E+02
α_3	2.10E-03	1.30E-02	1.08E-02	3.13E-02	1.13E-02	1.8508E+00	1.4109E+02

ALPHA FACTOR DISTRIBUTIONS
Pressurizer PORV Block Motor-Operated Valves

Table 35-14: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9164866	0.9783686	0.9902368	0.9999259	0.9991797	2.1710E+01	4.8000E-01
α_2	7.06E-05	2.16E-02	9.76E-03	8.35E-02	8.20E-04	4.8000E-01	2.1710E+01

Table 35-15: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9235517	0.9758396	0.9842998	0.9992411	0.9984675	3.3443E+01	8.2800E-01
α_2	1.61E-05	1.21E-02	4.65E-03	4.94E-02	1.48E-03	4.1420E-01	3.3857E+01
α_3	1.60E-05	1.21E-02	4.64E-03	4.94E-02	5.47E-05	4.1380E-01	3.3857E+01

36. PWR Refueling Water Storage Tank Suction Motor-Operated Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving motor-operated valves (MOVs) in the piping from the refueling water storage tank (RWST) to the emergency core cooling system (ECCS) pumps at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports retrieved from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open. The data cover the time period from 1980 through 1995.

The data review identified four common-cause failure-to-open events, two common-cause failure-to-close and no failure-to-remain closed events were identified. The maximum likelihood estimates(MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 36-1 and 36-2, respectively. Table 36-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode. Tables 36-4 through 36-6 contain the corresponding information for the failure to close failure mode. The size of the affected population of MOVs is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factor estimates are also included in this report in Tables 36-7 through 36-12.

2. SYSTEM DESCRIPTION

The refueling water storage tank stores borated water that is used for two purposes: injection into the reactor vessel following a loss of coolant accident (LOCA), and to fill the reactor cavity during refueling operations. The tank serves as a suction source for the containment spray, charging pumps, high pressure safety injection, and low pressure safety injection systems following a LOCA.

Several valves are in the piping lines from the RWST to the pumps; some are MOVs, and all are open during normal plant operations. Figure 36-1 shows a schematic diagram of the relationship between the RWST and the ECCS pumps. A typical plant has four RWST suction MOVs.

ALPHA FACTOR AND MGL PARAMETERS
Refueling Water Storage Tank Suction Motor-Operated Valves

Table 36-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9866757	0.9298096	0.9311714
α_2	1.33E-02	6.75E-02	3.0E-02
α_3		2.67E-03	3.68E-02
α_4			2.05E-03

Table 36-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.87E-01	9.30E-01	9.31E-01
Beta	1.33E-02	7.02E-02	6.88E-02
Gamma		3.80E-02	5.65E-01
Delta			5.26E-02

Table 36-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	22.22	33.33	44.44
N_1	3.3128	1.5360	1.0710
N_2	0.3448	2.5320	1.4640
N_3		0.1000	1.8000
N_4			0.1000

Total Number of Independent Failure Events: 50
Total Number of Common-Cause Failure Events: 4

ALPHA FACTOR AND MGL PARAMETERS
Refueling Water Storage Tank Suction Motor-Operated Valves

Table 36-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9951807	0.9903537	0.9854605
α_2	4.82E-03	9.65E-03	1.45E-02
α_3		0.00E+00	0.00E+00
α_4			0.00E+00

Table 36-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.95E-01	9.90E-01	9.86E-01
Beta	4.82E-03	9.65E-03	1.45E-02
Gamma		0.00E+00	0.00E+00
Delta			0.00E+00

Table 36-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	8.80	13.20	17.60
N_1	1.5662	2.2000	2.7335
N_2	0.0502	0.1500	0.3000
N_3		0.0000	0.0000
N_4			0.0000

Total Number of Independent Failure Events: 22
Total Number of Common-Cause Failure Events: 2

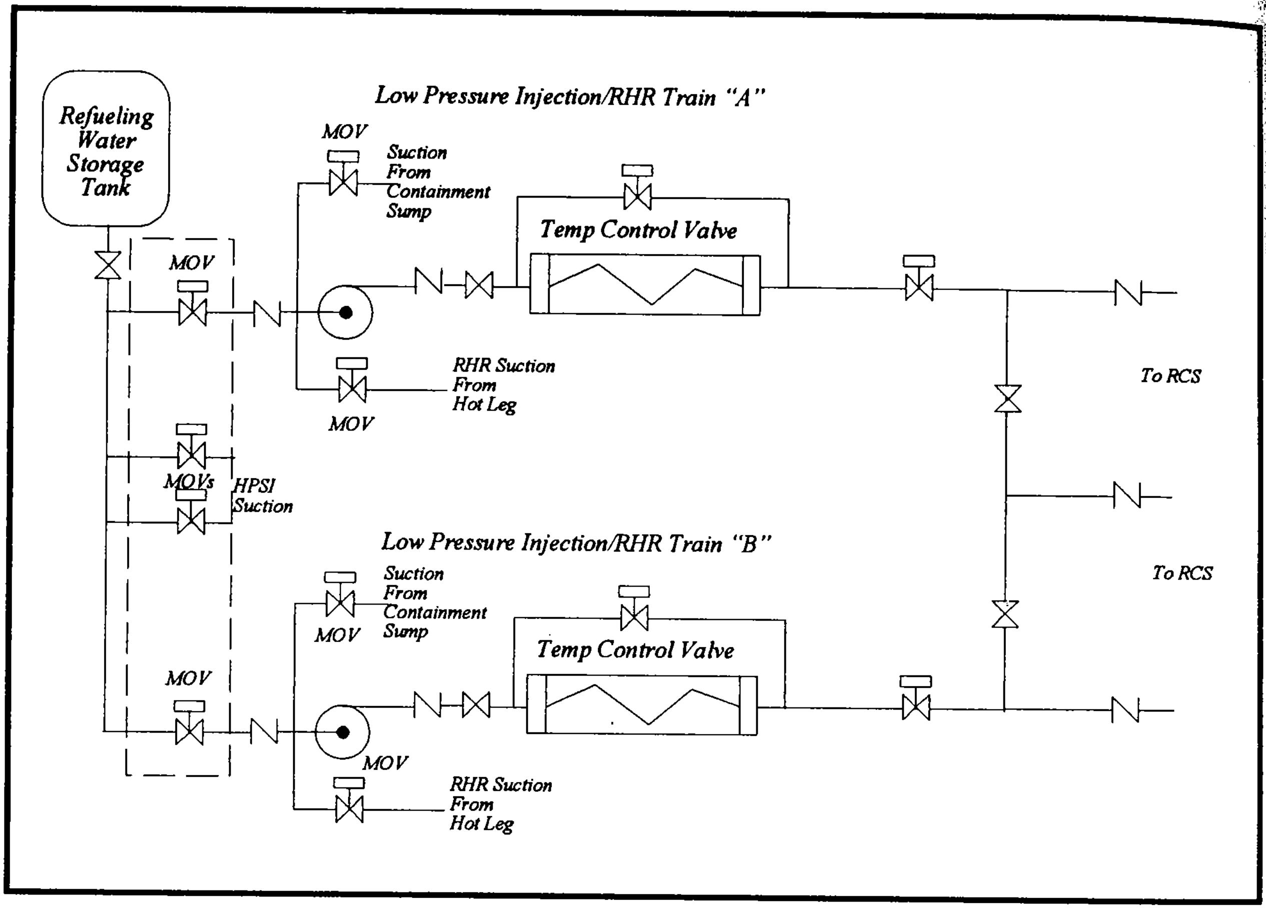

Figure 36-1. Refueling water storage tank system.

3. COMPONENT BOUNDARIES

The main components of a motor-operated valve are the valve, including its internal piece-part components (e.g. gate, stem), and the operator. The operator includes the circuit breaker, power leads, sensors (flow, pressure, and level) and motor as piece parts. Only sensors unique to the operation of the individual valve are included with the valve for CCF analysis. All MOVs have manual handwheels, and can be manually operated. AC or DC power is required for valve operation.

The MOVs in the RWST system are used to supply borated water to the suction of selected ECCS pumps. The valves are normally open, and will close, either automatically or by operator action, when the RWST reaches a low setpoint as the ECCS pump suction is shifted to the containment sump.

4. FAILURE EVENT DEFINITION

The function of the RWST MOVs is to allow primary coolant flow to the selected systems. All valves serve as a system containment boundary and would need to close to isolate leaks. The failure modes used in evaluating the RWST MOV data are:

CC Fail to Open: The valve must be in the fully open position. Anything less than fully open is considered a failure to open.

OO Failure to Close: The valve must be fully closed on a close signal, or it is considered a failure to close.

VR Failure to Remain Closed: In cases where the motor-operated valve has been closed for a substantial period of time and is then discovered leaking, the failure is coded as VR. If the discovery is made soon after a system configuration change (i.e., pump operation), then the failure is coded as OO.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. A stroke time testing failure was not considered a failure if the valve reached the required open state.

Valve failures include functional inoperabilities due to reasons not related to valve hardware malfunctions. Examples are breaker de-energized and locked open (human error), and system conditions (abnormal pressure and temperature) that prevent operation. Failure of the electrical operator without coincident failure of the manual operator is considered a failure. These events were considered individually to determine if the failure occurred within the component boundary, or if the failure was due to external factors such that the event was not a CCF event.

Failures of the operator and circuit breaker were evaluated to determine the ultimate effect on valve operability for assignment of failure mode. For example, a circuit breaker may fail to close, but the resulting effect on the valve is failure to open, so the failure mode is "CC."

Many LERs reported only one actual failure, but the report information indicated that failure of a second MOV would have occurred from the same cause if operation had been attempted. When the cause of the actual failure would have clearly caused failure of another MOV, the event was identified as a CCF. If, however, the report did not clearly identify that another MOV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered before an MOV operation demand (e.g. the condition was found during inspection, and no actual stroking failures occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 36-7 through 36-12 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of RWST MOVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Refueling Water Storage Tank Suction Motor-Operated Valves

Table 36-7: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9276680	0.9772896	0.9853721	0.9993218	0.9866757	3.5063E+01	8.1480E-01
α_2	6.75E-04	2.27E-02	1.46E-02	7.23E-02	1.33E-02	8.1480E-01	3.5063E+01

Table 36-8: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8734735	0.9358481	0.9412286	0.9797987	0.9298096	5.0660E+01	3.4320E+00
α_2	1.50E-02	5.46E-02	4.91E-02	1.13E-01	6.75E-02	2.9192E+00	5.0579E+01
α_3	4.36E-05	9.59E-03	4.51E-03	3.63E-02	2.67E-03	5.1280E-01	5.2985E+01

Table 36-9: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8863455	0.9377095	0.9415803	0.9758317	0.9311714	7.0211E+01	4.6640E+00
α_2	4.93E-03	2.70E-02	2.29E-02	6.30E-02	3.00E-02	2.0178E+00	7.2857E+01
α_3	5.18E-03	2.76E-02	2.35E-02	6.39E-02	3.68E-02	2.0626E+00	7.2812E+01
α_4	6.56E-05	7.79E-03	4.05E-03	2.82E-02	2.05E-03	5.8360E-01	7.4291E+01

ALPHA FACTOR DISTRIBUTIONS
Refueling Water Storage Tank Suction Motor-Operated Valves

Table 36-10: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9046363	0.9745202	0.9876153	0.9998744	0.9951807	1.9896E+01	5.2020E-01
α_2	1.28E-04	2.55E-02	1.24E-02	9.54E-02	4.82E-03	5.2020E-01	1.9896E+01

Table 36-11: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9095652	0.9698890	0.9791326	0.9986066	0.9903537	3.0600E+01	9.5000E-01
α_2	9.88E-05	1.70E-02	8.40E-03	6.33E-02	9.65E-03	5.3720E-01	3.1013E+01
α_3	1.71E-05	1.31E-02	5.02E-03	5.35E-02	0.00E+00	4.1280E-01	3.1137E+01

Table 36-12: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9139360	0.9656903	0.9721173	0.9954186	0.9854605	4.5034E+01	1.6000E+00
α_2	6.24E-04	1.83E-02	1.20E-02	5.75E-02	1.45E-02	8.5380E-01	4.5780E+01
α_3	1.64E-07	5.63E-03	1.10E-03	2.69E-02	0.00E+00	2.6260E-01	4.6371E+01
α_4	3.46E-05	1.04E-02	4.64E-03	4.01E-02	0.00E+00	4.8360E-01	4.6150E+01

37. PWR Pressurizer Power Operated Relief Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving power operated relief valves (PORVs) in the primary coolant system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and information from the Nuclear Plant Reliability Date System (NPRDS) have been screened to identify common-cause failure events for Pressurizer PORVs. Failure modes analyzed are failure to open, failure to close, and failure to remain closed (spurious opening or leakage past the valve seat). The data cover the time period from 1980 through 1995.

The data review identified 17 common-cause failure to open event, two common-cause failure to close events, and three common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 37-1 and 37-2, respectively. Table 37-3 contains the average impact vectors (N_1-N_3) and the number of adjusted independent events for this failure mode. Tables 37-4 through 37-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of configurations of pressurizer PORVs is denoted as CCCG and is either two or three for all plants. The alpha factor model parameters are denoted by α_1-α_3. Beta (β) and gamma (γ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 37-10 through 37-15.

2. SYSTEM DESCRIPTION

The primary coolant system in a PWR consists of the piping and other components necessary to remove heat from the reactor core. Part of the system is the pressurizer which serves to regulate the system pressure, both raising pressure to maintain solid water in the pressurizer flow path , and lowering pressure to control plant operations and prevent system over pressurization. The PORVs are used for pressure control and safety valves are used for over pressure protection purposes.

The pressurizer PORVs automatically actuate to lower pressure in the event of a power mismatch. The PORVs are not required in order to prevent over pressurization but rather function to increase plant operability. The PORVs may also be manually actuated. During shutdown conditions the PORVs may provide cold over pressure protection. In order to provide cold over pressure protection, operator action is required to reset the automatic lift setpoints. Figure 37-1 shows a typical configuration of pressurizer PORVs and safety valves.

ALPHA FACTOR AND MGL PARAMETERS
Pressurizer PORVs

Table 37-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Parameter	CCCG=2	CCCG=3
α_1	0.9314746	0.9282503
α_2	6.85E-02	2.73E-02
α_3		4.45E-02

Table 37-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3
1-Beta	9.32E-01	9.28E-01
Beta	6.85E-02	7.18E-02
Gamma		6.20E-01

Table 37-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3
Adj. Ind. Events	132.04	198.06
N_1	6.1070	1.2915
N_2	10.1630	5.8560
N_3		9.5530

Total Number of Independent Failure Events: 136
Total Number of Common-Cause failure Events: 17

ALPHA FACTOR AND MGL PARAMETERS
Pressurizer PORVs

Table 37-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Parameter	CCCG=2	CCCG=3
α_1	0.9641667	0.9635037
α_2	3.58E-02	1.83E-02
α_3		1.83E-02

Table 37-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3
1-Beta	9.64E-01	9.64E-01
Beta	3.58E-02	3.65E-02
Gamma		5.00E-01

Table 37-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3
Adj. Ind. Events	35.20	52.80
N_1	0.6670	0.0000
N_2	1.3330	1.0000
N_3		1.0000

Total Number of Independent Failure Events: 44
Total Number of Common-Cause Failure Events: 2

ALPHA FACTOR AND MGL PARAMETERS
Pressurizer PORVs

Table 37-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3
α_1	0.9859155	0.9895123
α_2	1.41E-02	1.57E-03
α_3		8.92E-03

Table 37-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3
1-Beta	9.86E-01	9.90E-01
Beta	1.41E-02	1.05E-02
Gamma		8.50E-01

Table 37-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vectors	CCCG=2	CCCG=3
Adj. Ind. Events	157.00	235.50
N_1	0.5000	0.3750
N_2	2.2500	0.3750
N_3		2.1250

Total Number of Independent Failure Events: 157
Total Number of Common-Cause Failure Events: 3

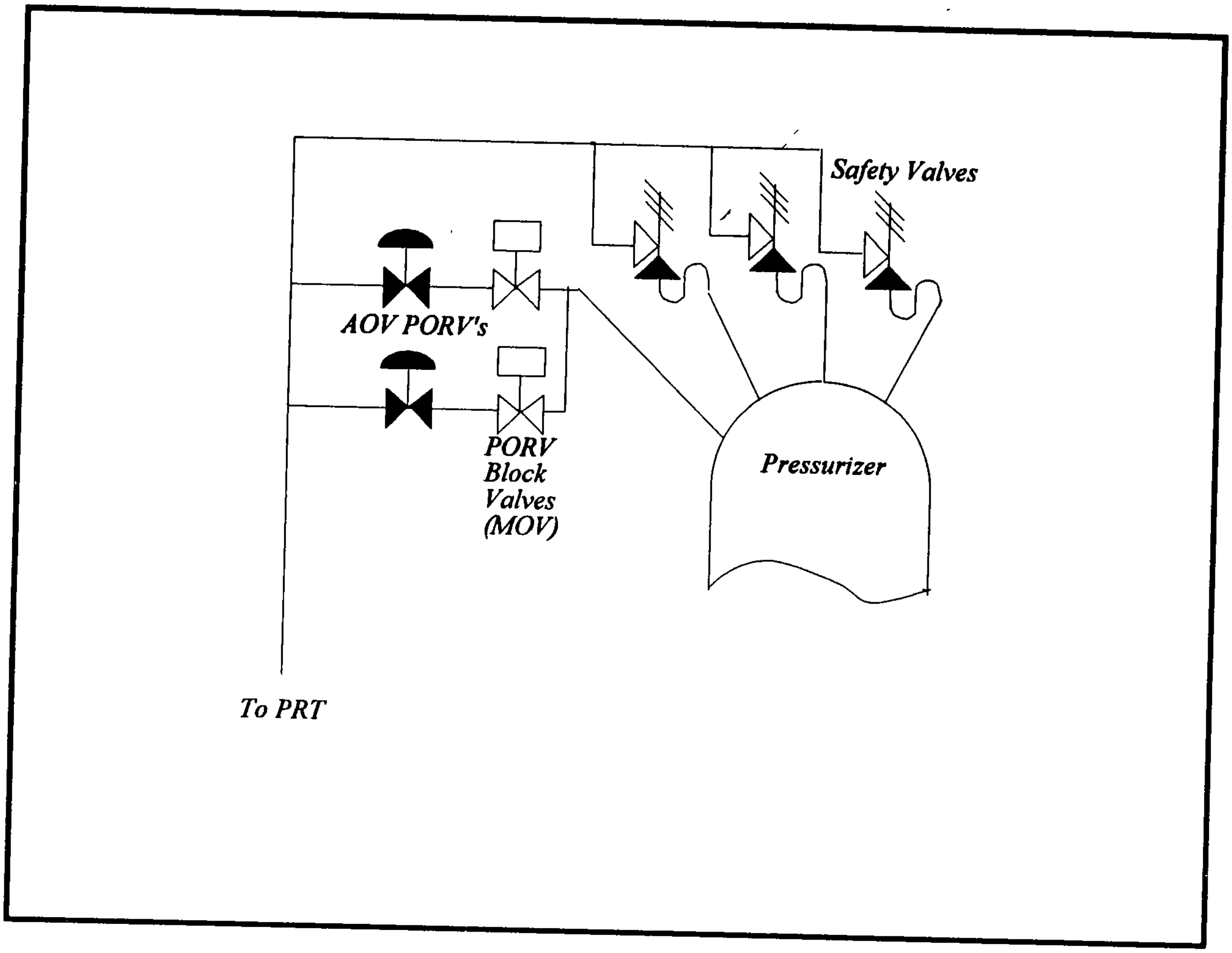

Figure 37-1. Pressurizer safety and relief valves.

3. COMPONENT BOUNDARIES

The pressurizer PORV consists of the valve itself along with control and power systems that are specific to the individual PORV. The air supply or gas accumulator to each individual valve is included with that valve. The instrument air system upstream of the PORV air supply isolation valve is not included. Specifically excluded are indication circuitry and control and power systems that are not specific to an individual PORV, but that provide input to multiple PORVs.

4. FAILURE EVENT DEFINITION

Successful operation of a relief valve is defined as opening in response to high system pressure, and reclosing when pressure is reduced. The failure modes used in evaluating the pressurizer PORV data are:

CC Failure to Open: Examples are:

- PORV sticks closed,
- PORV setpoint over 10% over the limit or words like "excessive" are considered failures,

- If piece-part(s) are replaced to calibrate a setpoint that was too high, then the PORV is considered failed;
- A stroke time test failure will be considered a failure if it is reported as "excessive, " otherwise it is not a failure, and
- Whenever a PORV is blocked shut.

OO Failure to Close: Examples are:
- Valve stays open when it should close,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed: Examples are:
- Spurious opening,
- Leakage past the valve seat, and
- If piece-part(s) are replaced to re-calibrate a setpoint that was low.

Relief valve malfunctions are considered to be failures to open or close on demand, failure to stay open or closed, including excessive leakage through the valve. Valve failures include those failures that are caused by power supplies or sensors that are unique to the valve. Relief valves that open in response to an actual system over pressure are not failures. Subsequent failures to reseat completely are defined as a failure to close event.

Valve operator failures are evaluated to determine the effect on valve operability. In general, if the failure causes the valve to fail to operate, it will be considered a valve failure. Failures of the valve to provide input to other systems (such as limit switches) will not be considered valve failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. The exception to this is if a licensee reported that the valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications (TS) in the proper configuration is not considered a failure, unless the improper configuration would have prevented the valve from operating properly on a safety demand. An example is low temperature/pressure conditions (outages) when the relief valve setpoints are required to be lowered. On occasion, licensees forget to lower the setpoints when they change modes, resulting in a TS violation, and preventing the valve from opening at the outage condition setpoint.

Many LERs reported only one actual failure, but the report information indicated that a second PORV would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another PORV, then the event was identified as a CCF. If, however, the report did not clearly identify that another PORV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to a PORV actuation demand (e.g. the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 37-10 through 37-15 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of PORVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the tables. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Pressurizer PORVs

Table 37-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8973900	0.9328356	0.9346561	0.9620702	0.9314746	1.4768E+02	1.0633E+01
α_2	3.79E-02	6.72E-02	6.54E-02	1.03E-01	6.85E-02	1.0633E+01	1.4768E+02

Table 37-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9001838	0.9297579	0.931008	0.9550983	0.9282503	2.1455E+02	1.6209E+01
α_2	1.21E-02	2.71E-02	2.57E-02	4.66E-02	2.73E-02	6.2432E+00	2.2452E+02
α_3	2.37E-02	4.32E-02	4.19E-02	6.72E-02	4.45E-02	9.9658E+00	2.2079E+02

ALPHA FACTOR DISTRIBUTIONS
Pressurizer PORVs

Table 37-12: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9079730	0.9618009	0.9681410	0.9939215	0.9641667	4.5397E+01	1.8030E+00
α_2	6.08E-03	3.82E-02	3.19E-02	9.20E-02	3.58E-02	1.8030E+00	4.5397E+01

Table 37-13: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9166621	0.9604520	0.9647151	0.9896466	0.9635037	6.8000E+01	2.8000E+00
α_2	2.04E-03	1.96E-02	1.53E-02	5.19E-02	1.83E-02	1.3872E+00	6.9413E+01
α_3	2.15E-03	2.00E-02	1.56E-02	5.25E-02	1.83E-02	1.4128E+00	6.9387E+01

ALPHA FACTOR DISTRIBUTIONS
Pressurizer PORVs

Table 37-14: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9656246	0.9839764	0.9858391	0.9959750	0.9859155	1.6703E+02	2.7200E+00
α_2	4.03E-03	1.60E-02	1.42E-02	3.44E-02	1.41E-02	2.7200E+00	1.6703E+02

Table 37-15: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9736259	0.9870273	0.9882829	0.9961391	0.9895123	2.5108E+02	3.3000E+00
α_2	7.03E-05	3.00E-03	1.84E-03	9.88E-03	1.57E-03	7.6220E-01	2.5362E+02
α_3	2.33E-03	9.98E-03	8.72E-03	2.19E-02	8.92E-03	2.5378E+00	2.5184E+02

38. PWR Steam Generator Power Operated Relief Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving steam generator power operated relief valves at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed (spurious opening and leakage past the valve seat). The data cover the time period from 1980 through 1995.

The data review identified 47 common-cause failure to open events, nine common-cause failure to close events, and five common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 38-1 and 38-2, respectively. Table 38-3 contains the average impact vectors (N_1-N_4) and the number of adjusted independent events for this failure mode. Tables 38-4 through 38-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of steam generator power operated relief valves (PORVs) is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_4. Beta (β), gamma (γ), and delta (δ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 38-10 through 38-18.

2. SYSTEM AND COMPONENT DESCRIPTION

The steam generator PORVs actuate to lower pressure in the secondary side of the steam generators prior to safety relief valves lifting. This need to lower pressure is normally the result of a high temperature in the reactor coolant system. Additionally, the valves must reclose following the pressure relief and remain closed during operation in order to preserve the secondary coolant boundary and control the heat removal rate. The steam generator PORVs are actuated by an external motive source such as electrical motor, air, nitrogen, hydraulics, or electrical solenoid. Manual initiation can be accomplished by the control room operator if necessary. Figure 38-1 shows the configuration of the steam generator PORVs and safety valves. The number of steam generator PORVs at a single plant is the same as the number of steam generators at that plant.

ALPHA FACTOR AND MGL PARAMETERS
Steam Generator Power Operated Relief Valves

Table 38-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9126846	0.8864152	0.8829514
α_2	8.73E-02	6.97E-02	4.97E-02
α_3		4.39E-02	3.57E-02
α_4			3.17E-02

Table 38-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.13E-01	8.86E-01	8.83E-01
Beta	8.73E-02	1.14E-01	1.17E-01
Gamma		3.87E-01	5.76E-01
Delta			4.70E-01

Table 38-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	108.93	163.40	217.87
N_1	26.1025	22.7447	20.0710
N_2	12.9184	14.6258	13.3824
N_3		9.2267	9.6206
N_4			8.5397

Total Number of Independent Failure Events: 189
Total Number of Common-Cause failure Events: 47

ALPHA FACTOR AND MGL PARAMETERS
Steam Generator Power Operated Relief Valves

Table 38-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	**CCCG=2**	**CCCG=3**	**CCCG=4**
α_1	0.9668929	0.9119550	0.9006279
α_2	3.31E-02	8.48E-02	5.61E-02
α_3		3.21E-03	4.21E-02
α_4			1.19E-03

Table 38-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	**CCCG=2**	**CCCG=3**	**CCCG=4**
1-Beta	9.67E-01	9.12E-01	9.01E-01
Beta	3.31E-02	8.81E-02	9.94E-02
Gamma		3.65E-02	4.35E-01
Delta			2.74E-02

Table 38-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**
Adj. Ind. Events	24.00	36.00	48.00
N_1	5.6840	4.2246	3.2677
N_2	1.0164	3.7419	3.1955
N_3		0.1416	2.3937
N_4			0.0675

Total Number of Independent Failure Events: 36
Total Number of Common-Cause Failure Events: 9

ALPHA FACTOR AND MGL PARAMETERS
Steam Generator Power Operated Relief Valves

Table 38-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4
α_1	0.9971518	0.9867363	0.9860369
α_2	2.85E-03	1.24E-02	5.33E-03
α_3		8.50E-04	8.22E-03
α_4			4.12E-04

Table 38-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4
1-Beta	9.97E-01	9.87E-01	9.86E-01
Beta	2.85E-03	1.33E-02	1.40E-02
Gamma		6.41E-02	6.18E-01
Delta			4.77E-02

Table 38-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4
Adj. Ind. Events	133.75	200.63	267.50
N_1	3.9809	2.4650	1.8407
N_2	0.3934	2.5550	1.4558
N_3		0.1750	2.2458
N_4			0.1125

Total Number of Independent Failure Events: 214
Total Number of Common-Cause Failure Events: 5

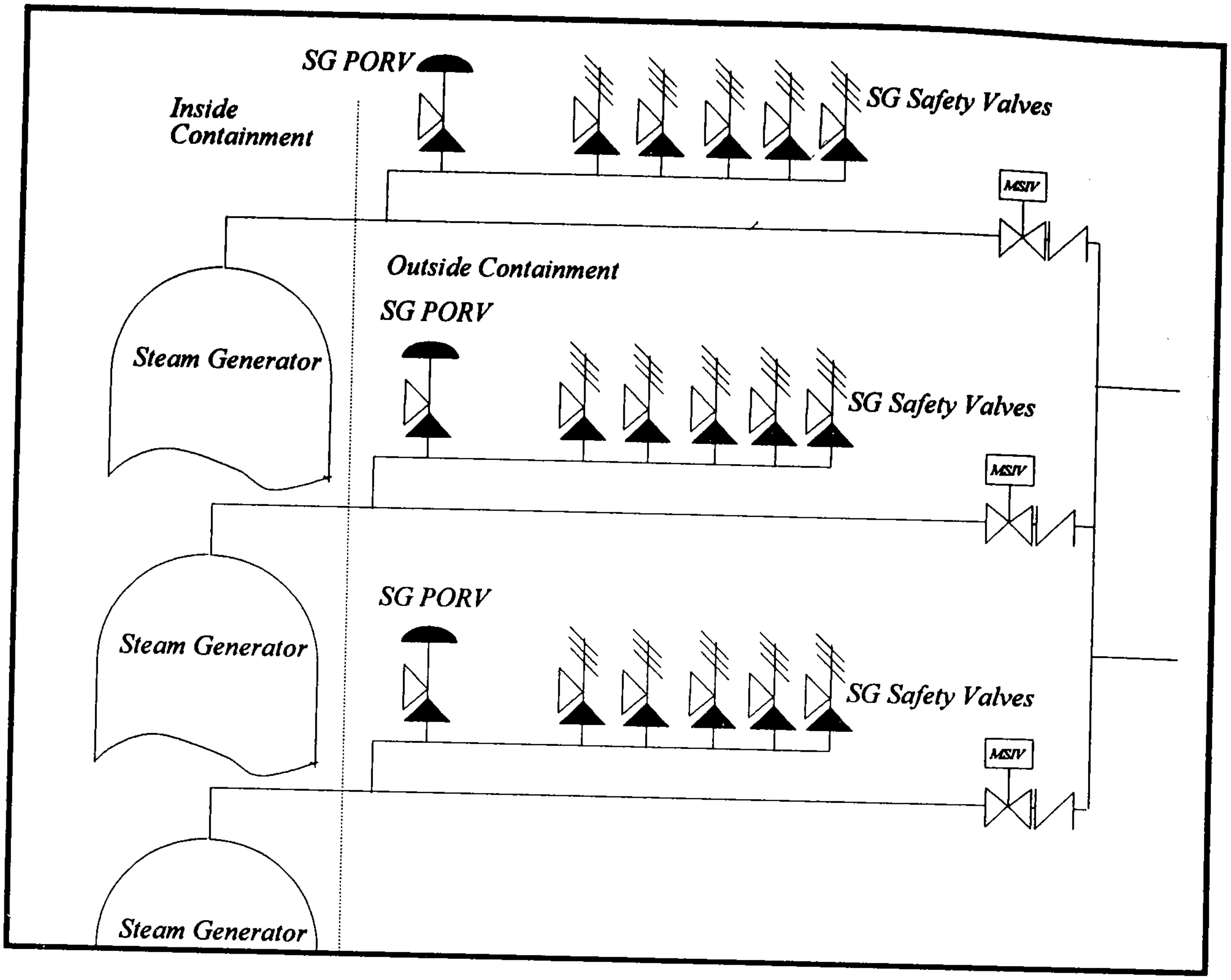

Figure 38-1. PWR steam generator relief and safety valves.

3. COMPONENT BOUNDARIES

The main component of a steam generator PORV is the valve itself. This component is normally operated by a sensor actuating the operating medium such as air or an electric motor which will in turn operate the valve. These valves can also be manually opened and closed via a remote control switch. In addition to opening to lower pressure, the valves are designed to re-close when the desired pressure is achieved. This may be only slightly less than the opening pressure.

The boundaries include the valve itself, the valve operator, any sensing lines, and the auxiliary equipment needed to open the valve or verify the valve position. Only the sensors and power supplies that provide direct input to the individual valves are included. Air or nitrogen lines leading directly to a single valve are included with the valve; failures of the air or nitrogen systems are not included with the valve. Other valve actuation logic, breakers, or air systems that affect other valves or other equipment are not considered part of the valve.

4. FAILURE EVENT DEFINITION

Successful operation of a steam generator PORV is defined as opening in response to high system pressure, and reclosing when pressure is reduced. The failure modes used in evaluating the data are:

CC Failure to Open: Examples are:

- PORV sticks closed,
- PORV setpoint over 10% over the limit or words like "excessive" are considered failures,
- If piece-part(s) are replaced to calibrate setpoint, then the PORV is considered failed,
- A stroke time test failure will be considered a failure if it is reported as "excessive, " otherwise it is no failure, and
- Whenever a PORV is blocked shut.

OO Failure to Close: Examples are:

- Valve stays open when it should close,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed: Examples are:

- Spurious opening,
- Leakage past the valve seat, and
- If piece-part(s) are replaced to re-calibrate a setpoint that was low.

Steam generator PORV malfunctions are considered to be failures to open or close on demand, failure to stay open or closed, including excessive leakage through the valve. Valve failures include those failures that are caused by power supplies or sensors that are unique to the valve. Steam generator PORVs that open in response to an actual system over pressure are not failures. Subsequent failures to reseat completely are defined as a failure to close event.

Valve operator failures are evaluated to determine the effect on valve operability. In general, if the failure causes the valve to fail to operate, it will be considered a valve failure. Failures of the valve to provide input to other systems (such as limit switches) will not be considered valve failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. The exception to this is if a licensee reported that the valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the valve from operating properly on a safety demand. An example is low temperature/pressure conditions (outages) when the steam generator PORV setpoints are required to be lowered. On occasion, licensees forget to lower the setpoints when they change modes, resulting in a TS violation, and preventing the valve from opening at the outage condition setpoint.

Many LERs reported only one actual failure, but the report information indicated that a second PORV would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another PORV, then the event was identified as a CCF. If, however, the report did not clearly identify that another PORV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to PORV actuation demand (e.g. the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 38-10 through 38-18 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of SG PORVs. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the tables. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Steam Generator Power Operated Relief Valves

Table 38-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8761342	0.9152379	0.9169904	0.9483629	0.9126846	1.4456E+02	1.3388E+01
α_2	5.16E-02	8.48E-02	8.30E-02	1.24E-01	8.73E-02	1.3388E+01	1.4456E+02

Table 38-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8550170	0.8909193	0.8920707	0.9228805	0.8864152	2.0135E+02	2.4653E+01
α_2	4.16E-02	6.64E-02	6.52E-02	9.56E-02	6.97E-02	1.5013E+01	2.1099E+02
α_3	2.31E-02	4.27E-02	4.13E-02	6.68E-02	4.39E-02	9.6395E+00	2.1636E+02

Table 38-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8573968	0.8888513	0.8897316	0.9173110	0.8829514	2.6264E+02	3.2843E+01
α_2	2.88E-02	4.72E-02	4.61E-02	6.90E-02	4.97E-02	1.3936E+01	2.8155E+02
α_3	1.82E-02	3.35E-02	3.24E-02	5.22E-02	3.57E-02	9.8832E+00	2.8560E+02
α_4	1.61E-02	3.05E-02	2.95E-02	4.86E-02	3.17E-02	9.0233E+00	2.8646E+02

ALPHA FACTOR DISTRIBUTIONS
Steam Generator Power Operated Relief Valves

Table 38-13: Alpha Factor Distribution Summary - Fail to Close, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9062541	0.9634795	0.9707900	0.9956557	0.9668929	3.9214E+01	1.4864E+00
α_2	4.34E-03	3.65E-02	2.92E-02	9.38E-02	3.31E-02	1.4864E+00	3.9214E+01

Table 38-14: Alpha Factor Distribution Summary - Fail to Close, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8587336	0.9220825	0.9267419	0.9694849	0.9119550	5.5425E+01	4.6835E+00
α_2	2.48E-02	6.87E-02	6.39E-02	1.29E-01	8.48E-02	4.1291E+00	5.5979E+01
α_3	6.15E-05	9.22E-03	4.62E-03	3.40E-02	3.21E-03	5.5440E-01	5.9554E+01

Table 38-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8612258	0.9161083	0.9194439	0.9595835	0.9006279	7.5968E+01	6.9567E+00
α_2	1.51E-02	4.52E-02	4.16E-02	8.77E-02	5.61E-02	3.7493E+00	7.9175E+01
α_3	7.94E-03	3.20E-02	2.83E-02	6.88E-02	4.21E-02	2.6563E+00	8.0268E+01
α_4	4.29E-05	6.65E-03	3.31E-03	2.46E-02	1.19E-03	5.5110E-01	8.2374E+01

ALPHA FACTOR DISTRIBUTIONS
Steam Generator Power Operated Relief Valves

Table 38-16: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9816583	0.9941711	0.9961941	0.9998004	0.9971518	1.4726E+02	8.6340E-01
α_2	2.02E-04	5.83E-03	3.81E-03	1.83E-02	2.85E-03	8.6340E-01	1.4726E+02

Table 38-17: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9682823	0.9840869	0.9855167	0.9950039	0.9867363	2.1830E+02	3.5300E+00
α_2	3.58E-03	1.33E-02	1.18E-02	2.79E-02	1.24E-02	2.9422E+00	2.1889E+02
α_3	2.29E-05	2.65E-03	1.38E-03	9.59E-03	8.50E-04	5.8780E-01	2.2124E+02

Table 38-18: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9690419	0.9829048	0.9839674	0.9931252	0.9860369	2.9404E+02	5.1141E+00
α_2	1.21E-03	6.72E-03	5.66E-03	1.59E-02	5.33E-03	2.0960E+00	2.9715E+02
α_3	1.94E-03	8.39E-03	7.32E-03	1.85E-02	8.22E-03	2.5084E+00	2.9665E+02
α_4	1.83E-05	1.99E-03	1.05E-03	7.18E-03	4.12E-04	5.9610E-01	2.9856E+02

39. BWR Pressure Relief and ADS Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving relief valves and automatic depressurization system valves (ADS) in the primary cooling system at boiling water reactor (BWR) power plants. Licensee Event Reports (LERs) and failure records from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed (leakage past the valve seat or spurious opening). The data cover the time period from 1980 through 1995.

The data review identified 27 common-cause failure to open events, 1 common-cause failure to close event and 10 common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 39-1 and 39-2, respectively. Table 39-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 39-4 through 39-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of BWR pressure relief and ADS valves is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 39-10 through 39-18.

2. SYSTEM DESCRIPTION

The BWR pressure relief and ADS valves actuate to lower pressure in the BWR primary system. The number of relief valves range from 4 to 20; a typical number is 11. This need to lower system pressure may be dictated by system pressure being above normal or by the need to allow injection from lower pressure systems. If valves open due to pressure being above normal, the valves must reclose following the pressure relief or remain close during operation in order to preserve the primary coolant boundary. If the valves open to allow injection from lower pressure sources, they will close only when system pressure is reduced to near atmospheric. The valves may also be operated manually via a remote control switch. Some relief valves may be actuated by an external motive source such as air or nitrogen. A typical BWR safety, pressure relief, and ADS valve arrangement is shown in Figure 39-1.

ALPHA FACTOR AND MGL PARAMETERS
BWR Pressure Relief and ADS Valves

Table 39-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9544554	0.9375297	0.9084257	0.8964265	0.8853880
α_2	4.55E-02	5.16E-02	6.97E-02	7.30E-02	7.19E-02
α_3		1.08E-02	1.78E-02	2.22E-02	2.83E-02
α_4			4.04E-03	6.87E-03	9.85E-03
α_5				1.54E-03	3.93E-03
α_6					6.90E-04

Table 39-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.55E-01	9.38E-01	9.08E-01	8.96E-01	8.85E-01
Beta	4.55E-02	6.25E-02	9.16E-02	1.04E-01	1.15E-01
Gamma		1.74E-01	2.39E-01	2.95E-01	3.73E-01
Delta			1.85E-01	2.75E-01	3.38E-01
Epsilon				1.83E-01	3.19E-01
Mu					1.49E-01

Table 39-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	28.09	42.14	56.18	70.23	84.27
N_1	9.5018	10.6297	10.8739	9.6970	9.0769
N_2	1.7938	2.9062	5.1471	6.5099	7.5756
N_3		0.6100	1.3139	1.9746	2.9831
N_4			0.2984	0.6128	1.0384
N_5				0.1375	0.4138
N_6					0.0727

Total Number of Independent Failure Events: 142
Total Number of Common-Cause Failure Events: 27

ALPHA FACTOR AND MGL PARAMETERS
BWR Pressure Relief and ADS Valves

Table 39-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9963328	0.9926740	0.9889695	0.9852336	0.9814815
α_2	3.67E-03	7.33E-03	1.10E-02	1.48E-02	1.85E-02
α_3		0.00E+00	0.00E+00	0.00E+00	0.00E+00
α_4			0.00E+00	0.00E+00	0.00E+00
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 39-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.96E-01	9.93E-01	9.89E-01	9.85E-01	9.82E-01
Beta	3.67E-03	7.33E-03	1.10E-02	1.48E-02	1.85E-02
Gamma		0.00E+00	0.00E+00	0.00E+00	0.00E+00
Delta			0.00E+00	0.00E+00	0.00E+00
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 39-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	17.67	26.50	35.33	44.17	53.00
N_1	0.5330	0.6000	0.5330	0.3330	0.0000
N_2	0.0670	0.2000	0.4000	0.6670	1.0000
N_3		0.0000	0.0000	0.0000	0.0000
N_4			0.0000	0.0000	0.0000
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 53
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
BWR Pressure Relief and ADS Valves

Table 39-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
α_1	0.9899146	0.9829415	0.9733513	0.9665930	0.9683204
α_2	1.01E-02	1.63E-02	2.47E-02	3.02E-02	2.04E-02
α_3		7.61E-04	1.84E-03	2.94E-03	1.04E-02
α_4			1.10E-04	2.83E-04	8.46E-04
α_5				1.18E-05	5.76E-05
α_6					0.00E+00

Table 39-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
1-Beta	9.90E-01	9.83E-01	9.73E-01	9.67E-01	9.68E-01
Beta	1.01E-02	1.71E-02	2.67E-02	3.34E-02	3.17E-02
Gamma		4.46E-02	7.33E-02	9.69E-02	3.56E-01
Delta			5.61E-02	9.11E-02	8.01E-02
Epsilon				4.00E-02	6.38E-02
Mu					0.00E+00

Table 39-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	**CCCG=2**	**CCCG=3**	**CCCG=4**	**CCCG=5**	**CCCG=6**
Adj. Ind. Events	18.77	28.15	37.53	46.91	56.30
N_1	1.9403	2.3434	2.4579	2.2486	2.5029
N_2	0.2110	0.5056	1.0146	1.5344	1.2387
N_3		0.0236	0.0757	0.1496	0.6302
N_4			0.0045	0.0144	0.0514
N_5				0.0006	0.0035
N_6					0.0000

Total Number of Independent Failure Events: 76
Total Number of Common-Cause Failure Events: 10

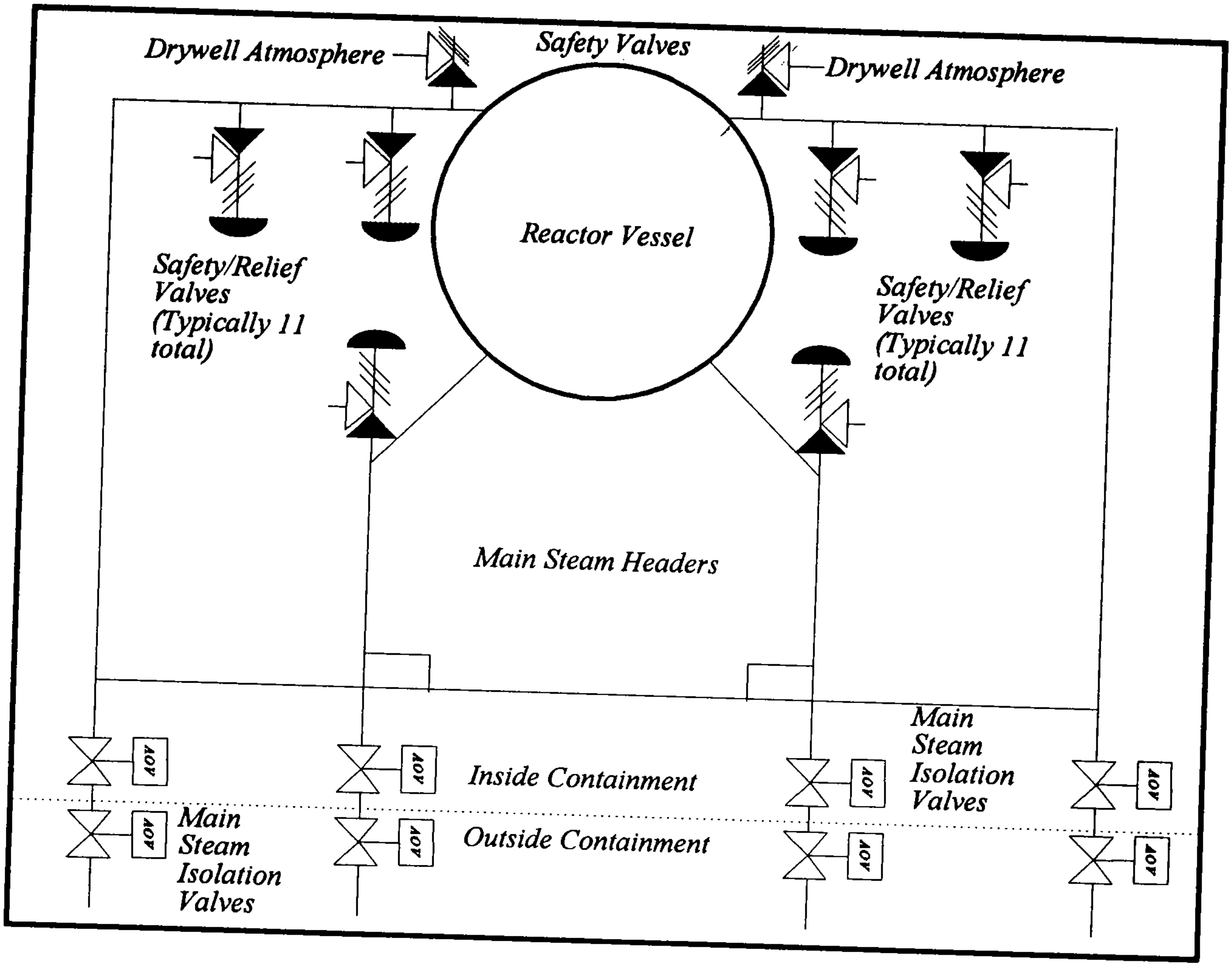

Figure 39-1. BWR safety, pressure relief, and ADS valves.

3. COMPONENT BOUNDARIES

The main component of a relief valve (RV) is the valve itself. This component is normally operated by a sensor actuating the operating medium such as air or nitrogen which will in turn operate the valve. These valves can also typically be manually opened and closed via a remote control switch. In addition to opening to lower pressure, the valves are designed to re-close when the desired pressure is achieved. This may be only slightly less than the opening pressure or in the case of valves which open to reduce pressure in preparation for low pressure injection, may be when system pressure is insufficient to hold the valve open.

The boundaries include the valve itself, the valve operator, any sensing lines, and the auxiliary equipment needed to open the valve or verify the valve position. Only the sensors and power supplies that only provide direct input to the individual valve are included. Air or nitrogen lines leading directly to a single valve are included with the valve; failures of the air or nitrogen systems are not included with the valve. Other valve actuation logic, breakers, or air systems that affect other valves or other equipment are not considered part of the valve.

4. FAILURE EVENT DEFINITION

Successful operation of a relief valve is defined as opening in response to high system pressure, and reclosing when pressure is reduced. The failure modes used in evaluating the data are:

CC Failure to Open: Examples are:
- RV sticks closed,
- RV setpoint over 10% over the limit or words like "excessive" are considered failures,
- If piece-part(s) are replaced to calibrate a setpoint that was too high, then the RV is considered failed,
- A stroke time test failure will be considered a failure if it is reported as "excessive, " otherwise it is not a failure, and
- Whenever a RV is blocked shut.

OO Failure to Close: Examples are:
- Valve stays open when it should close,
- Valve doesn't fully open, and
- Failure to re-seat.

VR Failure to Remain Closed: Examples are:
- Spurious opening,
- Leakage past the valve seat, and
- If piece-part(s) are replaced to re-calibrate a setpoint that was too low.

Relief valve malfunctions are considered to be failures to open or close on demand, failure to stay open or closed, including excessive leakage through the valve. Valve failures include those failures that are caused by power supplies or sensors that are unique to the valve. Relief valves that open in response to an actual system over pressure are not failures. Subsequent failures to reseat completely are defined as a failure to close event.

Valve operator failures are evaluated to determine the effect on valve operability. In general, if the failure causes the valve to fail to operate, it will be considered a valve failure. Failures of the valve to provide input to other systems (such as limit switches) will not be considered valve failures.

Administrative inoperability events, such as seismic qualification or Appendix R violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. The exception to this is if a licensee reported that the valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications (TS) in the proper configuration is not considered a failure, unless the improper configuration would have prevented the valve from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that a second RV would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another RV, then the event was identified as a CCF. If, however, the report did not clearly identify that another RV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to an RV actuation demand (e.g. the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 39-10 through 39-18 present the alpha factor uncertainty distribution summaries for each failure mode. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. The average CCCG for the BWR relief valve events is over 15, so the parameter estimations using a CCCG of 6 (due to software limitations) are conservative. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
BWR Pressure Relief and ADS Valves

Table 39-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8703195	0.9192553	0.9220476	0.9586444	0.9084257	9.1754E+01	8.0594E+00
α_2	2.48E-02	5.71E-02	5.42E-02	9.95E-02	6.97E-02	5.709E+00	9.4113E+01
α_3	2.03E-03	1.58E-02	1.27E-02	4.02E-02	1.78E-02	1.5765E+00	9.8237E+01
α_4	2.01E-04	7.84E-03	4.88E-03	2.55E-02	4.04E-03	7.8200E-01	9.9031E+01

Table 39-11: Alpha Factor Distribution Summary - Fail to Open, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8694438	0.9133463	0.9154745	0.9499641	0.8964265	1.1797E+02	1.1192E+01
α_2	2.72E-02	5.60E-02	5.38E-02	9.27E-02	7.30E-02	7.2379E+00	1.2192E+02
α_3	4.08E-03	1.85E-02	1.61E-02	4.12E-02	2.22E-02	2.3866E+00	1.2678E+02
α_4	2.15E-04	6.55E-03	4.24E-03	2.08E-02	6.87E-03	8.4640E-01	1.2832E+02
α_5	1.09E-04	5.59E-03	3.33E-03	1.88E-02	1.54E-03	7.2150E-01	1.2844E+02

Table 39-12: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8673607	0.9077758	0.9094923	0.9423348	0.8853880	1.4382E+02	1.4611E+01
α_2	2.72E-02	5.27E-02	5.09E-02	8.47E-02	7.19E-02	8.3547E+00	1.508E+02
α_3	7.00E-003	2.22E-002	2.03E-002	4.43E-002	2.83E-002	3.5237E+00	1.5491E+02
α_4	8.40E-04	8.53E-03	6.57E-03	2.29E-02	9.85E-03	1.3511E+00	1.5708E+02
α_5	5.70E-05	4.15E-03	2.33E-03	1.44E-02	3.93E-03	6.5710E-01	1.5777E+02
α_6	9.04E-05	4.57E-03	2.73E-03	1.53E-02	6.90E-04	7.2460E-01	1.5771E+02

ALPHA FACTOR DISTRIBUTIONS
BWR Pressure Relief and ADS Valves

Table 39-13: Alpha Factor Distribution Summary - Fail to Close, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9326245	0.9726965	0.9775888	0.9960292	0.9889695	6.0563E+01	1.700E+00
α_2	7.07E-04	1.53E-02	1.05E-02	4.63E-02	1.10E-02	9.5380E-01	6.1309E+01
α_3	1.23E-07	4.22E-03	8.20E-04	2.01E-02	0.00E+00	2.6260E-01	6.200E+01
α_4	2.58E-05	7.77E-03	3.46E-03	3.01E-02	0.00E+00	4.8360E-01	6.1779E+01

Table 39-14: Alpha Factor Distribution Summary - Fail to Close, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9335920	0.9691839	0.9727871	0.9924494	0.9852336	8.2545E+01	2.6246E+00
α_2	1.72E-03	1.64E-02	1.28E-02	4.34E-02	1.48E-02	1.3950E+00	8.3775E+01
α_3	6.15E-06	4.84E-03	1.83E-03	1.99E-02	0.00E+00	4.1200E-01	8.4758E+01
α_4	2.13E-08	2.74E-03	4.18E-04	1.36E-02	0.00E+00	2.3360E-01	8.4936E+01
α_5	5.78E-05	6.86E-03	3.57E-03	2.48E-02	0.00E+00	5.8400E-01	8.4586E+01

Table 39-15: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9346811	0.9670311	0.9699000	0.9895600	0.9814815	1.0347E+02	3.5276E+00
α_2	2.56E-03	1.66E-02	1.37E-02	4.06E-02	1.85E-02	1.7791E+00	1.0522E+02
α_3	2.97E-05	5.05E-03	2.47E-03	1.88E-02	0.00E+00	5.4060E-01	1.0646E+02
α_4	4.57E-07	2.92E-03	7.66E-04	1.32E-02	0.00E+00	3.1270E-01	1.0669E+02
α_5	2.84E-08	2.27E-03	3.78E-04	1.11E-02	0.00E+00	2.4330E-01	1.0675E+02
α_6	8.14E-05	6.09E-03	3.41E-03	2.12E-02	0.00E+00	6.5190E-01	1.0635E+02

ALPHA FACTOR DISTRIBUTIONS
BWR Pressure Relief and ADS Valves

Table 39-16: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9211192	0.9643008	0.9688233	0.9920085	0.9733513	6.4688E+01	2.3948E+00
α_2	3.00E-03	2.34E-02	1.88E-02	5.93E-02	2.47E-02	1.5684E+00	6.5514E+01
α_3	1.53E-06	5.04E-03	1.49E-03	2.22E-02	1.84E-03	3.3830E-01	6.6745E+01
α_4	2.54E-05	7.28E-03	3.27E-03	2.81E-02	1.10E-04	4.8810E-01	6.6595E+01

Table 39-17: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9212466	0.9597546	0.9630854	0.9868608	0.9665930	8.7201E+01	3.6566E+00
α_2	5.20E-03	2.49E-02	2.15E-02	5.62E-02	3.02E-02	2.2624E+00	8.8595E+01
α_3	4.36E-05	6.18E-03	3.12E-03	2.27E-02	2.94E-03	5.6160E-01	9.0296E+01
α_4	4.24E-08	2.73E-03	4.72E-04	1.33E-02	2.83E-04	2.4800E-01	9.0610E+01
α_5	5.45E-05	6.43E-03	3.35E-03	2.33E-02	1.18E-05	5.8460E-01	9.0273E+01

Table 39-18: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9271790	0.9608604	0.9635338	0.9853912	0.9683204	1.0928E+02	4.4514E+00
α_2	3.23E-03	1.77E-02	1.50E-02	4.16E-02	2.04E-02	2.0178E+00	1.1171E+02
α_3	7.66E-04	1.03E-02	7.60E-03	2.90E-02	1.04E-02	1.1708E+00	1.1256E+02
α_4	1.72E-06	3.20E-03	1.04E-03	1.37E-02	8.46E-04	3.6410E-01	1.1337E+02
α_5	3.19E-08	2.17E-03	3.71E-04	1.06E-02	5.76E-05	2.4680E-01	1.1349E+02
α_6	7.65E-05	5.73E-03	3.21E-03	2.00E-02	0.00E+00	6.5190E-01	1.1308E+02

40. PWR Steam Generator Safety Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving safety valves in the steam generator system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and failure reports from the Nuclear Plant Reliability Data System (NPRDS) have been screened to identify common-cause failure events. Failure modes analyzed are failure to open, failure to close, and failure to remain closed (spurious opening or leakage by the valve seat). The data cover the time period from 1980 through 1995.

The data review identified 23 common-cause failure to open events, one common-cause failure to close event, and eight common-cause failure to remain closed events. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to open are shown in Tables 40-1 and 40-2, respectively. Table 40-3 contains the average impact vectors (N_1-N_6) and the number of adjusted independent events for this failure mode. Tables 40-4 through 40-9 contain the corresponding information for the failure to close and failure to remain closed failure modes. The size of the affected population of for steam generator safety valves is denoted as CCCG. The alpha factor model parameters are denoted by α_1-α_6. Beta (β), gamma (γ), delta (δ), epsilon (ϵ), and mu (μ) are the multiple Greek letter model parameters. The quantity 1-β is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 40-10 through 40-12.

2. SYSTEM DESCRIPTION

The steam generator safety valves (SVs) are part of the secondary cooling system. They provide both over pressure protection to the steam generators and additional heat removal capacity. The setpoints for a bank of SVs on a single steam generator are staggered in order to provide the required pressure relief and to prevent exceeding the maximum flow for each valve. Figure 40-1 shows a typical configuration of the steam generator, safety valves, and relief valves. Most PWRs have at least 10 steam generator SVs, but the CCF software is limited to a CCCG of 6 for parameter estimation purposes. Typically, there are four or five SVs for each steam generator. Figure 40-1 shows the configuration of the steam generator safety and relief valves for a three-loop plant.

ALPHA FACTOR AND MGL PARAMETERS
Steam Generator Safety Valves

Table 40-1: Summary of Alpha Factor Parameter Estimations - Fail to Open

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.7521875	0.7736847	0.7494543	0.7388031	0.7400038
α_2	2.48E-01	6.64E-02	1.06E-01	1.12E-01	1.03E-01
α_3		1.60E-01	2.31E-02	4.10E-02	5.55E-02
α_4			1.21E-01	4.31E-03	1.13E-02
α_5				1.04E-01	9.88E-05
α_6					8.98E-02

Table 40-2: Summary of MGL Parameter Estimations - Fail to Open

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	7.52E-01	7.74E-01	7.50E-01	7.39E-01	7.40E-01
Beta	2.48E-01	2.26E-01	2.51E-01	2.61E-01	2.60E-01
Gamma		7.07E-01	5.76E-01	5.72E-01	6.03E-01
Delta			8.40E-01	7.25E-01	6.46E-01
Epsilon				9.60E-01	8.88E-01
Mu					9.99E-01

Table 40-3: Summary of Average Impact Vectors - Fail to Open

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	3.48	5.22	6.96	8.70	10.44
N_1	4.1192	5.0061	5.5023	5.5094	6.0424
N_2	2.5036	0.8777	1.7648	2.1517	2.2992
N_3		2.1136	0.3840	0.7886	1.2370
N_4			2.0174	0.0829	0.2525
N_5				2.0004	0.0022
N_6					2.0001

Total Number of Independent Failure Events: 27
Total Number of Common-Cause Failure Events: 23

ALPHA FACTOR AND MGL PARAMETERS
Steam Generator Safety Valves

Table 40-4: Summary of Alpha Factor Parameter Estimations - Fail to Close

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9975600	0.9967448	0.9934730	0.9918023	0.9904267
α_2	2.44E-03	3.12E-03	6.12E-03	7.38E-03	8.21E-03
α_3		1.34E-04	4.03E-04	8.23E-04	1.37E-03
α_4			0.00E+00	0.00E+00	0.00E+00
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 40-5: Summary of MGL Parameter Estimations - Fail to Close

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	9.98E-01	9.97E-01	9.94E-01	9.92E-01	9.90E-01
Beta	2.44E-03	3.26E-03	6.53E-03	8.20E-03	9.57E-03
Gamma		4.12E-02	6.17E-02	1.00E-01	1.43E-01
Delta			0.00E+00	0.00E+00	0.00E+00
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 40-6: Summary of Average Impact Vectors - Fail to Close

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	5.13	7.69	10.25	12.81	15.38
N_1	0.3483	0.4856	0.6026	0.6920	0.7903
N_2	0.0134	0.0256	0.0669	0.1004	0.1340
N_3		0.0011	0.0044	0.0112	0.0223
N_4			0.0000	0.0000	0.0000
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 41
Total Number of Common-Cause Failure Events: 1

ALPHA FACTOR AND MGL PARAMETERS
Steam Generator Safety Valves

Table 40-7: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
α_1	0.9997185	0.9994813	0.9992219	0.9989502	0.9986949
α_2	2.82E-04	5.19E-04	7.74E-04	1.04E-03	1.29E-03
α_3		0.00E+00	3.71E-06	8.90E-06	1.48E-05
α_4			0.00E+00	0.00E+00	0.00E+00
α_5				0.00E+00	0.00E+00
α_6					0.00E+00

Table 40-8: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
1-Beta	1.00E+01	1.00E+01	9.99E-01	9.99E-01	9.99E-01
Beta	2.82E-04	5.19E-04	7.78E-04	1.05E-03	1.31E-03
Gamma		0.00E+00	4.76E-03	8.48E-03	1.14E-02
Delta			0.00E+00	0.00E+00	0.00E+00
Epsilon				0.00E+00	0.00E+00
Mu					0.00E+00

Table 40-9: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3	CCCG=4	CCCG=5	CCCG=6
Adj. Ind. Events	13.05	19.58	26.11	32.63	39.16
N_1	0.4429	0.6538	0.8575	1.0543	1.2446
N_2	0.0038	0.0105	0.0209	0.0351	0.0522
N_3		0.0000	0.0001	0.0003	0.0006
N_4			0.0000	0.0000	0.0000
N_5				0.0000	0.0000
N_6					0.0000

Total Number of Independent Failure Events: 93
Total Number of Common-Cause Failure Events: 8

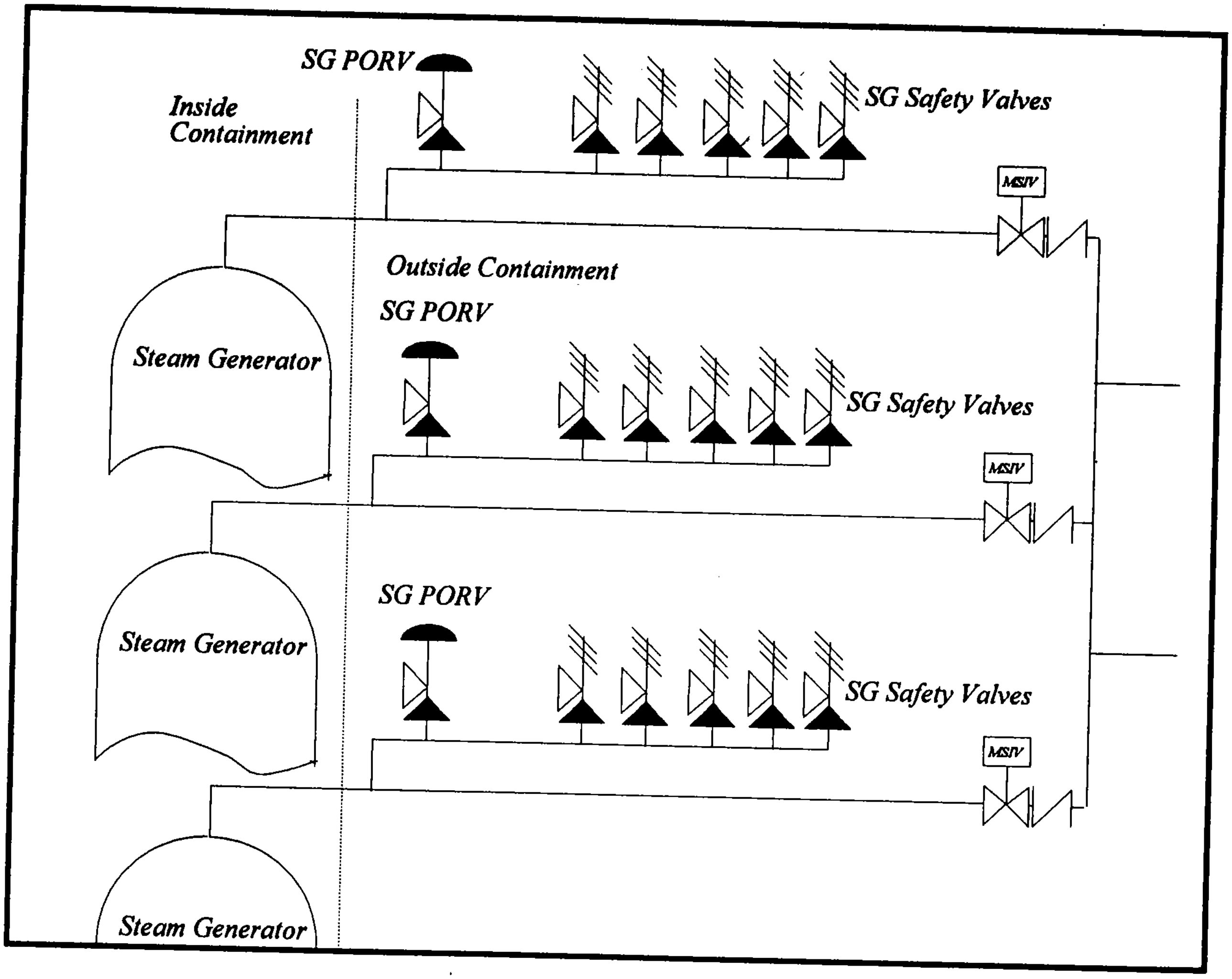

Figure 40-1. Steam generator relief and safety valves.

3. COMPONENT BOUNDARIES

The main component of the safety valve is the valve body and the mechanical (spring) operator. The operator is an integral part of the valve. This component is operated mechanically by the system operating pressure exceeding the spring setpoint. In addition to opening to lower pressure, the valves are designed to re-close when the desired pressure is achieved, or when system pressure is insufficient to hold the valve open. There are no electrical or instrumentation connections.

4. FAILURE EVENT DEFINITION

Successful operation of a safety valve is defined as opening in response to high system pressure, and reclosing when pressure is reduced. The failure modes used in evaluating the data are:

CC Failure to Open: Examples are:
- SV sticks closed,
- SV setpoint over 10% over the limit or words like "excessive" are considered failures,
- If piece-part(s) are replaced to calibrate a setpoint that is too high, then the SV is considered failed,
- A stroke time test failure will be considered a failure if it is reported as "excessive, " otherwise it is not a failure, and
- Whenever a SV is blocked shut.

OO Failure to Close: Examples are:
- Valve stays open when it should close,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed: Examples are:
- Spurious opening,
- Leakage past the valve seat, and
- If piece-part(s) are replaced to re-calibrate a setpoint that was low.

Safety valve malfunctions are considered to be failures to open or close on demand, failure to stay open or closed, including excessive leakage through the valve. Safety valves that open in response to an actual system over pressure are not failures. Subsequent failures to reseat completely are defined as a failure to close event.

Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. The exception to this is if a licensee reported that the valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis fire or seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the valve from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that a second SV would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another SV, then the event was identified as a CCF. If, however, the report did not clearly indicate that another SV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to an SV actuation demand (e.g. the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 40-10 through 40-12 present the alpha factor uncertainty distribution summaries for each failure mode of steam generator safety valves. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the table. The average CCCG for the steam generator safety valves is over 15, so the parameter estimations using a CCCG of six (due to software limitations) are conservative. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Steam Generator Safety Valves

Table 40-10: Alpha Factor Distribution Summary - Fail to Open, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8250617	0.8894870	0.8929347	0.9421186	0.7400038	6.6954E+01	8.3186E+00
α_2	1.17E-02	4.09E-02	3.69E-02	8.39E-02	1.03E-01	3.0783E+00	7.2194E+01
α_3	3.65E-03	2.36E-02	1.95E-02	5.75E-02	5.55E-02	1.7776E+00	7.3495E+01
α_4	5.47E-05	7.51E-03	3.81E-03	2.75E-02	1.13E-02	5.6520E-01	7.4707E+01
α_5	4.52E-08	3.26E-03	5.53E-04	1.59E-02	9.88E-05	2.4550E-01	7.5027E+01
α_6	8.74E-03	3.52E-02	3.12E-02	7.56E-02	8.98E-02	2.6520E+00	7.2621E+01

ALPHA FACTOR DISTRIBUTIONS
Steam Generator Safety Valves

Table 40-11: Alpha Factor Distribution Summary - Fail to Close, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9173890	0.9612858	0.9656478	0.9902697	0.9904267	6.6642E+01	2.6839E+00
α_2	5.40E-04	1.32E-02	8.87E-03	4.05E-02	8.21E-03	9.1310E-01	6.8413E+01
α_3	5.81E-05	8.12E-03	4.11E-03	2.98E-02	1.37E-03	5.6290E-01	6.8763E+01
α_4	7.07E-07	4.51E-03	1.19E-03	2.03E-02	0.00E+00	3.1270E-01	6.9013E+01
α_5	4.40E-08	3.51E-03	5.85E-04	1.71E-02	0.00E+00	2.4330E-01	6.9083E+01
α_6	1.26E-04	9.40E-03	5.29E-03	3.27E-02	0.00E+00	6.5190E-01	6.8674E+01

ALPHA FACTOR DISTRIBUTIONS
Steam Generator Safety Valves

Table 40-12: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9401227	0.9723896	0.9756929	0.9933639	0.9986949	9.0877E+01	2.5804E+00
α_2	2.77E-04	8.90E-03	5.72E-03	2.83E-02	1.29E-03	8.3130E-01	9.2626E+01
α_3	3.43E-05	5.79E-03	2.84E-03	2.16E-02	1.48E-05	5.4120E-01	9.2916E+01
α_4	5.23E-07	3.35E-03	8.77E-04	1.51E-02	0.00E+00	3.1270E-01	9.3145E+01
α_5	3.25E-08	2.60E-03	4.33E-04	1.27E-02	0.00E+00	2.4330E-01	9.3214E+01
α_6	9.33E-05	6.98E-03	3.91E-03	2.43E-02	0.00E+00	6.5190E-01	9.2806E+01

41. BWR Safety Valves

The data review identified no Boiling Water Reactor (BWR) safety valve CCF events.

42. PWR Pressurizer Safety Valves

1. INTRODUCTION

This report documents the results of an AEOD effort to estimate common-cause failure (CCF) parameters of various models using operational data involving pressurizer safety valves in the primary cooling system at pressurized water reactor (PWR) power plants. Licensee Event Reports (LERs) and Nuclear Plant Reliability Data System (NPRDS) data have been screened to identify common-cause failure events. The failure modes used to analyze the safety valves are failure to open, failure to close, and failure to remain closed (spurious opening or leakage past the valve seat). The data cover the time period from 1980 through 1995.

The data review identified six common-cause failure to remain closed events. There were no common-cause failure to open or failure to close events identified. The maximum likelihood estimates (MLE) for the alpha factor and the multiple Greek letter (MGL) parameters for failure to remain closed are shown in Tables 42-1 and 42-2, respectively. Table 42-3 contains the average impact vectors (N_1-N_3) and the number of adjusted independent events for this failure mode. The size of the affected population of pressurizer safety valves is denoted as CCCG and is either 2 or 3 for all plants. The alpha factor model parameters are denoted by α_1-α_3. Beta (β) and gamma (γ) are the multiple Greek letter model parameters. The quantity $1-\beta$ is defined as the probability that a failure event is an independent failure and is equal to α_1. The MGL calculations assume a staggered testing scheme. Uncertainty distributions of the mean values of the alpha factors are also included in this report in Tables 42-4 and 42-5.

2. SYSTEM AND COMPONENT DESCRIPTION

The primary coolant system in a PWR consists of the piping and other components necessary to remove heat from the reactor core. Part of the system is the pressurizer which serves to regulate the system pressure, both raising pressure to maintain solid water in the pressurizer flow path , and lowering pressure to control plant operations and prevent system over pressurization. The power operated relief valves (PORV) are used for pressure control and safety valves are used for over pressure protection purposes.

The pressurizer safety valves function to prevent primary plant over pressure. The valves are strictly mechanical in nature and require no external power or control to operate. Since the valves function to provide over pressure protection, no means of valve isolation is provided. Figure 42-1 shows the configuration of the pressurizer relief and safety valves.

ALPHA FACTOR AND MGL PARAMETERS

Pressurizer Safety Valves

Table 42-1: Summary of Alpha Factor Parameter Estimations - Fail to Remain Closed

Alpha Factor	CCCG=2	CCCG=3
α_1	0.9985231	0.9970754
α_2	1.48E-03	2.91E-03
α_3		1.77E-05

Table 42-2: Summary of MGL Parameter Estimations - Fail to Remain Closed

MGL Parameter	CCCG=2	CCCG=3
1-Beta	9.99E-01	9.97E-01
Beta	1.48E-03	2.93E-03
Gamma		6.04E-03

Table 42-3: Summary of Average Impact Vectors - Fail to Remain Closed

Avg. Impact Vector	CCCG=2	CCCG=3
Adj. Ind. Events	74.21	111.13
N_1	1.2439	1.5360
N_2	0.1116	0.3290
N_3		0.0020

Total Number of Independent Failure Events: 105
Total Number of Common-Cause Failure Events: 6

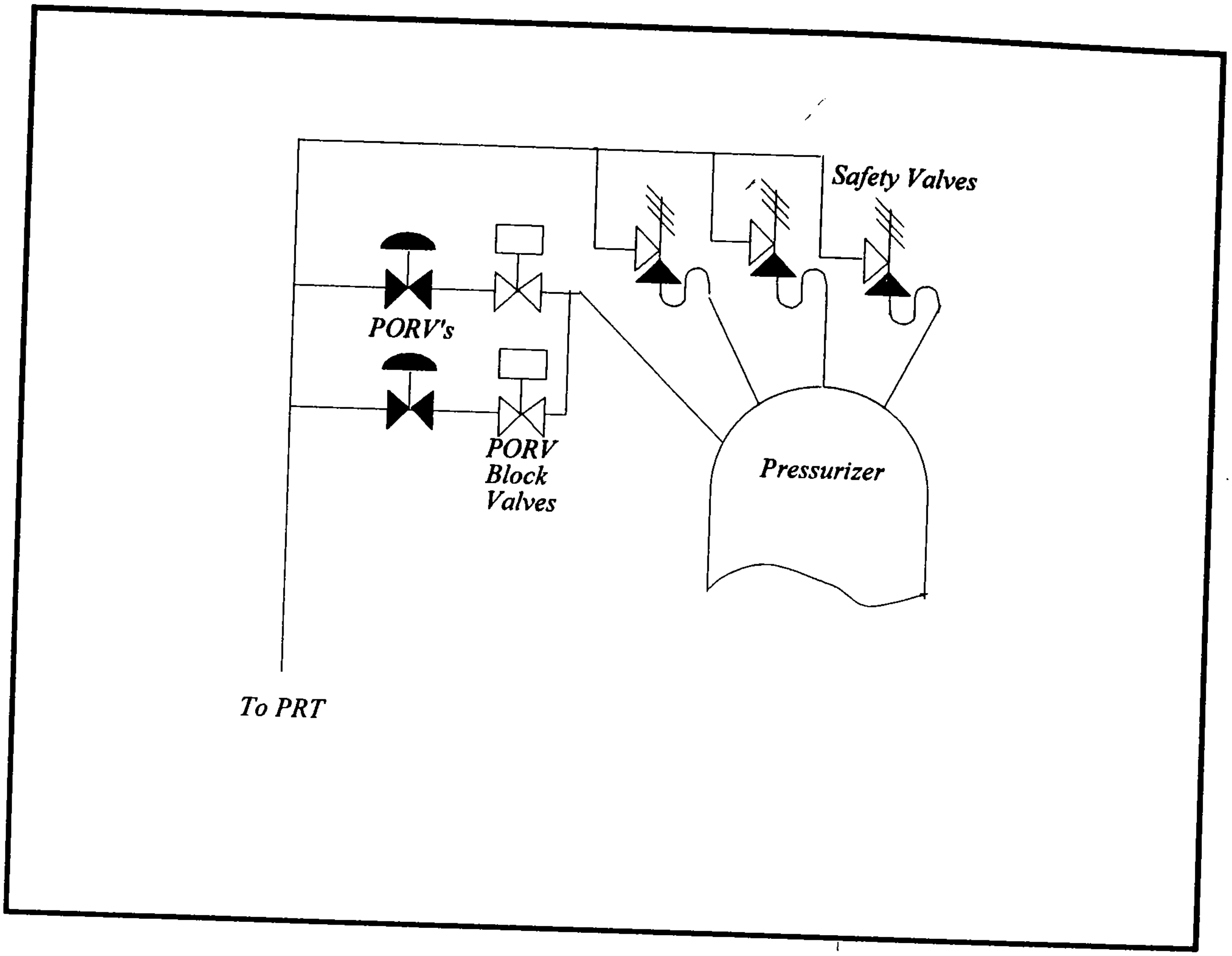

Figure 42-1. Pressurizer PORV and safety valves.

3. COMPONENT BOUNDARIES

The pressurizer safety valve includes only the valve itself and the mechanical (spring) operator. The operator is an integral part of the valve. This component is operated mechanically by the system operating pressure exceeding the spring setpoint. In addition to opening to lower pressure, the valves are designed to re-close when the desired pressure is achieved, or when system pressure is insufficient to hold the valve open. There are no electrical or instrumentation connections.

4. FAILURE EVENT DEFINITION

Successful operation of a safety valve is defined as opening in response to high system pressure, and reclosing when pressure is reduced. The failure modes used in evaluating the data are:

CC Failure to Open: Examples are:

- SV sticks closed,
- SV setpoint over 10% over the limit or words like "excessive" are considered failures,
- If piece-part(s) are replaced to calibrate a setpoint that was too high, then the SV is considered failed,
- A stroke time test failure will be considered a failure if it is reported as "excessive, " otherwise it is not a failure, and
- Whenever a SV is blocked shut.

OO Failure to Close: Examples are:

- Valve stays open when it should close,
- Valve doesn't fully close, and
- Failure to re-seat.

VR Failure to Remain Closed: Examples are:

- Spurious opening,
- Leakage past the valve seat, and
- If piece-part(s) are replaced to re-calibrate a setpoint that was too low.

Safety valve malfunctions are considered to be failures to open or close on demand, failure to stay open or closed, including excessive leakage through the valve. Safety valves that open in response to an actual system over pressure are not failures. Subsequent failures to reseat completely are defined as a failure to close event.

Administrative inoperability events, such as seismic qualification violations, were not considered failures because they are conditional upon the circumstances existing at the time of valve demand. The exception to this is if a licensee reported that the valve "would have" (instead of "may" or "could have") failed to perform its safety function in a design basis seismic event. In this case the event was considered to be a failure. Failure to meet Technical Specifications in the proper configuration is not considered a failure, unless the improper configuration would have prevented the valve from operating properly on a safety demand.

Many LERs reported only one actual failure, but the report information indicated that a second SV would have failed if a demand had occurred. If the cause of the actual failure would have clearly caused failure of another SV, then the event was identified as a CCF. If, however, the report did not clearly identify that another SV would have failed due to the same cause, the event was not considered a CCF, and was counted as an independent failure. Similarly, for reports identifying failures discovered prior to an SV actuation demand (e.g. the condition was found during inspection, and no actual demand occurred), only those cases for which a second failure could be certain were identified as CCF events.

5. ALPHA FACTOR DISTRIBUTION SUMMARIES

Tables 42-4 and 42-5 present the alpha factor uncertainty distribution summaries for each failure mode and each configuration of pressurizer safety valves. CCF and independent failure data were pooled, and do not reflect any variability across plants. For each alpha factor, the results reflect uncertainty about a mean value. The uncertainty distribution in each case is a beta distribution, with parameters a and b provided in the tables. Uncertainty distributions which capture plant-to-plant variability will be provided at a later date.

ALPHA FACTOR DISTRIBUTIONS
Pressurizer Safety Valves

Table 42-4: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9753426	0.9932029	0.9964744	0.9999453	0.9985231	8.4984E+01	5.8160E-01
α_2	5.63E-05	6.80E-03	3.52E-03	2.47E-02	1.48E-03	5.8160E-01	8.4984E+01

Table 42-5: Alpha Factor Distribution Summary - Fail to Remain Closed, CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9749890	0.9912449	0.9936143	0.9993933	0.9970754	1.2805E+02	1.1310E+00
α_2	1.05E-04	5.54E-03	3.29E-03	1.87E-02	2.91E-03	7.1620E-01	1.2847E+02
α_3	4.25E-06	3.21E-03	1.22E-03	1.32E-02	1.77E-05	4.1480E-01	1.2877E+02

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report documents the quantitative results of the common cause failure (CCF) data collection effort described in Volumes 1 - 4 of the Common Cause Failure System Database and Analysis System (References 2-5), as well as some qualitative insights about the data. These results are for use in Probabilistic Risk Assessment (PRA) studies of commercial nuclear power plants in the U.S. It summarizes the results of the parameter estimation quantification process, performed on the CCF data, as described in Volume 2 of that series of reports.

Equipment failures that contribute to CCF events are identified during searches of Licensee Event Reports and Nuclear Plant Reliability Data System failure reports. Once CCF events are identified by screening reports of equipment failures, they are coded for entry into a personal computer storage system. Once all data for a specific system and component data set have been entered, parameter estimations are performed, producing the results. The results of the database analysis are presented here as a summary of the entire database, and as individual reports for individual system/component combinations describe the system and component boundaries, along with the guidelines for identifying CCF events that may be unique to the data set.

The quantitative results are presented as both alpha factors and multiple Greek letter parameter estimations. The alpha factor uncertainty distributions are also presented.

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