NUREG/CR-4217
LA-10396-MS

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A Statistical Analysis of Nuclear Power Plant Valve Failure-Rate Variability— Some Preliminary Results

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NUREG/CR-4217
LA-10396-MS

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Manuscript submitted: March 1985
Date published: May 1985

Prepared for
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Office of Nuclear Regulatory Research
US Nuclear Regulatory Commission
Washington, DC 20555

NRC FIN No. A7225-5

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VALVE FAILURE-RATE VARIABILITY--SOME
PRELIMINARY RESULTS

by

R. J. Beckman and H. F. Martz

ABSTRACT

Valve failure data from the In-Plant Reliability Data System (IPRDS) are statistically analyzed using the Failure Rate Analysis Code (FRAC). Data from five failure modes, four of which are time related and the other demand related, are analyzed to determine which of the factors--operating system, valve size, valve type, operating type, and operating mode--most affect valve failure rates. A separate analysis is given for each of two plants, a pressurized water reactor (PWR) and a boiling water reactor (BWR).

For both plants and each failure mode, multiplicative adjustments for the mean are obtained for categories, such as nuclear or containment systems, of the various factors. These multipliers indicate whether a particular category of a factor has a corresponding failure rate that is less than the average failure rate (a multiplier less than one) or greater than the average (a multiplier greater than one).

Based on the multiplicative adjustments, ball valves are shown to be the most reliable valves for the PWR plant. Globe and gate valves have the highest failure rates for this plant. The average failure rate for the BWR plant is found to be half that of the PWR plant for three of the five failure modes studied.

In addition to the multipliers, point estimates and confidence intervals on the failure rates are given for selected valve factor combinations. These estimates and intervals are compared with several other estimates.

1. INTRODUCTION AND EXECUTIVE SUMMARY

Fault-tree models are widely used in probabilistic risk analyses of nuclear power plants. These models use estimates of the reliability of various components for quantifying system unavailability. The purpose of this report is to supply a preliminary model for estimating the reliability of nuclear power plant valves under differing failure modes and to determine which of several operating and environmental characteristics have the most effect on valve failure rates.

Following this Introduction and Executive Summary section, the data are described in Sec. 2. The models and techniques used to estimate the failure rates are given in Sec. 3, and the estimates are described in Sec. 4. Section 5 contains a discussion and comparisons between the present results and other valve failure-rate estimates.

1.1 Scope

The data for this report were obtained from the In-Plant Reliability Data System (IPRDS).[1] Preliminary valve failure and valve population records were obtained for two nuclear power plants, a pressurized water reactor (PWR) and a boiling water reactor (BWR). These two plants are treated separately in this report. A complete description of the IPRDS valve data base may be found in Borkowski et al.[2] For the two plants considered, there were over 4 000 valve population records, 3 800 valve maintenance records, and 15 000 corrective maintenance records.

These failure and population records were collapsed into unique categories using the factors valve type, reactor system, operation type, and size. In addition, for the PWR plant, operation mode was also available for consideration as a factor; however, this factor was not available for the BWR plant.

Analyses are presented for many different failure modes. However, not all modes considered by Borkowski et al.[2] are considered here because of a lack of valve failures for some of the modes. For both plants the following failure type/severity/mode combinations are considered, where the letter in parentheses is the failure-mode identifier used in the IPRDS data base:

1. Time-related, degraded failures--improper valve operation (E)

2. Time-related, degraded failures--debilitating internal leakage (F)

3. Time-related, incipient failures--external leakage (G)

4. Time-related, incipient failures--faulty indication (H)

5. Demand-related, catastrophic failures--failure to operate on demand (A, K).

The three failure severity categories may be described as

Catastrophic: The valve is completely unable to perform its function. For example, the valve fails to operate on demand.

Degraded: The valve operates at less than its specified performance level. For example, the valve experiences debilitating internal leakage.

Incipient: The valve performs as designed but exhibits characteristics that, if left unattended, will likely develop into either a degraded or catastrophic failure. For example, the valve leaks externally.

Not all the levels (subsequently referred to as "categories") for every factor are available for use in the analysis of each failure mode. A complete list of the factors for each analysis, their corresponding categories, and the data listings may be found in Tables A-I through A-IV in the Appendix.

The factors and associated categories considered in this study are

SYSTEM: The IPRDS data base contains valve failure data for the following generic systems: (1) Nuclear, (2) Engineered Safety, (3) Containment, (4) Power Conversion, (5) Process Auxiliary, and (6) Plant Auxiliary. Definitions of the systems in each of these categories are given in Table I.

OTYPE: The valve operator (for operated valves). In the data considered here these are (1) Pneumatic, (2) Solenoid, (3) Motor Driven, (4) Chain, and (5) Manual.

VTYPE: The type of valve. The types considered here are (1) Angle, (2) Ball, (3) Butterfly, (4) Check, (5) Diaphragm, (6) Gate, (7) Globe, (8) Relief/Safety, (9) Plug, and (10) Directional Control.

SIZE: The valve size. Valves are classified into the following four size categories: (1) Less than 2 inches, (2) Between 2 and 10 inches, (3) Between 10 and 30 inches, and (4) Greater than 30 inches.

OPMODE: Two operating modes are considered. These are (1) Normally Closed, and (2) Normally Open.

TABLE I

IN-PLANT RELIABILITY DATA GENERIC SYSTEMS LIST

Nuclear Systems (N)

BWR		PWR	
N01	Reactor core	N01	Reactor core
N02	Control-rod drive system	N02	Control-rod drive system
N02.A	Control-rod-drive hydraulic system		
N03	Reactor control system	N03	Reactor control system
N04	Reactor recirculation system	N04	Reactor coolant system
N05	Standby liquid control system	N05	Emergency boration system
N06	Reactor protection system	N06	Reactor protection system
N07	Neutron monitoring/nuclear instrumentation system	N07	Nuclear monitoring/nuclear instrumentation system
N08	Residual heat removal/low-pressure safety injection system	N08	Residual heat removal/low-pressure safety injection system
N09	Reactor water clean-up system	N09	Chemical and volume control system

Engineered Safety Systems (S)

BWR		PWR	
S01	Reactor-core isolation cooling system		
		S02	Engineered safety features actuation system
S03	Engineered safety features	S03	Safety injection system
S03.A	High-pressure coolant injection/core spray system	S03.A	High-pressure safety injection subsystem
		S03.B	Safety injection tank/core flood subsystem
S03.C	Low-pressure coolant injection	S03.C	Low-pressure safety injection subsystem
S03.D	Low-pressure core-spray system		
S03.E	Automatic depressurization system		
S04	Remote shut-down system	S04	Remote shut-down system
		S05	Auxiliary feedwater system

TABLE I (cont)

Containment Systems (C)

BWR		PWR	
C01	Primary containment and penetrations		
C02	Reactor building	C02	Reactor building: containment and penetrations
C03	Containment heat removal	C03	Containment cooling system
		C03.A	Ice condenser system
C04	Containment isolation system	C04	Containment isolation system
C05	Containment purge system	C05	Containment purge system
C06	Stand-by gas treatment system		
C07	Combustible gas control system	C07	Combustible gas control system
C08	Containment ventilation system	C08	Containment ventilation system
C09	Reactor building ventilation system		
C10	Containment spray system	C10	Containment spray system
		C11	Penetration of room ventilation system

Power Conversion Systems (P)

BWR		PWR	
P01	Main steam system	P04.A	Condenser evacuation system
P02	Turbine-generator system	P04.B	Condensate clean-up/polishing system
P02.A	Electrohydraulic control subsystem	P04.C	Condensate heater drain subsystem
P02.B	Turbine gland seal subsystem		
P02.C	Turbine lubrication subsystem	P05	Feedwater system
P02.D	Stator (hydrogen) cooling subsystem	P05.A	Feedwater heater drain subsystem
P02.E	Hydrogen-seal oil subsystem	P06	Circulating water system
P03	Turbine bypass system	P07	Steam generator blowdown (PWR)
P04	Condenser and condensate system	P08	Auxiliary steam system

TABLE I (cont)

Process Auxiliary Systems (W)

BWR

W01 Radioactive waste system
W01.A Gaseous radwaste system
- off-gas subsystem (BWR)

W01.B Liquid radioactive waste system
W01.C Solid radioactive waste system
W02 Radiation monitoring system
W02.A Plant area radiation monitors
W02.B Environmental radiation monitors
W02.C Process radiation monitors
W03 Cooling-water systems
W03.A Reactor building cooling-water system
W03.B Turbine building cooling-water system
W04 Service water systems
W04.A Demineralized make-up water system

PWR

W04.B Station service water system
- essential-service water system
- nonessential-service water system

W04.C Chilled water system
W05 Refueling system
W06 Spent-fuel storage system
W06.A Fuel-pool cooling and clean-up systems
W07 Compressed-air system
W07.A Service-air system
W07.B Instrument-air system
W08 Process sampling system
W09 Plant gas system
W09.A Nitrogen system
W09.B Hydrogen system

Plant Auxiliary Systems (X)

BWR

X01 Potable and sanitary water system
X02 Fire protection system
X02.A Water system
X02.B Carbon dioxide system
X03 Communications system
X04 Security system
X05 Heating, ventilating, and air-conditioning systems
X05.A Control-room habitability system
X05.B Turbine building ventilation system

PWR

X05.C Diesel building ventilation system
X05.D Auxiliary building ventilation system
X05.E Fuel building ventilation system
X06 Nonradioactive waste system
X06.A Gaseous waste subsystem
X06.B Liquid waste subsystem
X06.C Solid waste subsystem

For each failure mode and each plant, an analysis is provided in which the effect of each of these factors is simultaneously considered on valve failure rate, conditional on data availability. A brief discussion of the method of analysis and the conclusions from the analyses are given in Secs. 1.2 and 1.3.

1.2 Procedure

The data are analyzed using the Failure Rate Analysis Code (FRAC).[3] For the data and analyses presented here, the weighted least-squares option of FRAC was used to obtain estimates of the valve failure rates for combinations of the categories of the factors described above.

Using regression techniques, all factors were considered simultaneously. The failure rate was modeled as a product of failure-rate multipliers for the categories of the factors given in the model. For each failure mode and plant, an average failure rate is found, and multipliers that either raise or lower this failure rate are obtained for each factor category. For example, for the BWR plant it was found that the average valve failure rate for time-related, degraded failures for an improper operational failure mode is 3.15×10^{-6} failures per hour. The multiplicative adjustments for this failure mode for a 2- to 10-inch pneumatically operated butterfly valve in a nuclear system are 1.10, 1.04, 1.84, and 0.28, respectively. That is, the estimated failure rate for such a valve is $3.15 \times 10^{-6}(1.10)(1.04)(1.84)(0.28) = 1.86 \times 10^{-6}$ failures per hour, which is slightly below the average for the given plant. A summary of the multipliers for the best and worst categories for each factor for each failure type and mode is given in the next section.

By considering all factor combinations, the effects of competing components are removed. This is usually not the case when failure-rate estimates are provided for each factor separately. In this case the failure-rate estimates are obtained by combining data over all factors except one. When data are combined in this way, one or more categories of factors over which the pooling is done may unduly and unknowingly influence the failure rates of the factor being considered. Misleading conclusions may be obtained.

Failure-rate estimates using combined data are given by Borkowski et al.[2] Comparisons between these estimates and those obtained by using the FRAC method are given in Sec. 5, along with several other estimates.

1.3 Conclusions

Summaries of the best-case and worst-case failure-rate multipliers for the PWR and BWR plants are given in Table II and Table III, respectively. In both of these tables, each of the five failure modes described in Sec. 1.1 is considered. For each failure mode, the average failure rate is given. Five factors were considered in the analysis for the PWR, and four were considered for the BWR. Each of these factors is listed along with the categories of each factor that produce the lowest (best) and highest (worst) failure rate. Corresponding multiplicative adjustments to the average failure rate (multipliers) are also provided. The last column in both tables contains the ratio of the worst-category multipliers to the best-category multipliers. The factors are ordered by the magnitude of this ratio, as it measures the largest possible effect on the failure-rate estimates when all other factors are held fixed.

1.3.1 Summary of the PWR Failure Rates.

From Table II it is apparent that, of the five factors, OPMODE has the least effect on the failure-rate estimates. For all five failure modes, OPMODE has the smallest ratio, and this ratio is close to one. Only two operating modes were considered, normally open and normally closed, and neither seems to have much effect on valve failure rate.

Of the remaining factors, VTYPE has the largest ratio for four of the five failure modes. In the other failure mode--time-related, degraded failures that exhibit internal leakage--VTYPE is ranked as second in importance. The ratios are approximately equal to ten for three of the failure modes, which indicates at most one order of magnitude difference in the valve failure rates is accounted for by VTYPE.

Of all the valve types considered here, ball valves appear to be the most reliable. This is true for each of the failure modes. In each case, ball valves have a failure rate that is less than one-half the average failure rate, and for two of the failure modes, the rate is less than one-fourth the average rate.

Gate valves appear to be the most unreliable valves in this plant for the catastrophic and degraded failure modes, with multipliers ranging from 1.74 to 4.43. For the two incipient failure modes, globe valves have the highest failure rate (1.41 and 1.83 times the average).

TABLE II

SUMMARY OF PWR FAILURE-RATE ESTIMATES

Failure Type/Severity/Mode	Average Failure Rate	Factors	Best Category	Best Multiplier	Worst Category	Worst Multiplier	Ratio
Time-Related, Degraded--Improper Operation	7.37×10^{-6} f/h	VTYPE	Ball	0.45	Gate	4.43	9.84
		OTYPE	Hand	0.38	Solenoid	2.36	6.21
		SYSTEM	Containment	0.36	Nuclear	1.69	4.69
		SIZE	2-10 inches	0.55	10-30 inches	1.88	3.42
		OPMODE	Normally Closed	0.98	Normally Open	1.02	1.04
Time-Related, Degraded--Debilitating Internal Leakage	4.96×10^{-6} f/h	OTYPE	Hand	0.63	Pneumatic	1.58	2.51
		VTYPE	Ball	0.47	Gate	1.76	2.32
		SYSTEM	Safety	0.62	Nuclear	1.29	2.24
		SIZE	2-10 inches	0.70	<2 inches	1.27	1.81
		OPMODE	Normally Open	0.87	Normally Closed	1.15	1.32
Time-Related, Incipient--External Leakage	6.95×10^{-6} f/h	VTYPE	Ball	0.22	Globe	1.83	13.59
		OTYPE	Solenoid	0.42	Pneumatic	2.92	6.95
		SYSTEM	Containment	0.59	Safety	2.85	4.83
		SIZE	<2 inches	0.60	10-30 inches	1.77	2.95
		OPMODE	Normally Closed	0.81	Normally Open	1.23	1.52
Time-Related, Incipient--Faulty Indication	5.58×10^{-6} f/h	VTYPE	Ball	0.41	Globe	1.41	3.44
		SYSTEM	Power Conversion	0.69	Safety	2.19	3.17
		SIZE	2-10 inches	0.70	10-30 inches	2.03	2.90
		OTYPE	Solenoid	0.79	Pneumatic	1.60	2.03
		OPMODE	Normally Open	0.96	Normally Closed	1.04	1.08
Demand-Related, Catastrophic--Fails to Operate on Demand	3.27×10^{-3} f/d	VTYPE	Ball	0.21	Gate	1.74	8.29
		OTYPE	Solenoid	0.57	Motor Driven	2.50	4.39
		SYSTEM	Containment	0.51	Power Conversion	2.23	4.37
		SIZE	2-10 inches	0.59	<2 inches	2.08	3.53
		OPMODE	Normally Open	0.94	Normally Closed	1.07	1.19

TABLE III

SUMMARY OF BWR FAILURE-RATE ESTIMATES

Failure Type/Severity/Mode	Average Failure Rate	Factors	Best		Worst		Ratio
			Category	Multiplier	Category	Multiplier	
Time-Related, Degraded--Improper Operation	3.15×10^{-6} f/h	SYSTEM	Nuclear	0.28	Plant Auxiliary	2.59	10.39
		VTYPE	Relief/Safety	0.40	Diaphragm	3.20	8.00
		OTYPE	Chain	0.31	Motor-Driven	1.51	4.87
		SIZE	<2 inches	0.87	2-10 inches	1.10	1.26
Time-Related, Degraded--Debilitating Internal Leakage	3.39×10^{-6} f/h	VTYPE	Check	0.25	Diaphragm	3.40	13.60
		SIZE	>30 inches	0.32	<2 inches	2.03	6.34
		SYSTEM	Power Conversion	0.38	Containment	2.55	5.54
		OTYPE	Chain	0.49	Hand	1.69	3.45
Time-Related, Incipient--External Leakage	3.30×10^{-6} f/h	SIZE	>30 inches	0.33	10-30 inches	2.28	6.91
		OTYPE	Chain	0.44	Motor-Driven	2.84	6.45
		VTYPE	Check	0.53	Diaphragm	2.88	5.43
		SYSTEM	Process Auxiliary	0.61	Containment	1.47	2.41
Time-Related, Incipient--Faulty Indication	1.76×10^{-6} f/h	SYSTEM	Nuclear	0.28	Containment	3.07	10.96
		VTYPE	Relief/Safety	0.33	Plug	3.12	9.45
		OTYPE	Chain	0.36	Pneumatic	2.92	8.11
		SIZE	730 inches	0.73	<2 inches	1.32	1.81
Demand-Related, Catastrophic--Fails to Operate on Demand	2.35×10^{-3} f/d	VTYPE	Relief/Safety	0.31	Diaphragm	4.14	13.35
		SIZE	10-30 inches	0.54	>30 inches	3.64	6.74
		SYSTEM	Containment	0.36	Power	1.62	4.53
		OTYPE	Chain	0.72	Air	1.17	1.63

Whereas the SYSTEM, SIZE, and OTYPE factors are not as important as VTYPE, certain categories of these factors have large accompanying multipliers--in some cases larger than those of VTYPE. For example, pneumatically operated valves have an external leakage failure rate that is 2.92 times the average. This rate is higher than the rate for globe-type valves for this failure mode. However, for these three factors, all of the worst-case multipliers are less than three.

There can be a large difference between the failure-rate estimates for a valve consisting of all the best categories and one consisting of all the worst. It must be kept in mind that some of these configurations of valves may be either impossible or infeasible; nevertheless, these configurations give some idea of the largest possible differences in valve failure rates attributable to all five factors. The ratio of these differences can be obtained by the multiplication of all five ratios for each failure type/severity/mode in Table II. For example, for time-related, degraded, improper operation, the ratio of the failure rate for a 2- to 10-inch normally closed, hand-operated ball valve in a containment system to the failure rate of a 10- to 30-inch normally open, solenoid-operated gate valve in a nuclear system is (9.84)(6.21)(4.69)(3.42)(1.04) = 1 019, or three orders of magnitude. For the other failure modes, there are one to three orders of magnitude differences.

1.3.2 Summary of BWR Failure Rates. Summary statistics for the estimated failure rates for the BWR plant are given in Table III. As in Table II, the average failure rate given in this table is the overall average valve failure rate for the given BWR plant. Comparing the average failure rates for the two plants shows that, for all failure modes, the average failure rates of valves from the given BWR plant are less than those for the given PWR plant. For the improper operation failure mode and the two incipient failure modes, the valves of the BWR plant are more than twice as reliable as those of the PWR plant. This difference may be attributed to various plant-to-plant differences, such as operating utility, design differences, and so forth. Valve failure rates for the other two remaining modes are comparable.

In contrast to the PWR plant, there seems to be no single factor in the BWR plant that drives the failure rate for all failure modes. In terms of the size of the multiplier ratio, VTYPE is probably the most significant factor, with the smallest ratio being 5.43, and the largest, 13.60. Even then, the smallest valve type ratio, 5.43, for incipient failure of the external leakage

type is close to the maximum ratio, 6.91. Valve type ratios for all other failure modes are either the maximum for that mode or are near the maximum.

Of all the valve types in the BWR plant, the relief/safety and check valves are the most reliable for the five failure modes. However, it should be noted that these two types of valves cannot fail according to all five failure modes, and thus certain failure modes are infeasible. Check valves cannot fail to operate on demand, and safety/relief valves do not fail by having external leakage. The most unreliable valve type in this plant, under all but one failure mode, is the diaphragm valve, with failure rates roughly three to four times the average failure rate. For time-related, incipient failures of the faulty indication type, plug valves are the most unreliable, with a multiplier of 3.12.

Most of the multipliers in the worst-case categories for the four BWR factors range from two to four. The failure-rate differences between the worst-case and the best-case configurations for each failure type/severity/mode combination generally amount to two to three orders of magnitude.

It should be remembered when looking at the multipliers and average failure rates given in either Table II or Table III that these failure rates are for valves from only a single plant. Generalizations to other plants, even for those of the same design, may be misleading or incorrect. As valve failure data from other plants become available in the IPRDS, generalizations to the commercial reactor population will be accomplished using FRAC.

2. IPRDS VALVE FAILURE DATA

The data for this study were obtained from the preliminary valve failure data in the IPRDS. Valve failures were obtained from the preliminary failure and repair records in the data base. The number of valves was obtained from the data-base population records. Valve records from two plants, a PWR and a BWR, were used in this analysis. For these two plants over 4 000 population records were available. The Borkowski et al. report[2] contains further information on the IPRDS valve component.

The plants considered here are labeled 1 and 4 in Ref. 2. As in Ref. 2, each valve for the PWR plant was assumed to be in service roughly 43 800 h. Demanded valves were assumed to be demanded at the rate of approximately once

per month from the beginning of commercial operation. For the BWR plant, a total of 52 560 h of commercial operation has accumulated.

The raw failure and population records were scanned for completeness, and records from the PWR plant were discarded if the category for any one of the five factors considered in Table II was missing from the record. The same thing was done for the BWR plant, considering the four factors given in Table III.

For each of the five failure type/severity/mode combinations listed in Sec. 1.1, the data were collapsed into cells by combining all components having the same combinations of categories. For each cell, the total service hours, the total number of demands, and the number of failures were computed. To obtain analyses that were not driven by single data points, the data for those categories that appear only once in combination with the categories of the other factors were deleted. For example, for the PWR plant there was only one combination of factors in the data that included valves greater than 30 inches. Analyses using this point would greatly influence the multipliers for the other categories in combination with the 30-inch valve category. Therefore, valves exceeding 30 inches are not considered in the analysis of the PWR plant.

The raw data used in the analysis for each of the five failure type/severity/mode combinations are given in the tables in the Appendix with the factor-category coded identifiers noted in the footnotes. Three data tables are necessary for the BWR plant as relief/safety valves cannot exhibit incipient failures as a result of faulty indication, and check valves have no demand-related failure modes. Because of the paucity of failure data, no check or relief/safety valves were considered for the PWR plant, and hence only one data table was necessary for this plant.

3. FAILURE-RATE ANALYSIS

A complete description of the analysis methodology used here may be found in Martz, Beckman, and McInteer.[3] A short summary of the techniques that were used is given here.

FRAC was developed by Martz, Beckman, and McInteer[3] to estimate component failure rates using either weighted least squares or weighted maximum likelihood. Central to the code and the resulting analysis is the assumption that for any given valve, say valve s, the number of failures in time T_s follows

a Poisson distribution with parameter $T_s \lambda_s$, where λ_s is the failure rate per unit of time. It is λ_s that is of interest, and it is modeled in the following way. We assume that λ_s is a function of k factors, $F_1, F_2, \ldots, F_k$. The coded levels or categories of factor F_j are denoted by 1, 2, ..., m_j. For example, the factors used in the PWR valve analysis are SYSTEM, OTYPE, VTYPE, SIZE, and OPMODE, where the factor system has five categories: containment, nuclear, power conversion, safety, and process auxiliary.

We denote the specific categories of the k factors that describe the s^{th} valve as the set $S = \{(1, s(1)), (2, s(2)), \ldots (k, s(k))\}$, where s(j) is an integer from the set $\{1, 2, \ldots, m_j\}$. For example, if k = 2, then $S = \{(1,5),(2,3)\}$ means that factor 1 has a coded category value of 5, whereas factor 2 has a coded value of 3.

Basic to the FRAC analysis is the assumption that the failure rate λ_s can be expressed as a product of the effects of the various categories of the factors. That is,

$$\lambda_s = \lambda_g \prod_{j=1}^{k} A(j,s(j)) \quad ,$$

where A(j,s(j)) represents a multiplicative effect of factor F_j at the $s(j)^{th}$ level or category on the average failure rate λ_g. Thus, the A(j,s(j)) are multiplicative "adjustments" (or multipliers) to the average failure rate λ_g. If $A(j,s(j)) < 1$, then the $s(j)^{th}$ category of the j^{th} factor reduces the failure rate below the average value; if $A(j,s(j)) > 1$, then the failure rate exceeds the average. A main objective of the FRAC analysis is to provide estimates of the multipliers A(j,s(j)).

The factors and their corresponding categories used in the analyses here may be found in the tables in the Appendix. Each of the factors considered here is a "main effect." That is, the multiplicative factors A(j,s(j)) represent only effects directly attributable to single factors such as SYSTEM or OTYPE. In this study the A(j,s(j)) do not represent interactions that are simultaneous effects of two or more factors over and above their individual effects. Although it is desirable to include such interactions in the model, the small quantity of preliminary valve failure data currently in the IPRDS prohibits their consideration in this report.

There is another basic assumption used in FRAC. For each factor, say factor j, it is assumed that the effects for the categories of this factor multiply to one; that is, $\prod_{s(j)} A(j,s(j)) = 1$. Because this parameterization is used, the average failure rate λ_g represents a true overall average or generic failure rate, and the multipliers are interpretable as "adjustments" to this average rate.

4. FAILURE-RATE ESTIMATES

For each failure type/severity/mode combination, two tables are presented in the following subsection for each plant. The first table (A) contains the estimates of the failure-rate adjustments (multipliers) for each category for each factor, as well as the average failure rates. The standard deviations of the estimated multipliers are given in parentheses. The parameter R_j for each factor is the ratio of the largest multiplier for a factor to the smallest. The R_j values are used to rank the factors according to their effect on the average failure rate. The second table (B) in each subsection provides a listing of the best (point) estimates and 90% confidence intervals for those combinations of factor categories that appear in the data.

4.1 Estimates for the PWR Plant

The factors considered for the PWR plant are SYSTEM, OTYPE, VTYPE, SIZE, and OPMODE. A listing of the categories for each of these factors is given in Sec. 1.1. In the following subsections, the analysis of each failure type/severity/mode combination for the PWR plant is considered separately.

4.1.1 PWR: Demand-Dependent, Catastrophic Failures--Failure to Operate on Demand (A,K). The estimates of the multipliers for the five factors and the average failure-rate estimate for the PWR demand-related, catastrophic valve failures are found in Table IV-A. Table IV-B contains the best (point) estimates and 90% confidence interval estimates for the factor category combinations used as input data in the FRAC procedure.

From Table IV-A it is apparent that VTYPE is the factor for which the multipliers exhibit the greatest spread. This spread in the multipliers is largely a result of the high reliability of ball valves, which have a failure rate that is one-fifth that of the average failure rate.

TABLE IV-A

PWR: DEMAND-DEPENDENT, CATASTROPHIC FAILURES--FAILURE TO OPERATE ON DEMAND (A,K)

Average Failure-Rate Estimate--3.27 x 10^{-3} (1.20 x 10^{-3})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	VTYPE	1	Ball	8.3	0.21 (0.197)
		2	Butterfly		1.58 (0.664)
		3	Diaphragm		1.13 (0.529)
		4	Gate		1.74 (0.525)
		5	Globe		1.23 (0.368)
		6	Directional control		1.23 (1.463)
2	OTYPE	1	Air	4.4	0.84 (0.255)
		2	Solenoid		0.57 (0.411)
		3	Motor		2.50 (0.799)
		4	Manual		0.84 (0.713)
3	SYSTEM	1	Containment	4.4	0.51 (0.261)
		2	Nuclear		0.88 (0.282)
		3	Power conversion		2.23 (0.449)
		4	Safety		1.11 (0.381)
		5	Process auxiliary		0.91 (0.664)
4	SIZE	1	<2 inches	3.5	2.08 (0.341)
		2	2-10 inches		0.59 (0.097)
		3	10-30 inches		0.81 (0.189)
5	OPMODE	1	Normally closed	1.1	1.07 (0.123)
		2	Normally open		0.94 (0.108)

Note: Values in parentheses are standard deviations.

TABLE IV-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR PWR:
DEMAND-RELATED, CATASTROPHIC FAILURES--
FAILURE TO OPERATE ON DEMAND (A,K)

Factors[a]						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
1	3	4	3	1	6.2410E-03	(0.2232E-02,0.1745E-01)
1	3	4	3	2	5.5010E-03	(0.1840E-02,0.1645E-01)
1	3	5	1	1	1.1290E-02	(0.4113E-02,0.3100E-01)
2	1	2	2	2	2.1130E-03	(0.7695E-03,0.5800E-02)
2	1	3	2	1	1.7100E-03	(0.6402E-03,0.4567E-02)
2	1	3	2	2	1.5070E-03	(0.5404E-03,0.4203E-02)
2	1	5	1	1	6.5800E-03	(0.2945E-02,0.1470E-01)
2	1	5	1	2	5.7990E-03	(0.2646E-02,0.1271E-01)
2	1	5	2	1	1.8750E-03	(0.9662E-03,0.3640E-02)
2	1	5	2	2	1.6530E-03	(0.8003E-03,0.3415E-02)
2	2	5	2	2	1.1150E-03	(0.2122E-03,0.5861E-02)
2	3	4	2	1	7.8740E-03	(0.4059E-02,0.1527E-01)
2	3	4	2	2	6.9400E-03	(0.3428E-02,0.1405E-01)
2	3	4	3	1	1.0820E-02	(0.5251E-02,0.2229E-01)
2	3	4	3	2	9.5350E-03	(0.4527E-02,0.2008E-01)
2	3	5	1	1	1.9570E-02	(0.8746E-02,0.4381E-01)
2	3	5	2	2	4.9180E-03	(0.2375E-02,0.1018E-01)
2	3	5	3	2	6.7570E-03	(0.2943E-02,0.1551E-01)
2	4	3	1	2	5.2920E-03	(0.1886E-02,0.1485E-01)
2	4	3	2	1	1.7110E-03	(0.6131E-03,0.4777E-02)
2	4	4	1	1	9.2930E-03	(0.3296E-02,0.2620E-01)
2	4	5	2	1	1.8770E-03	(0.7548E-03,0.4668E-02)
3	1	1	2	1	8.2320E-04	(0.1385E-03,0.4891E-02)
3	1	1	2	2	7.2550E-04	(0.1235E-03,0.4263E-02)
3	1	1	3	2	9.9690E-04	(0.1659E-03,0.5991E-02)
3	1	2	2	1	6.0830E-03	(0.2766E-02,0.1338E-01)
3	1	2	3	1	8.3580E-03	(0.3657E-02,0.1910E-01)
3	1	3	2	1	4.3400E-03	(0.1738E-02,0.1084E-01)
3	1	3	2	2	3.8250E-03	(0.1490E-02,0.9819E-02)
3	1	4	1	1	2.3560E-02	(0.1326E-01,0.4187E-01)
3	1	4	1	2	2.0770E-02	(0.1184E-01,0.3644E-01)
3	1	4	2	1	6.7170E-03	(0.4089E-02,0.1103E-01)
3	1	4	2	2	5.9200E-03	(0.3280E-02,0.1069E-01)
3	1	4	3	2	8.1340E-03	(0.4196E-02,0.1577E-01)
3	1	5	1	1	1.6700E-02	(0.9855E-02,0.2829E-01)
3	1	5	1	2	1.4720E-02	(0.9284E-02,0.2333E-01)
3	1	5	2	1	4.7600E-03	(0.3192E-02,0.7097E-02)
3	1	5	2	2	4.1950E-03	(0.2652E-02,0.6636E-02)
3	1	5	3	2	5.7640E-03	(0.3054E-02,0.1088E-01)
3	1	6	2	1	4.7240E-03	(0.1280E-02,0.1743E-01)
3	1	6	2	2	4.1640E-03	(0.1131E-02,0.1533E-01)
3	1	6	3	2	5.7210E-03	(0.1494E-02,0.2191E-01)

[a]Refer to Table IV-A for the definition of numerical categories for each factor.

TABLE IV-B (cont)

Factors						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
3	2	6	2	2	2.8090E-03	(0.4454E-03,0.1772E-01)
3	3	2	2	1	1.8100E-02	(0.8260E-02,0.3964E-01)
3	3	2	3	2	2.1920E-02	(0.1044E-01,0.4599E-01)
3	3	4	1	1	7.0100E-02	(0.4496E-01,0.1093E+00)
3	3	4	1	2	6.1790E-02	(0.4480E-01,0.8521E-01)
3	3	4	2	1	1.9980E-02	(0.1287E-01,0.3102E-01)
3	3	4	2	2	1.7610E-02	(0.1106E-01,0.2803E-01)
3	3	4	3	1	2.7450E-02	(0.1699E-01,0.4436E-01)
3	3	4	3	2	2.4200E-02	(0.1503E-01,0.3897E-01)
3	3	5	1	2	4.3780E-02	(0.2810E-01,0.6821E-01)
3	3	5	2	2	1.2480E-02	(0.7389E-02,0.2108E-01)
3	4	4	2	2	5.9250E-03	(0.2621E-02,0.1339E-01)
3	4	4	3	2	8.1410E-03	(0.3458E-02,0.1917E-01)
3	4	5	2	2	4.1990E-03	(0.1946E-02,0.9057E-02)
4	3	3	3	2	7.7810E-03	(0.2791E-02,0.2169E-01)
4	3	4	2	1	9.9450E-03	(0.5399E-02,0.1832E-01)
4	3	4	2	2	8.7660E-03	(0.4618E-02,0.1664E-01)
4	3	4	3	2	1.2040E-02	(0.5695E-02,0.2547E-01)
4	3	5	1	2	2.1790E-02	(0.1003E-01,0.4735E-01)
5	1	2	2	1	2.4970E-03	(0.1211E-02,0.5147E-02)
5	1	2	2	2	2.2000E-03	(0.1033E-02,0.4687E-02)
5	1	2	3	1	3.4300E-03	(0.1525E-02,0.7717E-02)
5	1	2	3	2	3.0230E-03	(0.1325E-02,0.6897E-02)
5	1	3	1	1	6.2480E-03	(0.2500E-02,0.1562E-01)
5	1	3	1	2	5.5070E-03	(0.2296E-02,0.1321E-01)
5	1	3	2	2	1.5700E-03	(0.6326E-03,0.3896E-02)
5	1	4	2	1	2.7570E-03	(0.1517E-02,0.5008E-02)
5	1	4	2	2	2.4300E-03	(0.1242E-02,0.4753E-02)
5	1	5	1	1	6.8530E-03	(0.3325E-02,0.1412E-01)
5	1	5	1	2	6.0400E-03	(0.3091E-02,0.1181E-01)
5	1	5	2	2	1.7220E-03	(0.9035E-03,0.3281E-02)
5	1	6	1	1	6.8020E-03	(0.1650E-02,0.2804E-01)
5	1	6	2	2	1.7090E-03	(0.4458E-03,0.6551E-02)
5	2	3	2	2	1.0590E-03	(0.1944E-03,0.5770E-02)
5	2	4	1	1	6.5250E-03	(0.1214E-02,0.3506E-01)
5	3	2	2	1	7.4270E-03	(0.3336E-02,0.1654E-01)
5	3	2	2	2	6.5460E-03	(0.2999E-02,0.1429E-01)
5	3	2	3	1	1.0200E-02	(0.4430E-02,0.2350E-01)
5	3	2	3	2	8.9940E-03	(0.4044E-02,0.2000E-01)
5	3	4	2	1	8.2010E-03	(0.4267E-02,0.1576E-01)
5	3	4	2	2	7.2280E-03	(0.3720E-02,0.1404E-01)
5	3	5	2	2	5.1220E-03	(0.2355E-02,0.1114E-01)
5	4	3	1	1	6.2530E-03	(0.2308E-02,0.1694E-01)
5	4	3	1	2	5.5120E-03	(0.2224E-02,0.1366E-01)
5	4	3	2	1	1.7820E-03	(0.6855E-03,0.4635E-02)
5	4	4	1	2	8.5310E-03	(0.3600E-02,0.2021E-01)
5	4	4	2	1	2.7590E-03	(0.1179E-02,0.6458E-02)
5	4	5	2	2	1.7230E-03	(0.7243E-03,0.4100E-02)

In terms of the most unreliable categories of factors, it is seen that motor-operated valves, valves in the power conversion system, and valves of less than two inches all have multipliers greater than two and hence failure rates twice that of the average failure rate.

4.1.2 PWR: Time-Dependent, Degraded Failures--Improper Operation (E). Tables V-A and V-B contain the estimated multipliers, best estimates, and confidence intervals for PWR time-related, degraded failures related to improper operation. Once again VTYPE exhibits the most variability, whereas OPMODE has no effect. Ball valves once again are the most reliable, with a multiplier of 0.45. In contrast, gate valves are seen to be extremely unreliable regarding this failure mode, with a multiplier of 4.43. The only other category with a multiplier greater than two is solenoid-operated valves, having a multiplier of 2.36. Valves in containment systems are seen to be the most reliable, with a failure rate about one-third the average failure rate.

4.1.3 PWR: Time-Dependent, Degraded Failures--Internal Leakage (F). The estimated multipliers, best estimates, and confidence intervals for PWR time-related, degraded valve failures exhibiting internal leakage are found in Tables VI-A and VI-B. From Table VI-A, there are no factors for which the ratio R_j is greater than three, and the ratios for the factors SYSTEM, OTYPE, and VTYPE are roughly the same.

Of all the categories, ball valves are the only ones that change the average failure rate by more than a factor of two. They are more than twice as reliable as the "average" valve. Gate valves have the highest estimated failure rate, with a multiplier of 1.76. Manual valves and valves in safety systems have small failure rates, with multipliers of 0.63 and 0.62 respectively.

4.1.4 PWR: Time-Dependent, Incipient Failures--External Leakage (G). For time-related, incipient valve failures resulting in external leakage, the PWR plant multipliers, best estimates, and 90% confidence intervals are given in Tables VII-A and VII-B. The ratio R_j in Table VII-A is large for three of the factors: VTYPE, OTYPE, and SYSTEM. The factors OPMODE and SIZE have little effect on the failure rate for this failure mode.

Ball valves are extremely reliable, with a failure rate roughly one-fourth of the average. On the other hand, gate valves have a multiplier of 2.99, which

TABLE V-A

PWR: TIME-DEPENDENT, DEGRADED FAILURES--IMPROPER OPERATION (E)

Average Failure-Rate Estimate--7.37 x 10^{-6} (2.31 x 10^{-6})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	VTYPE	1	Ball	9.84	0.45 (0.30)
		2	Butterfly		0.52 (0.25)
		3	Diaphragm		0.97 (0.47)
		4	Gate		4.43 (1.16)
		5	Globe		1.19 (0.37)
		6	Directional control		0.83 (0.86)
2	OTYPE	1	Air	6.21	1.43 (0.37)
		2	Solenoid		2.36 (1.32)
		3	Motor		0.77 (0.24)
		4	Manual		0.38 (0.26)
3	SYSTEM	1	Containment	4.69	0.36 (0.19)
		2	Nuclear		1.69 (0.60)
		3	Power conversion		1.44 (0.36)
		4	Safety		1.12 (0.45)
		5	Process auxiliary		1.01 (0.80)
4	SIZE	1	<2 inches	3.42	0.97 (0.28)
		2	2-10 inches		0.55 (0.09)
		3	10-30 inches		1.88 (0.62)
5	OPMODE	1	Normally closed	1.04	0.98 (0.12)
		2	Normally open		1.02 (0.13)

Note: Values in parentheses are standard deviations.

TABLE V-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR PWR:
TIME-DEPENDENT, DEGRADED FAILURES--
IMPROPER OPERATION (E)

Factors[a]						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
1	3	4	3	1	1.6680E-05	(0.5932E-05,0.4691E-04)
1	3	4	3	2	1.7340E-05	(0.6169E-05,0.4873E-04)
1	3	5	1	1	2.3180E-06	(0.7108E-06,0.7556E-05)
2	1	2	2	2	5.2470E-06	(0.1768E-05,0.1557E-04)
2	1	3	2	1	9.3620E-06	(0.2965E-05,0.2956E-04)
2	1	3	2	2	9.7300E-06	(0.3184E-05,0.2974E-04)
2	1	5	1	1	2.0330E-05	(0.1018E-04,0.4060E-04)
2	1	5	1	2	2.1130E-05	(0.1081E-04,0.4133E-04)
2	1	5	2	1	1.1530E-05	(0.5455E-05,0.2439E-04)
2	1	5	2	2	1.1990E-05	(0.5867E-05,0.2449E-04)
2	2	5	2	2	1.9720E-05	(0.6585E-05,0.5903E-04)
2	3	4	2	1	2.2800E-05	(0.1029E-04,0.5054E-04)
2	3	4	2	2	2.3700E-05	(0.1027E-04,0.5467E-04)
2	3	4	3	1	7.7940E-05	(0.3397E-04,0.1788E-03)
2	3	4	3	2	8.1000E-05	(0.3577E-04,0.1834E-03)
2	3	5	1	1	1.0830E-05	(0.5079E-05,0.2308E-04)
2	3	5	2	2	6.3830E-06	(0.2669E-05,0.1527E-04)
2	3	5	3	2	2.1820E-05	(0.8885E-05,0.5357E-04)
2	4	3	1	2	4.5860E-06	(0.1446E-05,0.1454E-04)
2	4	3	2	1	2.5030E-06	(0.7510E-06,0.8343E-05)
2	4	4	1	1	2.0180E-05	(0.7307E-05,0.5575E-04)
2	4	5	2	1	3.0840E-06	(0.1028E-05,0.9254E-05)
3	1	1	2	1	3.6990E-06	(0.1052E-05,0.1301E-04)
3	1	1	2	2	3.8450E-06	(0.1120E-05,0.1320E-04)
3	1	1	3	2	1.3140E-05	(0.3628E-05,0.4759E-04)
3	1	2	2	1	4.3010E-06	(0.1722E-05,0.1074E-04)
3	1	2	3	1	1.4700E-05	(0.6159E-05,0.3509E-04)
3	1	3	2	1	7.9770E-06	(0.3088E-05,0.2060E-04)
3	1	3	2	2	8.2900E-06	(0.3227E-05,0.2129E-04)
3	1	4	1	1	6.4320E-05	(0.2911E-04,0.1421E-03)
3	1	4	1	2	6.6850E-05	(0.3094E-04,0.1444E-03)
3	1	4	2	1	3.6480E-05	(0.2347E-04,0.5671E-04)
3	1	4	2	2	3.7920E-05	(0.2617E-04,0.5493E-04)
3	1	4	3	2	1.2960E-04	(0.8801E-04,0.1908E-03)
3	1	5	1	1	1.7320E-05	(0.8432E-05,0.3559E-04)
3	1	5	1	2	1.8000E-05	(0.8557E-05,0.3788E-04)
3	1	5	2	1	9.8270E-06	(0.5894E-05,0.1638E-04)
3	1	5	2	2	1.0210E-05	(0.6049E-05,0.1724E-04)
3	1	5	3	2	3.4900E-05	(0.1910E-04,0.6380E-04)
3	1	6	2	1	6.8420E-06	(0.1869E-05,0.2505E-04)
3	1	6	2	2	7.1110E-06	(0.1937E-05,0.2611E-04)

[a]Refer to Table V-A for the definition of numerical categories for each factor.

TABLE V-B (cont)

Factors						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
3	1	6	3	2	2.4300E-05	(0.6406E-05,0.9220E-04)
3	2	6	2	2	1.1700E-05	(0.2650E-05,0.5161E-04)
3	3	2	2	1	2.2900E-06	(0.8555E-06,0.6132E-05)
3	3	2	3	2	8.1350E-06	(0.3057E-05,0.2165E-04)
3	3	4	1	1	3.4250E-05	(0.1489E-04,0.7878E-04)
3	3	4	1	2	3.5600E-05	(0.1420E-04,0.8924E-04)
3	3	4	2	1	1.9430E-05	(0.1204E-04,0.3136E-04)
3	3	4	2	2	2.0190E-05	(0.1110E-04,0.3673E-04)
3	3	4	3	1	6.6400E-05	(0.4182E-04,0.1054E-03)
3	3	4	3	2	6.9010E-05	(0.4162E-04,0.1144E-03)
3	3	5	1	2	9.5880E-06	(0.3617E-05,0.2541E-04)
3	3	5	2	2	5.4380E-06	(0.2443E-05,0.1211E-04)
3	4	4	2	2	1.0140E-05	(0.3976E-05,0.2585E-04)
3	4	4	3	2	3.4650E-05	(0.1352E-04,0.8883E-04)
3	4	5	2	2	2.7310E-06	(0.8920E-06,0.8359E-05)
4	3	3	3	2	1.1760E-05	(0.4295E-05,0.3217E-04)
4	3	4	2	1	1.5140E-05	(0.6757E-05,0.3392E-04)
4	3	4	2	2	1.5730E-05	(0.7281E-05,0.3400E-04)
4	3	4	3	2	5.3770E-05	(0.2722E-04,0.1062E-03)
4	3	5	1	2	7.4700E-06	(0.2691E-05,0.2074E-04)
5	1	2	2	1	3.0070E-06	(0.1238E-05,0.7300E-05)
5	1	2	2	2	3.1250E-06	(0.1234E-05,0.7910E-05)
5	1	2	3	1	1.0280E-05	(0.4171E-05,0.2532E-04)
5	1	2	3	2	1.0680E-05	(0.4361E-05,0.2615E-04)
5	1	3	1	1	9.8300E-06	(0.3421E-05,0.2824E-04)
5	1	3	1	2	1.0220E-05	(0.3551E-05,0.2940E-04)
5	1	3	2	2	5.7950E-06	(0.2123E-05,0.1582E-04)
5	1	4	2	1	2.5500E-05	(0.1241E-04,0.5241E-04)
5	1	4	2	2	2.6510E-05	(0.1352E-04,0.5196E-04)
5	1	5	1	1	1.2110E-05	(0.5929E-05,0.2473E-04)
5	1	5	1	2	1.2590E-05	(0.6051E-05,0.2618E-04)
5	1	5	2	2	7.1390E-06	(0.3391E-05,0.1503E-04)
5	1	6	1	1	8.4320E-06	(0.2038E-05,0.3489E-04)
5	1	6	2	2	4.9710E-06	(0.1206E-05,0.2048E-04)
5	2	3	2	2	9.5320E-06	(0.2275E-05,0.3993E-04)
5	2	4	1	1	7.3950E-05	(0.1645E-04,0.3325E-03)
5	3	2	2	1	1.6010E-06	(0.6443E-06,0.3979E-05)
5	3	2	2	2	1.6640E-06	(0.5857E-06,0.4727E-05)
5	3	2	3	1	5.4720E-06	(0.2315E-05,0.1294E-04)
5	3	2	3	2	5.6870E-06	(0.2185E-05,0.1480E-04)
5	3	4	2	1	1.3580E-05	(0.6877E-05,0.2682E-04)
5	3	4	2	2	1.4110E-05	(0.6577E-05,0.3029E-04)
5	3	5	2	2	3.8020E-06	(0.1529E-05,0.9454E-05)
5	4	3	1	1	2.6280E-06	(0.8798E-06,0.7852E-05)
5	4	3	1	2	2.7320E-06	(0.8826E-06,0.8454E-05)
5	4	3	2	1	1.4910E-06	(0.4775E-06,0.4655E-05)
5	4	4	1	2	1.2490E-05	(0.4479E-05,0.3485E-04)
5	4	4	2	1	6.8190E-06	(0.2425E-05,0.1917E-04)
5	4	5	2	2	1.9090E-06	(0.5801E-06,0.6280E-05)

TABLE VI-A

PWR: TIME-DEPENDENT, DEGRADED FAILURES--INTERNAL LEAKAGE (F)

Average Failure-Rate Estimate--4.96×10^{-6} (1.21×10^{-6})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	OTYPE	1	Air	2.51	1.58 (0.31)
		2	Solenoid		1.17 (0.52)
		3	Motor		0.86 (0.21)
		4	Manual		0.63 (0.34)
2	VTYPE	1	Ball	2.32	0.47 (0.20)
		2	Butterfly		1.12 (0.33)
		3	Diaphragm		0.76 (0.22)
		4	Gate		1.76 (0.34)
		5	Globe		0.95 (0.19)
		6	Directional control		1.50 (0.99)
3	SYSTEM	1	Containment	2.24	1.08 (0.46)
		2	Nuclear		1.29 (0.33)
		3	Power conversion		0.83 (0.18)
		4	Safety		0.62 (0.30)
		5	Process auxiliary		1.39 (1.02)
4	SIZE	1	<2 inches	1.81	1.27 (0.21)
		2	2-10 inches		0.70 (0.10)
		3	10-30 inches		1.12 (0.24)
5	OPMODE	1	Normally closed	1.32	1.15 (0.11)
			Normally open		0.87 (0.08)

Note: Values in parentheses are standard deviations.

TABLE VI-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR PWR:
TIME-DEPENDENT, DEGRADED FAILURES--
INTERNAL LEAKAGE (F)

Factors[a]						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
1	3	4	3	1	1.0460E-05	(0.4813E-05,0.2272E-04)
1	3	4	3	2	7.8820E-06	(0.3751E-05,0.1656E-04)
1	3	5	1	1	6.3880E-06	(0.2499E-05,0.1633E-04)
2	1	2	2	2	6.9430E-06	(0.3278E-05,0.1471E-04)
2	1	3	2	1	6.2590E-06	(0.3343E-05,0.1172E-04)
2	1	3	2	2	4.7180E-06	(0.2543E-05,0.8753E-05)
2	1	5	1	1	1.4090E-05	(0.8885E-05,0.2235E-04)
2	1	5	1	2	1.0620E-05	(0.6875E-05,0.1641E-04)
2	1	5	2	1	7.8200E-06	(0.4791E-05,0.1276E-04)
2	1	5	2	2	5.8940E-06	(0.3760E-05,0.9239E-05)
2	2	5	2	2	4.3700E-06	(0.1578E-05,0.1211E-04)
2	3	4	2	1	7.8630E-06	(0.4536E-05,0.1363E-04)
2	3	4	2	2	5.9270E-06	(0.3396E-05,0.1034E-04)
2	3	4	3	1	1.2580E-05	(0.6251E-05,0.2533E-04)
2	3	4	3	2	9.4840E-06	(0.4855E-05,0.1853E-04)
2	3	5	1	1	7.6860E-06	(0.4532E-05,0.1303E-04)
2	3	5	2	2	3.2150E-06	(0.1806E-05,0.5722E-05)
2	3	5	3	2	5.1440E-06	(0.2519E-05,0.1051E-04)
2	4	3	1	2	3.3700E-06	(0.1583E-05,0.7175E-05)
2	4	3	2	1	2.4810E-06	(0.1156E-05,0.5327E-05)
2	4	4	1	1	1.0300E-05	(0.4777E-05,0.2220E-04)
2	4	5	2	1	3.1000E-06	(0.1440E-05,0.6673E-05)
3	1	1	2	1	2.4600E-06	(0.1075E-05,0.5632E-05)
3	1	1	2	2	1.8540E-06	(0.8063E-06,0.4265E-05)
3	1	1	3	2	2.9680E-06	(0.1276E-05,0.6900E-05)
3	1	2	2	1	5.9190E-06	(0.3327E-05,0.1053E-04)
3	1	2	3	1	9.4720E-06	(0.6068E-05,0.1479E-04)
3	1	3	2	1	4.0220E-06	(0.2317E-05,0.6980E-05)
3	1	3	2	2	3.0310E-06	(0.1693E-05,0.5429E-05)
3	1	4	1	1	1.6700E-05	(0.1059E-04,0.2633E-04)
3	1	4	1	2	1.2580E-05	(0.7620E-05,0.2078E-04)
3	1	4	2	1	9.2640E-06	(0.6661E-05,0.1288E-04)
3	1	4	2	2	6.9820E-06	(0.4813E-05,0.1013E-04)
3	1	4	3	2	1.1170E-05	(0.6361E-05,0.1963E-04)
3	1	5	1	1	9.0550E-06	(0.6066E-05,0.1352E-04)
3	1	5	1	2	6.8250E-06	(0.4445E-05,0.1048E-04)
3	1	5	2	1	5.0240E-06	(0.3599E-05,0.7015E-05)
3	1	5	2	2	3.7870E-06	(0.2677E-05,0.5357E-05)
3	1	5	3	2	6.0600E-06	(0.3388E-05,0.1084E-04)
3	1	6	2	1	7.9300E-06	(0.3402E-05,0.1849E-04)

[a] Refer to Table VI-A for the definition of numerical categories for each factor.

TABLE VI-B (cont)

Factors						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
3	1	6	2	2	5.9770E-06	(0.2585E-05,0.1382E-04)
3	1	6	3	2	9.5650E-06	(0.3810E-05,0.2401E-04)
3	2	6	2	2	4.4320E-06	(0.1704E-05,0.1152E-04)
3	3	2	2	1	3.2280E-06	(0.1645E-05,0.6335E-05)
3	3	2	3	2	3.8940E-06	(0.2146E-05,0.7066E-05)
3	3	4	1	1	9.1060E-06	(0.5777E-05,0.1435E-04)
3	3	4	1	2	6.8630E-06	(0.4059E-05,0.1160E-04)
3	3	4	2	1	5.0520E-06	(0.3440E-05,0.7422E-05)
3	3	4	2	2	3.8080E-06	(0.2429E-05,0.5971E-05)
3	3	4	3	1	8.0850E-06	(0.4512E-05,0.1449E-04)
3	3	4	3	2	6.0940E-06	(0.3383E-05,0.1098E-04)
3	3	5	1	2	3.7220E-06	(0.2116E-05,0.6548E-05)
3	3	5	2	2	2.0650E-06	(0.1200E-05,0.3555E-05)
3	4	4	2	2	2.7670E-06	(0.1384E-05,0.5535E-05)
3	4	4	3	2	4.4290E-06	(0.2008E-05,0.9768E-05)
3	4	5	2	2	1.5010E-06	(0.7318E-06,0.3079E-05)
4	3	3	3	2	1.9720E-06	(0.6757E-06,0.5758E-05)
4	3	4	2	1	3.7670E-06	(0.1394E-05,0.1018E-04)
4	3	4	2	2	2.8390E-06	(0.1070E-05,0.7534E-05)
4	3	4	3	2	4.5430E-06	(0.1690E-05,0.1221E-04)
4	3	5	1	2	2.7750E-06	(0.1010E-05,0.7625E-05)
5	1	2	2	1	9.9350E-06	(0.5520E-05,0.1788E-04)
5	1	2	2	2	7.4880E-06	(0.3968E-05,0.1413E-04)
5	1	2	3	1	1.5900E-05	(0.9345E-05,0.2705E-04)
5	1	2	3	2	1.1980E-05	(0.6981E-05,0.2057E-04)
5	1	3	1	1	1.2170E-05	(0.6515E-05,0.2272E-04)
5	1	3	1	2	9.1690E-06	(0.4851E-05,0.1733E-04)
5	1	3	2	2	5.0880E-06	(0.2900E-05,0.8925E-05)
5	1	4	2	1	1.5550E-05	(0.1026E-04,0.2357E-04)
5	1	4	2	2	1.1720E-05	(0.7778E-05,0.1766E-04)
5	1	5	1	1	1.5200E-05	(0.9474E-05,0.2438E-04)
5	1	5	1	2	1.1460E-05	(0.7228E-05,0.1815E-04)
5	1	5	2	2	6.3560E-06	(0.4191E-05,0.9639E-05)
5	1	6	1	1	2.3990E-05	(0.9471E-05,0.6075E-04)
5	1	6	2	2	1.0030E-05	(0.4203E-05,0.2395E-04)
5	2	3	2	2	3.7720E-06	(0.1325E-05,0.1074E-04)
5	2	4	1	1	2.0780E-05	(0.7141E-05,0.6044E-04)
5	3	2	2	1	5.4180E-06	(0.2822E-05,0.1040E-04)
5	3	2	2	2	4.0840E-06	(0.2002E-05,0.8332E-05)
5	3	2	3	1	8.6710E-06	(0.4892E-05,0.1537E-04)
5	3	2	3	2	6.5350E-06	(0.3581E-05,0.1193E-04)
5	3	4	2	1	8.4800E-06	(0.5614E-05,0.1281E-04)
5	3	4	2	2	6.3910E-06	(0.4134E-05,0.9881E-05)
5	3	5	2	2	3.4670E-06	(0.1994E-05,0.6027E-05)
5	4	3	1	1	4.8220E-06	(0.2294E-05,0.1013E-04)
5	4	3	1	2	3.6340E-06	(0.1718E-05,0.7689E-05)
5	4	3	2	1	2.6760E-06	(0.1309E-05,0.5467E-05)
5	4	4	1	2	8.3710E-06	(0.4081E-05,0.1717E-04)
5	4	4	2	1	6.1630E-06	(0.3099E-05,0.1226E-04)
5	4	5	2	2	2.5190E-06	(0.1224E-05,0.5185E-05)

TABLE VII-A

PWR: TIME-DEPENDENT INCIPIENT FAILURES--EXTERNAL LEAKAGE (G)

Average Failure-Rate Estimates--6.95×10^{-6} (2.82×10^{-6})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	VTYPE	1	Ball	13.59	0.22 (0.15)
		2	Butterfly		1.19 (0.53)
		3	Diaphragm		0.92 (0.38)
		4	Gate		2.99 (0.78)
		5	Globe		1.83 (0.59)
		6	Directional control		0.76 (0.76)
2	OTYPE	1	Air	6.95	2.92 (1.04)
		2	Solenoid		0.42 (0.40)
		3	Motor		1.18 (0.46)
		4	Manual		0.70 (0.76)
3	SYSTEM	1	Containment	4.83	0.59 (0.32)
		2	Nuclear		1.82 (0.46)
		3	Power conversion		0.52 (0.12)
		4	Safety		2.85 (0.80)
		5	Process auxiliary		0.62 (0.44)
4	SIZE	1	<2 inches	2.95	0.60 (0.15)
		2	2-10 inches		0.94 (0.15)
		3	10-30 inches		1.77 (0.52)
5	OPMODE	1	Normally closed	1.52	0.81 (0.09)
		2	Normally open		1.23 (0.14)

Note: Values in parentheses are standard deviations.

TABLE VII-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR PWR:
TIME-DEPENDENT, INCIPIENT FAILURES--
EXTERNAL LEAKAGE (G)

Factors[a]						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
1	3	4	3	1	2.0840E-05	(0.6956E-05,0.6246E-04)
1	3	4	3	2	3.1500E-05	(0.1043E-04,0.9511E-04)
1	3	5	1	1	4.3290E-06	(0.1403E-05,0.1336E-04)
2	1	2	2	2	5.1010E-05	(0.1875E-04,0.1388E-03)
2	1	3	2	1	2.6150E-05	(0.1194E-04,0.5725E-04)
2	1	3	2	2	3.9520E-05	(0.1732E-04,0.9015E-04)
2	1	5	1	1	3.3050E-05	(0.1825E-04,0.5987E-04)
2	1	5	1	2	4.9960E-05	(0.2770E-04,0.9010E-04)
2	1	5	2	1	5.2120E-05	(0.3170E-04,0.8568E-04)
2	1	5	2	2	7.8770E-05	(0.4786E-04,0.1296E-03)
2	2	5	2	2	1.1190E-05	(0.1321E-05,0.9472E-04)
2	3	4	2	1	3.4380E-05	(0.1919E-04,0.6161E-04)
2	3	4	2	2	5.1970E-05	(0.2628E-04,0.1028E-03)
2	3	4	3	1	6.4450E-05	(0.3610E-04,0.1151E-03)
2	3	4	3	2	9.7410E-05	(0.5504E-04,0.1724E-03)
2	3	5	1	1	1.3390E-05	(0.7093E-05,0.2527E-04)
2	3	5	2	2	3.1900E-05	(0.1738E-04,0.5855E-04)
2	3	5	3	2	5.9800E-05	(0.3137E-04,0.1140E-03)
2	4	3	1	2	5.9580E-06	(0.1943E-05,0.1827E-04)
2	4	3	2	1	6.2150E-06	(0.2215E-05,0.1744E-04)
2	4	4	1	1	1.2800E-05	(0.4732E-05,0.3462E-04)
2	4	5	2	1	1.2390E-05	(0.4995E-05,0.3072E-04)
3	1	1	2	1	1.7750E-06	(0.5166E-06,0.6101E-05)
3	1	1	2	2	2.6830E-06	(0.7491E-06,0.9611E-05)
3	1	1	3	2	5.0300E-06	(0.1377E-05,0.1838E-04)
3	1	2	2	1	9.7030E-06	(0.4001E-05,0.2353E-04)
3	1	2	3	1	1.8190E-05	(0.7472E-05,0.4428E-04)
3	1	3	2	1	7.5160E-06	(0.3406E-05,0.1658E-04)
3	1	3	2	2	1.1360E-05	(0.5247E-05,0.2459E-04)
3	1	4	1	1	1.5480E-05	(0.7567E-05,0.3167E-04)
3	1	4	1	2	2.3400E-05	(0.1146E-04,0.4776E-04)
3	1	4	2	1	2.4410E-05	(0.1623E-04,0.3671E-04)
3	1	4	2	2	3.6890E-05	(0.2443E-04,0.5570E-04)
3	1	4	3	2	6.9150E-05	(0.4650E-04,0.1028E-03)
3	1	5	1	1	9.5030E-06	(0.4856E-05,0.1860E-04)
3	1	5	1	2	1.4360E-05	(0.7949E-05,0.2595E-04)
3	1	5	2	1	1.4980E-05	(0.8777E-05,0.2557E-04)
3	1	5	2	2	2.2640E-05	(0.1463E-04,0.3506E-04)
3	1	5	3	2	4.2450E-05	(0.2320E-04,0.7765E-04)
3	1	6	2	1	6.2360E-06	(0.1350E-05,0.2880E-04)
3	1	6	2	2	9.4250E-06	(0.2090E-05,0.4250E-04)

[a] Refer to Table VII-A for the definition of numerical categories for each factor.

TABLE VII-B (cont)

Factors						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
3	1	6	3	2	1.7670E-05	(0.3848E-05,0.8112E-04)
3	2	6	2	2	1.3380E-06	(0.1239E-06,0.1446E-04)
3	3	2	2	1	3.9300E-06	(0.1494E-05,0.1033E-04)
3	3	2	3	2	1.1130E-05	(0.4611E-05,0.2688E-04)
3	3	4	1	1	6.2690E-06	(0.2913E-05,0.1349E-04)
3	3	4	1	2	9.4750E-06	(0.4338E-05,0.2070E-04)
3	3	4	2	1	9.8840E-06	(0.5788E-05,0.1688E-04)
3	3	4	2	2	1.4940E-05	(0.8521E-05,0.2619E-04)
3	3	4	3	1	1.8530E-05	(0.1037E-04,0.3311E-04)
3	3	4	3	2	2.8000E-05	(0.1731E-04,0.4529E-04)
3	3	5	1	2	5.8160E-06	(0.2909E-05,0.1163E-04)
3	3	5	2	2	9.1700E-06	(0.5010E-05,0.1679E-04)
3	4	4	2	2	8.7680E-06	(0.3978E-05,0.1933E-04)
3	4	4	3	2	1.6440E-05	(0.8125E-05,0.3325E-04)
3	4	5	2	2	5.3830E-06	(0.2320E-05,0.1249E-04)
4	3	3	3	2	4.7020E-05	(0.2148E-04,0.1029E-03)
4	3	4	2	1	5.3890E-05	(0.3431E-04,0.8466E-04)
4	3	4	2	2	8.1460E-05	(0.4887E-04,0.1358E-03)
4	3	4	3	2	1.5270E-04	(0.1008E-03,0.2313E-03)
4	3	5	1	2	3.1710E-05	(0.1569E-04,0.6410E-04)
5	1	2	2	1	1.1630E-05	(0.6072E-05,0.2227E-04)
5	1	2	2	2	1.7570E-05	(0.8709E-05,0.3547E-04)
5	1	2	3	1	2.1800E-05	(0.1059E-04,0.4485E-04)
5	1	2	3	2	3.2940E-05	(0.1676E-04,0.6476E-04)
5	1	3	1	1	5.7130E-06	(0.2121E-05,0.1539E-04)
5	1	3	1	2	8.6340E-06	(0.3175E-05,0.2348E-04)
5	1	3	2	2	1.3610E-05	(0.5606E-05,0.3306E-04)
5	1	4	2	1	2.9250E-05	(0.1583E-04,0.5403E-04)
5	1	4	2	2	4.4200E-05	(0.2286E-04,0.8547E-04)
5	1	5	1	1	1.1390E-05	(0.4969E-05,0.2610E-04)
5	1	5	1	2	1.7210E-05	(0.7725E-05,0.3834E-04)
5	1	5	2	2	2.7140E-05	(0.1288E-04,0.5715E-04)
5	1	6	1	1	4.7400E-06	(0.9599E-06,0.2341E-04)
5	1	6	2	2	1.1300E-05	(0.2474E-05,0.5157E-04)
5	2	3	2	2	1.9330E-06	(0.2196E-06,0.1702E-04)
5	2	4	1	1	2.6340E-06	(0.2954E-06,0.2349E-04)
5	3	2	2	1	4.7090E-06	(0.2183E-05,0.1016E-04)
5	3	2	2	2	7.1180E-06	(0.3106E-05,0.1631E-04)
5	3	2	3	1	8.8280E-06	(0.4022E-05,0.1937E-04)
5	3	2	3	2	1.3340E-05	(0.6231E-05,0.2857E-04)
5	3	4	2	1	1.1850E-05	(0.5778E-05,0.2428E-04)
5	3	4	2	2	1.7900E-05	(0.8256E-05,0.3882E-04)
5	3	5	2	2	1.0990E-05	(0.4627E-05,0.2610E-04)
5	4	3	1	1	1.3580E-06	(0.4424E-06,0.4168E-05)
5	4	3	1	2	2.0520E-06	(0.6677E-06,0.6309E-05)
5	4	3	2	1	2.1410E-06	(0.7416E-06,0.6181E-05)
5	4	4	1	2	6.6650E-06	(0.2418E-05,0.1837E-04)
5	4	4	2	1	6.9520E-06	(0.2836E-05,0.1704E-04)
5	4	5	2	2	6.4500E-06	(0.2339E-05,0.1779E-04)

indicates that the associated failure rate is three times larger than the average. Pneumatically operated valves also have a failure rate that is roughly three times the average, whereas solenoid-operated valves have a multiplier of 0.42. Valves in safety systems also have a failure rate roughly three times as large as the average.

4.1.5 PWR: Time-Dependent, Incipient Failures--Faulty Indication (H). Tables VIII-A and VIII-B, which contain the multipliers, best estimates, and 90% confidence intervals for incipient valve failures of faulty indication for the PWR plant, show that, for the most part, the given factors do not have much effect on the failure rate. However, a few of the categories of the factors significantly influence the failure rate. Once again, ball valves are the most reliable, the multiplier being 0.41. The remaining valve types have multipliers close to one. Valves in safety systems, as well as 10- to 30-inch valves, have multipliers larger than two and thus corresponding failure rates that are twice that of the average. Of the five factors, OPMODE has the least effect on the failure mode, with an R_j value of 1.08.

4.2 Estimates for the BWR Plant

Only four factors are considered in the analysis of the BWR plant. They are SYSTEM, OTYPE, VTYPE, and SIZE. OPMODE is not considered for the BWR plant because of a lack of data for that factor. However, for the PWR plant, OPMODE was the least significant factor and could probably have been deleted from the analyses without affecting the results. The following subsections contain the analyses for each of the five failure modes for the BWR plant.

4.2.1 BWR: Demand-Dependent, Catastrophic Failures--Failure to Operate on Demand (A,K). For the BWR plant, the valve multipliers, best estimates, and 90% confidence intervals can be found in Tables IX-A and IX-B. Of the four factors, VTYPE and SIZE have the largest R_j values. The multipliers for the categories of these factors are large for diaphragm valves and valves greater than 30 inches. Multipliers of 4.14 and 3.64 for these two categories indicate failure rates roughly four times that of the average failure rate. Relief and safety valves are the most reliable, with failure rates approximately one-third the average. Also, valves in containment systems have failure rates nearly one-third the average. The remaining factor categories do not have much effect on the valve failure rates.

TABLE VIII-A

PWR: TIME-DEPENDENT, INCIPIENT FAILURES--FAULTY INDICATION (H)

Average Failure-Rate Estimate--5.58 x 10^{-6} (1.23 x 10^{-6})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	VTYPE	1	Ball	3.44	0.41 (0.14)
		2	Butterfly		1.18 (0.33)
		3	Diaphragm		1.19 (0.32)
		4	Gate		1.07 (0.19)
		5	Globe		1.41 (0.25)
		6	Directional control		1.14 (0.65)
2	SYSTEM	1	Containment	3.17	0.81 (0.31)
		2	Nuclear		1.08 (0.22)
		3	Power conversion		0.69 (0.13)
		4	Safety		2.19 (0.61)
		5	Process auxiliary		0.76 (0.42)
3	SIZE	1	<2 inches	2.90	0.70 (0.12)
		2	2-10 inches		0.70 (0.08)
		3	10-30 inches		2.03 (0.42)
4	OTYPE	1	Air	2.03	1.60 (0.33)
		2	Solenoid		0.79 (0.37)
		3	Motor		0.87 (0.21)
		4	Manual		0.90 (0.50)
5	OPMODE	1	Normally closed	1.08	1.04 (0.09)
		2	Normally open		0.96 (0.08)

Note: Values in parentheses are standard deviations.

TABLE VIII-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR PWR:
TIME-DEPENDENT, INCIPIENT FAILURES--
FAULTY INDICATION (H)

Factors[a]						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
1	3	4	3	1	8.8520E-06	(0.4467E-05,0.1754E-04)
1	3	4	3	2	8.2230E-06	(0.3985E-05,0.1698E-04)
1	3	5	1	1	4.0500E-06	(0.1783E-05,0.9200E-05)
2	1	2	2	2	7.6930E-06	(0.4037E-05,0.1466E-04)
2	1	3	2	1	8.3760E-06	(0.4451E-05,0.1576E-04)
2	1	3	2	2	7.7810E-06	(0.4178E-05,0.1449E-04)
2	1	5	1	1	9.8720E-06	(0.6153E-05,0.1584E-04)
2	1	5	1	2	9.1700E-06	(0.5696E-05,0.1476E-04)
2	1	5	2	1	9.9220E-06	(0.6379E-05,0.1543E-04)
2	1	5	2	2	9.2170E-06	(0.5900E-05,0.1440E-04)
2	2	5	2	2	4.5560E-06	(0.1593E-05,0.1303E-04)
2	3	4	2	1	4.0880E-06	(0.2473E-05,0.6756E-05)
2	3	4	2	2	3.7970E-06	(0.2268E-05,0.6359E-05)
2	3	4	3	1	1.1790E-05	(0.6771E-05,0.2052E-04)
2	3	4	3	2	1.0950E-05	(0.6590E-05,0.1819E-04)
2	3	5	1	1	5.3920E-06	(0.3222E-05,0.9024E-05)
2	3	5	2	2	5.0350E-06	(0.3156E-05,0.8032E-05)
2	3	5	3	2	1.4520E-05	(0.8477E-05,0.2486E-04)
2	4	3	1	2	4.3610E-06	(0.2090E-05,0.9099E-05)
2	4	3	2	1	4.7180E-06	(0.2267E-05,0.9819E-05)
2	4	4	1	1	4.1940E-06	(0.2075E-05,0.8479E-05)
2	4	5	2	1	5.5890E-06	(0.2793E-05,0.1118E-04)
3	1	1	2	1	1.8650E-06	(0.1042E-05,0.3338E-05)
3	1	1	2	2	1.7330E-06	(0.9228E-06,0.3253E-05)
3	1	1	3	2	4.9960E-06	(0.2530E-05,0.9866E-05)
3	1	2	2	1	5.3290E-06	(0.3042E-05,0.9334E-05)
3	1	2	3	1	1.5370E-05	(0.8418E-05,0.2805E-04)
3	1	3	2	1	5.3900E-06	(0.3016E-05,0.9633E-05)
3	1	3	2	2	5.0070E-06	(0.2848E-05,0.8802E-05)
3	1	4	1	1	4.7910E-06	(0.2887E-05,0.7951E-05)
3	1	4	1	2	4.4500E-06	(0.2616E-05,0.7570E-05)
3	1	4	2	1	4.8150E-06	(0.3407E-05,0.6806E-05)
3	1	4	2	2	4.4730E-06	(0.3053E-05,0.6555E-05)
3	1	4	3	2	1.2900E-05	(0.8822E-05,0.1886E-04)
3	1	5	1	1	6.3520E-06	(0.4106E-05,0.9827E-05)
3	1	5	1	2	5.9010E-06	(0.3826E-05,0.9101E-05)
3	1	5	2	1	6.3840E-06	(0.4776E-05,0.8533E-05)
3	1	5	2	2	5.9300E-06	(0.4453E-05,0.7899E-05)
3	1	5	3	2	1.7100E-05	(0.1147E-04,0.2550E-04)
3	1	6	2	1	5.1720E-06	(0.2246E-05,0.1191E-04)
3	1	6	2	2	4.8040E-06	(0.2099E-05,0.1100E-04)
3	1	6	3	2	1.3850E-05	(0.5915E-05,0.3244E-04)

[a]Refer to Table VIII-A for definition of numerical categories for each factor.

TABLE VIII-B (cont)

Factors						
SYSTEM	OTYPE	VTYPE	SIZE	OPMODE	Estimate	90% Confidence Interval
3	2	6	2	2	2.3750E-06	(0.7352E-06,0.7672E-05)
3	3	2	2	1	2.9110E-06	(0.1518E-05,0.5580E-05)
3	3	2	3	2	7.7970E-06	(0.4132E-05,0.1471E-04)
3	3	4	1	1	2.6170E-06	(0.1445E-05,0.4738E-05)
3	3	4	1	2	2.4310E-06	(0.1335E-05,0.4427E-05)
3	3	4	2	1	2.6300E-06	(0.1660E-05,0.4168E-05)
3	3	4	2	2	2.4430E-06	(0.1529E-05,0.3903E-05)
3	3	4	3	1	7.5840E-06	(0.4624E-05,0.1244E-04)
3	3	4	3	2	7.0450E-06	(0.4558E-05,0.1089E-04)
3	3	5	1	2	3.2230E-06	(0.1860E-05,0.5587E-05)
3	3	5	2	2	3.2390E-06	(0.2087E-05,0.5028E-05)
3	4	4	2	2	2.5200E-06	(0.1311E-05,0.4842E-05)
3	4	4	3	2	7.2650E-06	(0.3711E-05,0.1422E-04)
3	4	5	2	2	3.3400E-06	(0.1730E-05,0.6450E-05)
4	3	3	3	2	2.4970E-05	(0.1368E-04,0.4558E-04)
4	3	4	2	1	8.3280E-06	(0.4987E-05,0.1391E-04)
4	3	4	2	2	7.7360E-06	(0.4457E-05,0.1343E-04)
4	3	4	3	2	2.2310E-05	(0.1292E-04,0.3853E-04)
4	3	5	1	2	1.0210E-05	(0.5266E-05,0.1978E-04)
5	1	2	2	1	5.8420E-06	(0.3627E-05,0.9409E-05)
5	1	2	2	2	5.4270E-06	(0.3238E-05,0.9095E-05)
5	1	2	3	1	1.6850E-05	(0.9434E-05,0.3008E-04)
5	1	2	3	2	1.5650E-05	(0.8945E-05,0.2738E-04)
5	1	3	1	1	5.8790E-06	(0.3158E-05,0.1094E-04)
5	1	3	1	2	5.4610E-06	(0.2985E-05,0.9990E-05)
5	1	3	2	2	5.4890E-06	(0.3127E-05,0.9636E-05)
5	1	4	2	1	5.2790E-06	(0.3269E-05,0.8526E-05)
5	1	4	2	2	4.9040E-06	(0.2962E-05,0.8119E-05)
5	1	5	1	1	6.9640E-06	(0.4168E-05,0.1163E-04)
5	1	5	1	2	6.4690E-06	(0.3889E-05,0.1076E-04)
5	1	5	2	2	6.5020E-06	(0.3999E-05,0.1057E-04)
5	1	6	1	1	5.6410E-06	(0.2276E-05,0.1398E-04)
5	1	6	2	2	5.2670E-06	(0.2190E-05,0.1267E-04)
5	2	3	2	2	2.7130E-06	(0.9399E-06,0.7834E-05)
5	2	4	1	1	2.5970E-06	(0.8768E-06,0.7689E-05)
5	3	2	2	1	3.1910E-06	(0.1835E-05,0.5551E-05)
5	3	2	2	2	2.9640E-06	(0.1673E-05,0.5252E-05)
5	3	2	3	1	9.2020E-06	(0.4939E-05,0.1715E-04)
5	3	2	3	2	8.5480E-06	(0.4750E-05,0.1538E-04)
5	3	4	2	1	2.8840E-06	(0.1680E-05,0.4949E-05)
5	3	4	2	2	2.6790E-06	(0.1552E-05,0.4622E-05)
5	3	5	2	2	3.5510E-06	(0.2022E-05,0.6237E-05)
5	4	3	1	1	3.3120E-06	(0.1649E-05,0.6649E-05)
5	4	3	1	2	3.0760E-06	(0.1561E-05,0.6061E-05)
5	4	3	2	1	3.3280E-06	(0.1678E-05,0.6600E-05)
5	4	4	1	2	2.7480E-06	(0.1373E-05,0.5500E-05)
5	4	4	2	1	2.9740E-06	(0.1532E-05,0.5770E-05)
5	4	5	2	2	3.6620E-06	(0.1791E-05,0.7486E-05)

TABLE IX-A

BWR: DEMAND-DEPENDENT, CATASTROPHIC FAILURES--FAILURE TO OPERATE ON DEMAND (A,K)

Average Failure-Rate Estimate--2.35×10^{-3} (8.32×10^{-4})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	VTYPE	1	Angle	13.35	1.33 (0.76)
		2	Butterfly		1.20 (0.49)
		3	Plug		0.44 (0.35)
		4	Diaphragm		4.14 (3.37)
		5	Gate		1.27 (0.45)
		6	Globe		0.87 (0.37)
		7	Relief/Safety		0.31 (0.45)
2	SIZE	1	<2 inches	6.74	0.91 (0.28)
		2	2-10 inches		0.56 (0.14)
		3	10-30 inches		0.54 (0.14)
		4	>30 inches		3.64 (1.73)
3	SYSTEM	1	Containment	4.53	0.36 (0.17)
		2	Nuclear		1.46 (0.48)
		3	Power conversion		1.62 (0.52)
		4	Safety		1.63 (0.77)
		5	Process auxiliary		0.73 (0.59)
4	OTYPE	1	Air	1.63	1.17 (0.42)
		2	Solenoid		1.17 (0.89)
		3	Motor		0.95 (0.36)
		4	Chain		0.72 (0.44)
		5	Manual		1.07 (1.18)

Note: Values in parentheses are standard deviations.

TABLE IX-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR BWR:
DEMAND-DEPENDENT, CATASTROPHIC FAILURES--
FAILURE TO OPERATE ON DEMAND (A,K)

Factors[a]					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
1	1	2	3	6.3420E-04	(0.2771E-03,0.1452E-02)
1	1	2	4	4.2660E-03	(0.1380E-02,0.1319E-01)
1	3	5	3	5.4210E-04	(0.1947E-03,0.1509E-02)
2	1	2	2	2.6770E-03	(0.1577E-02,0.4543E-02)
2	1	5	1	4.6420E-03	(0.1936E-02,0.1113E-01)
2	1	5	2	2.8330E-03	(0.1355E-02,0.5923E-02)
2	3	5	1	3.7490E-03	(0.1640E-02,0.8569E-02)
2	3	5	2	2.2880E-03	(0.1164E-02,0.4497E-02)
2	3	5	3	2.2190E-03	(0.9775E-03,0.5035E-02)
2	5	5	2	2.5950E-03	(0.7993E-03,0.8428E-02)
3	1	3	1	1.7870E-03	(0.4270E-03,0.7482E-02)
3	1	6	3	2.1100E-03	(0.7939E-03,0.5609E-02)
3	1	7	2	7.7880E-04	(0.2468E-03,0.2458E-02)
3	1	7	3	7.5520E-04	(0.2474E-03,0.2305E-02)
3	3	1	2	2.6750E-03	(0.1091E-02,0.6557E-02)
3	3	1	3	2.5930E-03	(0.9493E-03,0.7085E-02)
3	3	5	1	4.1690E-03	(0.2305E-02,0.7538E-02)
3	3	5	2	2.5440E-03	(0.1297E-02,0.4989E-02)
3	3	5	3	2.4670E-03	(0.1581E-02,0.3849E-02)
3	3	6	1	2.8800E-03	(0.1091E-02,0.7598E-02)
3	3	6	2	1.7570E-03	(0.7323E-03,0.4217E-02)
3	5	3	2	9.9930E-04	(0.2387E-03,0.4183E-02)
4	1	7	1	1.2780E-03	(0.3598E-03,0.4540E-02)
4	3	5	2	2.5480E-03	(0.9679E-03,0.6709E-02)
4	3	5	3	2.4710E-03	(0.9737E-03,0.6270E-02)
4	3	6	2	1.7600E-03	(0.5945E-03,0.5212E-02)
4	4	5	3	1.8770E-03	(0.5174E-03,0.6808E-02)
5	1	2	2	1.3380E-03	(0.6992E-03,0.2559E-02)
5	1	2	3	1.2970E-03	(0.6051E-03,0.2781E-02)
5	1	4	2	4.6330E-03	(0.1061E-02,0.2023E-01)
5	1	5	2	1.4160E-03	(0.5879E-03,0.3410E-02)
5	1	6	2	9.7810E-04	(0.4376E-03,0.2186E-02)
5	2	4	2	4.6260E-03	(0.1059E-02,0.2020E-01)
5	2	5	1	2.3170E-03	(0.5305E-03,0.1011E-01)
5	3	2	3	1.0480E-03	(0.4087E-03,0.2685E-02)
5	3	2	4	7.0460E-03	(0.4681E-02,0.1061E-01)
5	3	5	2	1.1430E-03	(0.5209E-03,0.2510E-02)
5	4	2	2	8.2050E-04	(0.2577E-03,0.2612E-02)
5	4	2	3	7.9560E-04	(0.2599E-03,0.2436E-02)
5	5	5	1	2.1250E-03	(0.5954E-03,0.7587E-02)

[a]Refer to Table IX-A for the definition of numerical categories for each factor.

4.2.2 BWR: Time-Dependent, Degraded Failures--Improper Operation (E). Failure rates for degraded valve failures of improper operation are largely affected by the system in which they operate. Table X-A contains the multipliers for the factor categories for this failure mode. The factor SYSTEM, with an R_j value of 10.39, has two categories, safety systems and plant auxiliary systems, with failure rates that are 2.91 and 2.59 times the average failure rate, respectively. The most unreliable valves for this failure mode are diaphragm valves, with a multiplier of 3.20.

The most reliable valves for this failure mode are valves in nuclear systems (with a multiplier of 0.28), chain-operated valves (with a multiplier of 0.31), and relief/safety valves (with a multiplier of 0.40). The remaining categories do not change the average failure rate by more than a factor of 2.

The corresponding best estimates and confidence intervals for selected category combinations may be found in Table X-B.

4.2.3 BWR: Time-Dependent, Degraded Failures--Internal Leakage (F). Failure-rate multipliers, best estimates, and 90% confidence intervals for time-dependent, degraded valve failures in the internal leakage mode are given in Tables XI-A and XI-B. From Table XI-A it is apparent that VTYPE is the most influential factor in determining the failure rate. Two categories of this factor, check valves and diaphragm valves, have significantly different failure rates. Check valves are four times as reliable as the "average" valve (multiplier of 0.25), whereas diaphragm valves have estimated failure rates that are slightly over three times larger than the average valve failure rate.

Other categories that exhibit large failure rates are valves in containment or safety systems. Both of these systems have multipliers of about 2.5. Small valves (less than 2 inches) are also unreliable, with a multiplier slightly larger than two.

The categories that lead to the most reliable valves are large valves exceeding 30 inches. The multiplier for such valves is 0.32. Valves in the power conversion system have a failure rate of 0.38 times that of the average failure rate. All other components have a failure rate ranging from approximately half to twice the average rate.

4.2.4 BWR: Time-Dependent, Incipient Failures--External Leakage (G). Tables XII-A and XII-B contain the failure-rate multipliers, best estimates, and 90% confidence intervals for BWR incipient time-dependent valve failures resulting in external leakage. Whereas the ratio R_j is not as large as it is for

TABLE X-A

BWR: TIME-DEPENDENT, DEGRADED FAILURES--IMPROPER OPERATION (E)

Average Failure-Rate Estimate--3.15 x 10^{-6} (1.14 x 10^{-6})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	SYSTEM	1	Containment	10.39	1.81 (0.55)
		2	Nuclear		0.28 (0.11)
		3	Power conversion		0.57 (0.16)
		4	Safety		2.91 (0.95)
		5	Process auxiliary		0.47 (0.14)
		6	Plant auxiliary		2.59 (1.87)
2	VTYPE	1	Angle	8.00	0.71 (0.60)
		2	Butterfly		1.84 (0.71)
		3	Check		0.71 (0.26)
		4	Diaphragm		3.20 (3.02)
		5	Gate		1.48 (0.50)
		6	Globe		0.68 (0.30)
		7	Relief/safety		0.40 (0.28)
		8	Plug		0.85 (1.39)
3	OTYPE	1	Air	4.87	1.04 (0.40)
		2	Solenoid		1.42 (1.23)
		3	Motor		1.51 (0.56)
		4	Chain		0.31 (0.20)
		5	Manual		1.46 (1.77)
4	SIZE	1	<2 inches	1.26	0.87 (0.31)
		2	2-10 inches		1.10 (0.26)
		3	10-30 inches		0.99 (0.20)
		4	>30 inches		1.05 (0.50)

Note: Values in parentheses are standard deviations.

TABLE X-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR BWR:
TIME-DEPENDENT, DEGRADED FAILURES--
IMPROPER OPERATION (E)

Factors[a]					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
1	1	2	3	1.0750E-05	(0.7808E-05,0.1480E-04)
1	1	2	4	1.1410E-05	(0.5993E-05,0.2171E-04)
1	1	3	3	4.1290E-06	(0.2532E-05,0.6731E-05)
1	3	5	3	1.2620E-05	(0.6598E-05,0.2414E-04)
2	1	2	2	1.8190E-06	(0.7728E-06,0.4280E-05)
2	1	3	1	5.5100E-07	(0.2174E-06,0.1396E-05)
2	1	3	2	6.9860E-07	(0.3007E-06,0.1623E-05)
2	1	5	1	1.1580E-06	(0.4466E-06,0.3003E-05)
2	1	5	2	1.4680E-06	(0.6070E-06,0.3552E-05)
2	3	5	1	1.6840E-06	(0.6781E-06,0.4183E-05)
2	3	5	2	2.1350E-06	(0.9435E-06,0.4833E-05)
2	3	5	3	1.9250E-06	(0.8245E-06,0.4496E-05)
2	5	5	2	2.0720E-06	(0.5213E-06,0.8235E-05)
3	1	3	1	1.1350E-06	(0.4682E-06,0.2752E-05)
3	1	3	2	1.4390E-06	(0.7371E-06,0.2810E-05)
3	1	3	3	1.2980E-06	(0.6999E-06,0.2405E-05)
3	1	6	3	1.2480E-06	(0.4642E-06,0.3357E-05)
3	1	7	2	8.0930E-07	(0.2308E-06,0.2839E-05)
3	1	7	3	7.2970E-07	(0.2144E-06,0.2483E-05)
3	1	8	1	1.3690E-06	(0.2674E-06,0.7005E-05)
3	3	1	2	2.1120E-06	(0.4933E-06,0.9043E-05)
3	3	1	3	1.9040E-06	(0.4448E-06,0.8153E-05)
3	3	5	1	3.4700E-06	(0.1484E-05,0.8114E-05)
3	3	5	2	4.4000E-06	(0.2378E-05,0.8139E-05)
3	3	5	3	3.9660E-06	(0.2469E-05,0.6373E-05)
3	3	6	1	1.5880E-06	(0.5832E-06,0.4326E-05)
3	3	6	2	2.0140E-06	(0.8887E-06,0.4563E-05)
3	5	8	2	2.4490E-06	(0.4785E-06,0.1253E-04)
4	1	3	2	7.3780E-06	(0.3879E-05,0.1403E-04)
4	1	3	3	6.6520E-06	(0.2921E-05,0.1515E-04)
4	1	7	1	3.2720E-06	(0.8612E-06,0.1243E-04)
4	3	5	2	2.2550E-05	(0.1555E-04,0.3271E-04)
4	3	5	3	2.0330E-05	(0.1160E-04,0.3565E-04)
4	3	6	2	1.0320E-05	(0.5234E-05,0.2036E-04)
4	4	5	3	4.1340E-06	(0.1116E-05,0.1531E-04)
5	1	2	2	3.1090E-06	(0.1961E-05,0.4929E-05)
5	1	2	3	2.8030E-06	(0.1543E-05,0.5092E-05)
5	1	3	1	9.4170E-07	(0.4100E-06,0.2163E-05)
5	1	3	2	1.1940E-06	(0.6470E-06,0.2204E-05)
5	1	3	3	1.0760E-06	(0.5323E-06,0.2177E-05)
5	1	4	2	5.4200E-06	(0.1003E-05,0.2929E-04)

[a]Refer to Table X-A for the definition of numerical categories for each factor.

TABLE X-B (cont)

Factors					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
5	1	5	2	2.5100E-06	(0.1042E-05,0.6045E-05)
5	1	6	2	1.1490E-06	(0.4189E-06,0.3150E-05)
5	2	4	2	7.4210E-06	(0.1373E-05,0.4010E-04)
5	2	5	1	2.7100E-06	(0.5015E-06,0.1464E-04)
5	3	2	3	4.0760E-06	(0.2123E-05,0.7829E-05)
5	3	2	4	4.3760E-06	(0.1748E-05,0.1071E-04)
5	3	5	2	3.6500E-06	(0.1816E-05,0.7337E-05)
5	4	2	2	9.1920E-07	(0.2583E-06,0.3271E-05)
5	4	2	3	8.2870E-07	(0.2507E-06,0.2739E-05)
5	5	5	1	2.7930E-06	(0.6304E-06,0.1238E-04)
6	1	3	2	6.5700E-06	(0.2219E-05,0.1945E-04)
6	1	3	3	5.9230E-06	(0.2136E-05,0.1642E-04)

TABLE XI-A

BWR: TIME-DEPENDENT, DEGRADED FAILURES--INTERNAL LEAKAGE (F)

Average Failure-Rate Estimate--3.39 x 10^{-6} (1.07 x 10^{-6})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	VTYPE	1	Angle	13.60	1.42 (0.90)
		2	Butterfly		0.83 (0.26)
		3	Check		0.25 (0.07)
		4	Diaphragm		3.40 (2.38)
		5	Gate		0.77 (0.22)
		6	Globe		1.51 (0.52)
		7	Relief/safety		1.21 (0.52)
		8	Plug		0.72 (0.87)
2	SIZE	1	<2 inches	6.34	2.03 (0.60)
		2	2-10 inches		1.03 (0.25)
		3	10-30 inches		1.51 (0.36)
		4	>30 inches		0.32 (0.14)
3	SYSTEM	1	Containment	5.54	2.55 (0.73)
		2	Nuclear		0.46 (0.15)
		3	Power conversion		0.38 (0.10)
		4	Safety		2.47 (0.72)
		5	Process auxiliary		0.46 (0.12)
		6	Plant auxiliary		1.96 (1.24)
4	OTYPE	1	Air	3.45	1.10 (0.32)
		2	Solenoid		1.22 (0.78)
		3	Motor		0.88 (0.28)
		4	Chain		0.49 (0.24)
		5	Manual		1.69 (1.55)

Note: Values in parentheses are standard deviations.

TABLE XI-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR BWR:
TIME-DEPENDENT, DEGRADED FAILURES--
INTERNAL LEAKAGE (F)

Factors[a]					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
1	1	2	3	1.2010E-05	(0.9686E-05,0.1489E-04)
1	1	2	4	2.5190E-06	(0.8199E-06,0.7738E-05)
1	1	3	3	3.5530E-06	(0.2335E-05,0.5406E-05)
1	3	5	3	8.9490E-06	(0.4816E-05,0.1663E-04)
2	1	2	2	1.4740E-06	(0.7566E-06,0.2873E-05)
2	1	3	1	8.6390E-07	(0.4257E-06,0.1753E-05)
2	1	3	2	4.3610E-07	(0.2281E-06,0.8338E-06)
2	1	5	1	2.7290E-06	(0.1320E-05,0.5642E-05)
2	1	5	2	1.3780E-06	(0.6804E-06,0.2790E-05)
2	3	5	1	2.1760E-06	(0.1086E-05,0.4360E-05)
2	3	5	2	1.0980E-06	(0.5815E-06,0.2075E-05)
2	3	5	3	1.6210E-06	(0.8108E-06,0.3239E-05)
2	5	5	2	2.1100E-06	(0.7624E-06,0.5841E-05)
3	1	3	1	7.0990E-07	(0.3439E-06,0.1465E-05)
3	1	3	2	3.5840E-07	(0.1880E-06,0.6834E-06)
3	1	3	3	5.2880E-07	(0.2915E-06,0.9592E-06)
3	1	6	3	3.2620E-06	(0.1370E-05,0.7767E-05)
3	1	7	2	1.7700E-06	(0.8091E-06,0.3870E-05)
3	1	7	3	2.6110E-06	(0.1201E-05,0.5673E-05)
3	1	8	1	2.0820E-06	(0.6267E-06,0.6917E-05)
3	3	1	2	1.6510E-06	(0.5603E-06,0.4865E-05)
3	3	1	3	2.4360E-06	(0.8267E-06,0.7178E-05)
3	3	5	1	1.7880E-06	(0.9122E-06,0.3505E-05)
3	3	5	2	9.0270E-07	(0.5010E-06,0.1627E-05)
3	3	5	3	1.3320E-06	(0.8497E-06,0.2087E-05)
3	3	6	1	3.4910E-06	(0.1631E-05,0.7474E-05)
3	3	6	2	1.7630E-06	(0.9770E-06,0.3180E-05)
3	5	8	2	1.6100E-06	(0.4846E-06,0.5348E-05)
4	1	3	2	2.3300E-06	(0.1205E-05,0.4506E-05)
4	1	3	3	3.4380E-06	(0.1745E-05,0.6774E-05)
4	1	7	1	2.2790E-05	(0.1428E-04,0.3637E-04)
4	3	5	2	5.8690E-06	(0.3259E-05,0.1057E-04)
4	3	5	3	8.6580E-06	(0.5062E-05,0.1481E-04)
4	3	6	2	1.1460E-05	(0.7319E-05,0.1794E-04)
4	4	5	3	4.8810E-06	(0.1748E-05,0.1363E-04)
5	1	2	2	1.4710E-06	(0.9441E-06,0.2293E-05)
5	1	2	3	2.1710E-06	(0.1242E-05,0.3794E-05)
5	1	3	1	8.6210E-07	(0.4617E-06,0.1610E-05)
5	1	3	2	4.3530E-07	(0.2606E-06,0.7269E-06)
5	1	3	3	6.4210E-07	(0.3499E-06,0.1178E-05)
5	1	4	2	6.0290E-06	(0.1739E-05,0.2090E-04)
5	1	5	2	1.3750E-06	(0.6601E-06,0.2865E-05)

[a] Refer to Table XI-A for the definition of numerical categories for each factor.

TABLE XI-B (cont)

Factors					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
5	1	6	2	2.6850E-06	(0.1213E-05,0.5942E-05)
5	2	4	2	6.6720E-06	(0.1925E-05,0.2313E-04)
5	2	5	1	3.0140E-06	(0.8696E-06,0.1045E-04)
5	3	2	3	1.7310E-06	(0.8074E-06,0.3709E-05)
5	3	2	4	3.6290E-07	(0.1181E-06,0.1115E-05)
5	3	5	2	1.0960E-06	(0.5784E-06,0.2078E-05)
5	4	2	2	6.6130E-07	(0.2562E-06,0.1707E-05)
5	4	2	3	9.7560E-07	(0.3867E-06,0.2461E-05)
5	5	5	1	4.1710E-06	(0.1405E-05,0.1239E-04)
6	1	3	2	1.8460E-06	(0.6265E-06,0.5440E-05)
6	1	3	3	2.7230E-06	(0.9242E-06,0.8025E-05)

TABLE XII-A

BWR: TIME-DEPENDENT, INCIPIENT FAILURES--EXTERNAL LEAKAGE (G)

Average Failure-Rate Estimate--3.30×10^{-6} (1.70×10^{-6})

Size	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	SIZE	1	<2 inches	6.91	1.14 (0.47)
		2	2-10 inches		1.15 (0.40)
		3	10-30 inches		2.28 (0.79)
		4	>30 inches		0.33 (0.21)
2	OTYPE	1	Air	6.45	0.80 (0.39)
		2	Solenoid		1.12 (1.22)
		3	Motor		2.84 (1.31)
		4	Chain		0.44 (0.36)
		5	Manual		0.89 (1.36)
3	VTYPE	1	Angle	5.43	0.69 (0.40)
		2	Butterfly		0.60 (0.34)
		3	Check		0.53 (0.26)
		4	Diaphragm		2.88 (3.33)
		5	Gate		1.04 (0.39)
		6	Globe		2.53 (1.08)
		7	Plug		0.60 (0.97)
4	SYSTEM	1	Containment	2.41	1.47 (0.54)
		2	Nuclear		0.98 (0.39)
		3	Power conversion		0.95 (0.29)
		4	Safety		1.21 (0.50)
		5	Process auxiliary		0.61 (0.28)
		6	Plant auxiliary		0.98 (0.86)

Note: Values in parentheses are standard deviations.

TABLE XII-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR BWR:
TIME-DEPENDENT, INCIPIENT FAILURES--
EXTERNAL LEAKAGE (G)

Factors[a]					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
1	1	2	3	5.3540E-06	(0.1798E-05,0.1595E-04)
1	1	2	4	7.8480E-07	(0.1125E-06,0.5475E-05)
1	1	3	3	4.7170E-06	(0.2655E-05,0.8383E-05)
1	3	5	3	3.2640E-05	(0.1678E-04,0.6346E-04)
2	1	2	2	1.7960E-06	(0.5994E-06,0.5381E-05)
2	1	3	1	1.5720E-06	(0.6846E-06,0.3608E-05)
2	1	3	2	1.5820E-06	(0.7082E-06,0.3535E-05)
2	1	5	1	3.0680E-06	(0.1092E-05,0.8623E-05)
2	1	5	2	3.0890E-06	(0.1236E-05,0.7717E-05)
2	3	5	1	1.0870E-05	(0.5067E-05,0.2333E-04)
2	3	5	2	1.0950E-05	(0.5986E-05,0.2002E-04)
2	3	5	3	2.1780E-05	(0.1045E-04,0.4539E-04)
2	5	5	2	3.4270E-06	(0.6236E-06,0.1884E-04)
3	1	3	1	1.5290E-06	(0.6834E-06,0.3420E-05)
3	1	3	2	1.5390E-06	(0.6847E-06,0.3460E-05)
3	1	3	3	3.0620E-06	(0.1506E-05,0.6228E-05)
3	1	6	3	1.4540E-05	(0.5529E-05,0.3826E-04)
3	1	7	1	1.7320E-06	(0.2221E-06,0.1351E-04)
3	3	1	2	7.0340E-06	(0.2795E-05,0.1770E-04)
3	3	1	3	1.3990E-05	(0.5824E-05,0.3362E-04)
3	3	5	1	1.0580E-05	(0.5650E-05,0.1980E-04)
3	3	5	2	1.0650E-05	(0.6613E-05,0.1715E-04)
3	3	5	3	2.1190E-05	(0.1624E-04,0.2764E-04)
3	3	6	1	2.5730E-05	(0.1430E-04,0.4631E-04)
3	3	6	2	2.5910E-05	(0.1509E-04,0.4449E-04)
3	5	7	2	1.9350E-06	(0.2481E-06,0.1509E-04)
4	1	3	2	1.9590E-06	(0.8080E-06,0.4749E-05)
4	1	3	3	3.8970E-06	(0.1615E-05,0.9401E-05)
4	3	5	2	1.3550E-05	(0.6660E-05,0.2757E-04)
4	3	5	3	2.6960E-05	(0.1337E-04,0.5436E-04)
4	3	6	2	3.2970E-05	(0.2066E-04,0.5261E-04)
4	4	5	3	4.1620E-06	(0.7791E-06,0.2224E-04)
5	1	2	2	1.1270E-06	(0.5582E-06,0.2276E-05)
5	1	2	3	2.2420E-06	(0.1036E-05,0.4854E-05)
5	1	3	1	9.8640E-07	(0.4068E-06,0.2392E-05)
5	1	3	2	9.9310E-07	(0.4027E-06,0.2449E-05)
5	1	3	3	1.9760E-06	(0.7771E-06,0.5023E-05)
5	1	4	2	5.3710E-06	(0.6295E-06,0.4582E-04)
5	1	5	2	1.9390E-06	(0.6440E-06,0.5838E-05)
5	1	6	2	4.7170E-06	(0.1491E-05,0.1492E-04)

[a]Refer to Table XII-A for the definition of numerical categories for each factor.

TABLE XII-B (cont)

Factors					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
5	2	4	2	7.4890E-06	(0.8777E-06,0.6390E-04)
5	2	5	1	2.6850E-06	(0.3147E-06,0.2291E-04)
5	3	2	3	7.9460E-06	(0.2982E-05,0.2117E-04)
5	3	2	4	1.1650E-06	(0.1670E-06,0.8126E-05)
5	3	5	2	6.8710E-06	(0.2768E-05,0.1705E-04)
5	4	2	2	6.1670E-07	(0.1287E-06,0.2954E-05)
5	4	2	3	1.2270E-06	(0.2600E-06,0.5789E-05)
5	5	5	1	2.1370E-06	(0.3627E-06,0.1259E-04)
6	1	3	2	1.5900E-06	(0.2518E-06,0.1004E-04)
6	1	3	3	3.1630E-06	(0.5009E-06,0.1997E-04)

other failure modes, categories of three of the four factors--OTYPE, VTYPE, and SIZE--have multipliers greater than 2.2. Two of the factors (namely, OTYPE and SIZE) have category multipliers less than 0.5.

Of the three factors with category multipliers greater than 2.2, VTYPE has two such categories. Diaphragm valves have a failure rate nearly three times that of the average, and globe valves have a failure rate that is roughly 2.5 times as large as the average. There are no valve types with failure rates less than half the average failure rate.

Two additional categories have much larger than average failure rates. Ten- to thirty-inch valves have failure rates 2.28 times the average, and motor-driven valves have a multiplier of 2.84. Other than these categories, there are no others with a failure rate more than twice as large as the average.

Valves that are greater than 30 inches are the most reliable, with a multiplier of 0.33. Also, chain-operated valves have a failure rate that is less than half the average. All other valve categories for this failure mode have multipliers greater than 0.5.

<u>4.2.5 BWR: Time-Dependent, Incipient Failures--Faulty Indication (H)</u>. Of the four factors considered in the analysis for this failure mode, only SIZE does not greatly influence the failure rate. From the table of multipliers, Table XIII-A, the ratio R_j is greater than eight for the other three factors, and each of these factors has categories with both large and small multipliers.

Two of the largest multipliers are found in the factor SYSTEM. Valves in containment and process auxiliary systems have multipliers of 3.07 and 2.58, respectively. Valves in nuclear systems on the other hand are very reliable, with failure rates less than one-third the average failure rate.

Air-operated valves are nearly three times as unreliable as the "average" valve, whereas chain-operated valves have failure rates about one-third that of the average valve.

Plug valves are the most unreliable, with a multiplier of 3.12. Relief/safety valves have a multiplier of 0.33 and are the most reliable type of valve in this BWR.

Table XIII-B contains the best estimates and 90% confidence intervals for this category of valve failures.

TABLE XIII-A

BWR: TIME-DEPENDENT, INCIPIENT FAILURES--FAULTY INDICATION (H)

Average Failure-Rate Estimate--1.76×10^{-6} (8.85×10^{-7})

Rank	Factor	Category	Description	R_j	Failure-Rate Adjustment
1	SYSTEM	1	Containment	10.96	3.07 (1.28)
		2	Nuclear		0.28 (0.17)
		3	Power conversion		0.93 (0.49)
		4	Safety		0.76 (0.50)
		5	Process auxiliary		2.58 (1.00)
		6	Plant auxiliary		0.63 (0.73)
2	VTYPE	1	Angle	9.45	1.11 (1.33)
		2	Butterfly		1.38 (0.69)
		3	Check		0.68 (0.34)
		4	Diaphragm		0.78 (1.02)
		5	Gate		1.42 (0.76)
		6	Globe		0.84 (0.58)
		7	Relief/safety		0.33 (0.27)
		8	Plug		3.12 (7.05)
3	OTYPE	1	Air	8.11	2.92 (1.41)
		2	Solenoid		0.74 (0.90)
		3	Motor		1.08 (0.58)
		4	Chain		0.36 (0.33)
		5	Manual		1.20 (2.02)
4	SIZE	1	<2 inches	1.81	1.32 (0.54)
		2	2-10 inches		1.22 (0.30)
		3	10-30 inches		0.86 (0.20)
		4	>30 inches		0.73 (0.39)

Note: Values in parentheses are standard deviations.

TABLE XIII-B

BEST ESTIMATES AND 90% CONFIDENCE INTERVALS FOR BWR:
TIME-DEPENDENT, INCIPIENT FAILURES--
FAULTY INDICATION (H)

Factors[a]					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
1	1	2	3	1.8840E-05	(0.1274E-04,0.2785E-04)
1	1	2	4	1.5960E-05	(0.7421E-05,0.3432E-04)
1	1	3	3	9.2420E-06	(0.5862E-05,0.1457E-04)
1	3	5	3	7.1110E-06	(0.2431E-05,0.2081E-04)
2	1	2	2	2.4640E-06	(0.7684E-06,0.7904E-05)
2	1	3	1	1.3070E-06	(0.3349E-06,0.5101E-05)
2	1	3	2	1.2090E-06	(0.3769E-06,0.3880E-05)
2	1	5	1	2.7380E-06	(0.7990E-06,0.9381E-05)
2	1	5	2	2.5330E-06	(0.7127E-06,0.9000E-05)
2	3	5	1	1.0060E-06	(0.2974E-06,0.3402E-05)
2	3	5	2	9.3040E-07	(0.2839E-06,0.3049E-05)
2	3	5	3	6.5270E-07	(0.1928E-06,0.2209E-05)
2	5	5	2	1.0350E-06	(0.2419E-06,0.4429E-05)
3	1	3	1	4.3060E-06	(0.1256E-05,0.1477E-04)
3	1	3	2	3.9840E-06	(0.1323E-05,0.1200E-04)
3	1	3	3	2.7950E-06	(0.8908E-06,0.8768E-05)
3	1	6	3	3.4510E-06	(0.7747E-06,0.1537E-04)
3	1	7	2	1.9450E-06	(0.5044E-06,0.7500E-05)
3	1	7	3	1.3640E-06	(0.3339E-06,0.5576E-05)
3	1	8	1	1.9800E-05	(0.1016E-04,0.3859E-04)
3	3	1	2	2.3940E-06	(0.3000E-06,0.1911E-04)
3	3	1	3	1.6800E-06	(0.2105E-06,0.1341E-04)
3	3	5	1	3.3140E-06	(0.1347E-05,0.8152E-05)
3	3	5	2	3.0650E-06	(0.1171E-05,0.8027E-05)
3	3	5	3	2.1500E-06	(0.8243E-06,0.5610E-05)
3	3	6	1	1.9530E-06	(0.5040E-06,0.7571E-05)
3	3	6	2	1.8070E-06	(0.5599E-06,0.5832E-05)
3	5	8	2	7.4860E-06	(0.1882E-05,0.2977E-04)
4	1	3	2	3.2730E-06	(0.8608E-06,0.1245E-04)
4	1	3	3	2.2960E-06	(0.5910E-06,0.8921E-05)
4	1	7	1	1.7280E-06	(0.2710E-06,0.1101E-04)
4	3	5	2	2.5190E-06	(0.6759E-06,0.9386E-05)
4	3	5	3	1.7670E-06	(0.4817E-06,0.6481E-05)
4	3	6	2	1.4850E-06	(0.3056E-06,0.7214E-05)
4	4	5	3	5.8940E-07	(0.8288E-07,0.4191E-05)
5	1	2	2	2.2520E-05	(0.1702E-04,0.2981E-04)
5	1	2	3	1.5800E-05	(0.9408E-05,0.2653E-04)
5	1	3	1	1.1950E-05	(0.4647E-05,0.3070E-04)
5	1	3	2	1.1050E-05	(0.5968E-05,0.2046E-04)
5	1	3	3	7.7520E-06	(0.3760E-05,0.1598E-04)
5	1	4	2	1.2630E-05	(0.1136E-05,0.1404E-03)

[a] Refer to Table XIII-A for the definition of numerical categories for each factor.

TABLE XIII-B (cont)

Factors					
SYSTEM	OTYPE	VTYPE	SIZE	Estimate	90% Confidence Interval
5	1	5	2	2.3140E-05	(0.6918E-05,0.7744E-04)
5	1	6	2	1.3640E-05	(0.3126E-05,0.5956E-04)
5	2	4	2	3.1860E-06	(0.2865E-06,0.3542E-04)
5	2	5	1	6.3130E-06	(0.5678E-06,0.7019E-04)
5	3	2	3	5.8040E-06	(0.2132E-05,0.1580E-04)
5	3	2	4	4.9170E-06	(0.1872E-05,0.1292E-04)
5	3	5	2	8.5030E-06	(0.2867E-05,0.2521E-04)
5	4	2	2	2.7600E-06	(0.4606E-06,0.1654E-04)
5	4	2	3	1.9360E-06	(0.3318E-06,0.1130E-04)
5	5	5	1	1.0220E-05	(0.2526E-05,0.4138E-04)
6	1	3	2	2.6770E-06	(0.3354E-06,0.2137E-04)
6	1	3	3	1.8780E-06	(0.2353E-06,0.1499E-04)

5. DISCUSSION AND PRELIMINARY COMPARISONS WITH OTHER ESTIMATES

It is interesting and informative to compare the FRAC valve failure-rate estimates with some estimates from other sources. However, such a comparison must be considered preliminary for several reasons. First, each individual valve is assumed to be demanded an average of once per month, the same value considered in the initial IPRDS interim report on the valve component.[2] This estimate is applied to all valves in all plant systems and may differ from the actual number of demands for any particular valve. Second, various degrees of aggregation are represented in each of the estimates being compared, and as a consequence, the estimates may not in fact be precisely estimating the same failure rate. The FRAC estimates are more specialized estimates because they reflect the effect of various intrinsic valve characteristics, as well as environmental and operating conditions, on the failure rate. Many of these effects are "averaged over" in other estimates, and as a result, most other estimates are rather general. Third, the FRAC estimates are based on the preliminary valve data currently in the IPRDS. The IPRDS valve data are based on a pilot study using only two units for which the number of reactor-years of commercial operation is relatively small. Consequently, in many cases there are relatively few valve failures at the level of resolution required for a full-scale FRAC analysis. The failure rates and multipliers in this report must therefore be considered as preliminary values. As more IPRDS valve data are collected, the FRAC multiplicative adjustments are likely to change, especially as valve failure data from other plants are placed in the data base. Finally, the maintenance policies of the two plants considered here may not be representative of the overall population of commercial nuclear power plants in the U.S. Consequently, the FRAC valve failure-rate estimates and multiplicative adjustments presented here may or may not be applicable to the general population of nuclear valve components.

The catastrophic, demand-related valve data are used for comparing the various estimates. Table XIV presents the FRAC estimates, along with the WASH-1400,[4] LER,[5] and Institute of the Electrical and Electronics Engineers (IEEE) Std 500 (Ref. 6) estimates, for four types of valve operators for both PWR and BWR reactors. The "lower" and "upper" values in Table XIV are the lower and upper bounds, respectively, of an approximate 90% confidence interval estimate for

TABLE XIV

A PRELIMINARY COMPARISON OF SOME PRELIMINARY PWR AND BWR CATASTROPHIC VALVE DEMAND-RELATED FAILURE-RATE ESTIMATES (per 10^3 d)

		FRAC						WASH-1400		
		PWR[a]			BWR[b]					
Valve Operator	Failure Mode	Lower	Est	Upper	Lower	Est	Upper	Lower	Est	Upper
Motor	Failure to Operate	2.4	4.9[c]	10.2	0.52	1.1[d]	2.5	0.3	1.0	3.0
Solenoid	Failure to Operate	0.21	1.1[c]	5.9	0.53	2.3[e]	10.1	0.3	1.0	3.0
Air	Failure to Operate	0.80	1.7[c]	3.4	0.59	1.4[d]	3.4	0.1	0.3	1.0
Manual	Failure to Operate	0.75	1.9[f]	4.7	0.60	2.1[e]	7.6	0.03	0.1	0.3

		LER						IEEE Std 500-1984[g]					
		PWR			BWR			PWR			BWR		
Valve Operator	Failure Mode	Lower	Est	Upper	Lower	Est	Upper	Lower	Est	Upper	Lower	Est	Upper
Motor	Failure to Operate	2.2	2.8	3.6	4.8	5.7	6.8	-	4.0	-	-	8.0	-
Solenoid	Failure to Operate	-	-	-	-	-	-	-	-	-	-	-	-
Air	Failure to Operate	0.2	0.9	2.3	-	-	2.5	-	2.0	-	-	3.0	-
Manual	Failure to Operate	0.01	0.08	0.2	.005	0.1	0.5	-	0.07	-	-	0.06	-

[a] globe valves in nuclear systems

[b] gate valves in process auxiliary systems

[c] normally open 2- to 10-inch valves

[d] 2- to 10-inch valves

[e] <2-inch valves

[f] normally closed 2- to 10-inch valves

[g] based primarily on LER data

the corresponding unknown failure rate. It is observed that the FRAC PWR estimates are also universally larger than the corresponding WASH-1400, LER, or IEEE estimates. For PWR motor-operated valves, the FRAC estimate is roughly a factor of five larger than the WASH-1400 estimate, a factor of two larger than the LER estimate, and roughly equivalent to the IEEE estimate. However, the corresponding estimate of the FRAC 90% confidence interval is roughly half as wide as the WASH-1400 interval and roughly two to three times as wide as the LER interval.

On the other hand, the FRAC BWR motor-operated valve failure-rate estimate agrees quite closely with the WASH-1400 estimate. However, it is roughly five times smaller than the corresponding LER estimate and almost seven times smaller than the IEEE estimate.

Table XV compares the FRAC and simple single-cell estimates (Ref. 2, Sec. 3). The single-cell estimates are based on the data in Tables A-I and A-IV. The comparison considers valve catastrophic failure to operate per 10^3 demands for both the PWR and BWR and for four types of valve operators. For PWR motor-operated valves, the FRAC estimate is slightly larger than the corresponding single-cell estimate. This difference is the result of considering additional failure data for the other valves in the PWR by means of the FRAC regression procedure. Now consider the estimate for the 90% confidence interval. The FRAC estimate is $(2.4 \times 10^{-3}, 10.2 \times 10^{-3})$, and the corresponding single-cell estimate is $(0.21 \times 10^{-3}, 19.8 \times 10^{-3})$. The FRAC interval is roughly 22 times narrower than the single-cell interval. This reduction in uncertainty is also the result of the pooled utilization of all the demand-related catastrophic valve failure data by means of the FRAC procedure. Similarly, reductions in uncertainty are apparent in Table XV in all other cases as well.

Figure 1 illustrates the preliminary FRAC, IPRDS (Ref. 2, pp. 44-45), and single-cell estimates of the valve catastrophic frequency of failure to operate per 10^3 demands for 2- to 10-inch pneumatically operated valves in the BWR process auxiliary system. The corresponding WASH-1400 median and uncertainty bounds are also shown in Fig. 1. The single-cell estimates utilize only the data in the single cell that represent the desired characteristics of the given valve. Thus, there is little data aggregation in their computation. On the other hand, the IPRDS (Ref. 2, pp. 44-45) estimates in Fig. 1 are computed from data aggregated over all BWR systems, sizes of valves, and valve operators.

TABLE XV

A PRELIMINARY COMPARISON OF FRAC AND SINGLE-CELL ESTIMATES OF VALVE CATASTROPHIC FAILURE TO OPERATE PER 10^3 DEMANDS

		FRAC						Single-Cell					
		PWR[a]			BWR[b]			PWR[a]			BWR[b]		
Valve Operator	Failure Mode	Lower	Est	Upper	Lower	Est	Upper	Lower	Est	Upper	Lower	Est	Upper
Motor	Failure to Operate	2.4	4.9[c]	10.2	0.52	1.1[d]	2.5	0.21	4.2[e]	19.8	-	1.1[f]	13.9
Solenoid	Failure to Operate	0.21	1.1[c]	5.9	0.53	2.3[g]	10.1	-	1.9[h]	25.0	-	1.6[i]	20.8
Air	Failure to Operate	0.80	1.7[c]	3.4	0.59	1.4[d]	3.4	-	3.8[j]	49.9	-	3.2[k]	41.6
Manual	Failure to Operate	0.75	1.9[l]	4.7	0.60	2.1[g]	7.6	-	1.9[m]	25.0	-	1.1[n]	13.9

[a] globe valves in nuclear systems
[b] gate valves in process auxiliary systems
[c] normally open 2- to 10-in. valves
[d] 2- to 10-in. valves
[e] 1 failure in 240 demands; normally open 2- to 10-in. valves
[f] 0 failures in 216 demands; 2- to 10-in. valves
[g] <2-in. valves
[h] 0 failures in 120 demands
[i] 0 failures in 144 demands; <2-in. valves
[j] 0 failures in 60 demands; normally open 2- to 10-in. valves
[k] 0 failures in 72 demands; 2- to 10-in. valves
[l] normally closed 2- to 10-in. valves
[m] 0 failures in 120 demands; normally closed 2- to 10-in. valves
[n] 0 failures in 216 demands; <2-in. valves

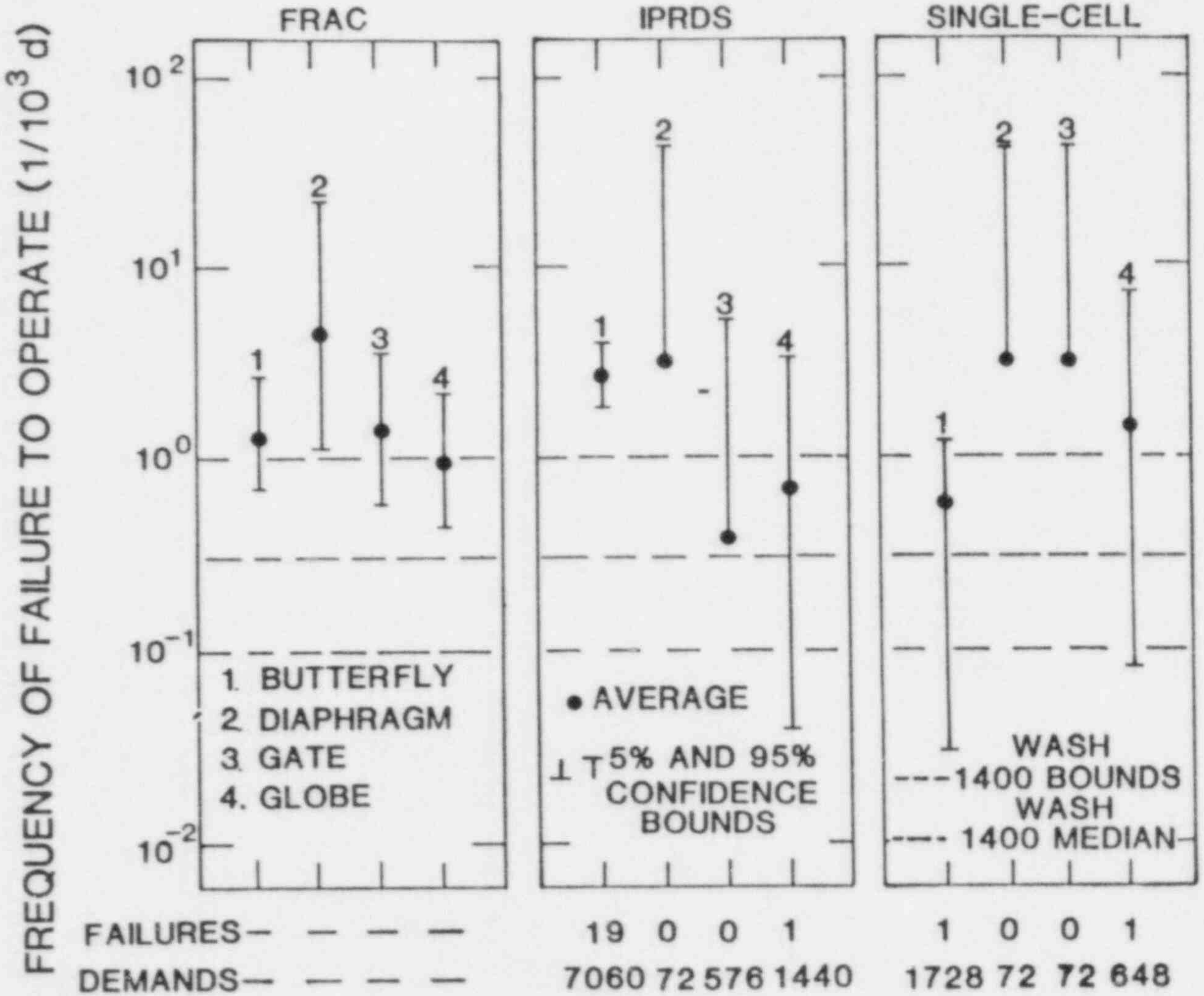

Fig. 1. A preliminary comparison of the Failure Rate Analysis Code (FRAC), the In-plant Reliability Data Systems (IPRDS), and the single-cell system estimates of BWR valve catastrophic frequency of failure to operate per 10^3 demands for process auxiliary system 2- to 10-inch pneumatic valves.

Thus, there is significant data aggregation, as evidenced by the large number of demands for the IPRDS estimates given at the bottom of Fig. 1.

It is interesting to observe that the FRAC point estimates in Fig. 1 fall generally between the corresponding single-cell and IPRDS estimates, the aggregation extremes present in Fig. 1. The FRAC estimates also represent aggregated data; however, the aggregation is controlled by means of the factors present in the FRAC regression model (namely, valve type, size, system, and operator). It may be that such controlled aggregation (that is, accounting for effects of valve type, size, system, and operator on the valve failure rate using the FRAC regression model) yields estimates that are less extreme than those produced by methods based on either no aggregation or virtually complete aggregation. Also, there is less variability between the four FRAC point estimates in Fig. 1 than between the point estimates for either of the other two procedures. Again, this is the result of the use of a regression approach for failure-rate estimation.

Finally, the 90% confidence intervals for the FRAC procedure agree quite nicely with the WASH-1400 bounds; however, it appears for the given BWR situation depicted in Fig. 1 that the WASH-1400 distribution is located somewhat too low. That is, although the spread of the WASH-1400 distribution may be satisfactory, the entire distribution may be centered over a range of values that is too small to satisfactorily describe the historical valve failure data of the specified type for the given BWR.

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APPENDIX

PWR AND BWR VALVE-FAILURE DATA

This Appendix contains tables of the raw data used in the analyses of the PWR and BWR power plants.

TABLE A-I

PWR VALVE FAILURE DATA FOR ALL FAILURE MODES

FACTORS SYSTEM[a]	OTYPE[b]	VTYPE[c]	SIZE[d]	OPMODE[e]	DEGRADED E	F	INCIPIENT G	H	CATASTROPHIC A	TIME	DEMAND
1	3	4	3	1	2	0	1	2	0	175200.0	240.0
1	3	4	3	2	2	2	2	0	1	175200.0	240.0
1	3	5	1	1	1	0	2	0	2	87600.0	120.0
2	1	2	2	2	0	0	0	1	0	87600.0	120.0
2	1	3	2	1	0	1	3	0	0	87600.0	120.0
2	1	3	2	2	0	0	0	0	0	43800.0	60.0
2	1	5	1	1	2	1	5	2	0	175200.0	240.0
2	1	5	1	2	4	4	6	1	0	262800.0	360.0
2	1	5	2	1	1	0	6	0	0	43800.0	60.0
2	1	5	2	2	2	0	9	0	0	43800.0	60.0
2	2	5	2	2	3	0	0	0	0	87600.0	120.0
2	3	4	2	1	0	0	1	0	2	87600.0	120.0
2	3	4	2	2	0	0	3	0	0	175200.0	240.0
2	3	4	3	1	0	0	5	1	1	131400.0	180.0
2	3	4	3	2	0	0	1	0	0	43800.0	60.0
2	3	5	1	1	1	0	0	0	0	87600.0	120.0
2	3	5	2	2	0	0	0	2	1	175200.0	240.0
2	3	5	3	2	0	0	0	0	0	87600.0	120.0
2	4	3	1	2	0	0	0	0	0	43800.0	60.0
2	4	3	2	1	0	0	0	0	0	43800.0	60.0
2	4	4	1	1	2	0	0	0	0	43800.0	60.0
2	4	5	2	1	0	0	0	0	0	87600.0	120.0
3	1	1	2	1	1	1	3	3	0	1576800.0	2160.0
3	1	1	2	2	2	0	0	0	0	175200.0	240.0
3	1	1	3	2	0	1	0	0	0	87600.0	120.0
3	1	2	2	1	0	0	0	0	0	87600.0	120.0
3	1	2	3	1	3	5	1	0	0	350400.0	480.0
3	1	3	2	1	1	1	1	0	0	657000.0	900.0
3	1	3	2	2	0	0	1	0	0	175200.0	240.0
3	1	4	1	1	0	0	0	0	0	43800.0	60.0
3	1	4	1	2	0	0	0	0	0	87600.0	120.0
3	1	4	2	1	5	5	8	2	3	481800.0	660.0
3	1	4	2	2	23	3	17	2	0	262800.0	360.0
3	1	4	3	2	21	0	18	4	0	175200.0	240.0
3	1	5	1	1	0	0	0	0	0	175200.0	240.0
3	1	5	1	2	0	0	0	0	5	175200.0	240.0
3	1	5	2	1	11	7	6	9	11	1357800.0	1860.0
3	1	5	2	2	3	4	7	5	1	1357800.0	1860.0
3	1	5	3	2	2	0	0	2	0	43800.0	60.0
3	1	6	2	1	1	0	0	0	0	87600.0	120.0
3	1	6	2	2	0	0	0	0	0	43800.0	60.0
3	1	6	3	2	0	0	0	0	0	43800.0	60.0
3	2	6	2	2	1	1	0	0	0	87600.0	120.0
3	3	2	2	1	0	0	0	0	2	43800.0	60.0
3	3	2	3	2	0	0	0	0	1	43800.0	60.0
3	3	4	1	1	0	4	1	0	2	306600.0	420.0
3	3	4	1	2	0	0	0	0	23	175200.0	240.0
3	3	4	2	1	8	0	0	0	1	350400.0	480.0
3	3	4	2	2	0	0	0	0	1	131400.0	180.0
3	3	4	3	1	13	0	3	1	8	87600.0	120.0
3	3	4	3	2	3	0	2	0	2	131400.0	180.0
3	3	5	1	2	0	0	4	1	4	131400.0	180.0
3	3	5	2	2	0	0	6	1	4	219000.0	300.0
3	4	4	2	2	1	0	0	0	0	175200.0	240.0
3	4	4	3	2	1	0	8	0	1	438000.0	600.0
3	4	5	2	2	0	0	0	0	2	175200.0	240.0
4	3	3	3	2	2	0	4	2	1	43800.0	60.0
4	3	4	2	1	2	0	18	3	5	350400.0	480.0
4	3	4	2	2	0	0	0	0	2	175200.0	240.0
4	3	4	3	2	7	0	20	0	0	131400.0	180.0
4	3	5	1	2	0	0	0	0	1	43800.0	60.0
5	1	2	2	1	0	0	5	2	0	131400.0	180.0

[a] 1 - containment, 2 - nuclear, 3 - power conversion, 4 - safety, 5 - process auxiliary
[b] 1 - air, 2 - solenoid, 3 - motor drive, 4 - manual
[c] 1 - ball, 2 - butterfly, 3 - diaphragm, 4 - gate, 5 - globe, 6 - directional control
[d] 1 - ≤2 inches, 2 - 2 < size < 10 inches, 3 - 10 < size < 30 inches
[e] 1 - normally closed, 2 - normally open

TABLE A-I (cont)

FACTORS					DEGRADED		INCIPIENT		CATASTROPHIC		
SYSTEM[a]	OTYPE[b]	VTYPE[c]	SIZE[d]	OPMODE[e]	E	F	G	H	A	TIME	DEMAND
5	1	2	2	2	0	0	0	0	1	87600.0	120.0
5	1	2	3	1	0	0	0	0	0	43800.0	60.0
5	1	2	3	2	0	0	5	0	1	219000.0	300.0
5	1	3	1	1	0	0	0	0	0	43800.0	60.0
5	1	3	1	2	0	0	0	0	0	131400.0	180.0
5	1	3	2	2	0	1	0	1	0	87600.0	120.0
5	1	4	2	1	3	1	8	1	2	175200.0	240.0
5	1	4	2	2	0	3	0	0	1	175200.0	240.0
5	1	5	1	1	3	2	0	0	1	43800.0	60.0
5	1	5	1	2	2	1	0	1	0	131400.0	180.0
5	1	5	2	2	0	0	0	0	0	350400.0	480.0
5	1	6	1	1	0	0	0	0	0	43800.0	60.0
5	1	6	2	2	0	0	1	0	0	87600.0	120.0
5	2	3	2	2	0	0	0	0	0	481800.0	660.0
5	2	4	1	1	0	0	0	0	0	43800.0	60.0
5	3	2	2	1	0	0	0	0	0	43800.0	60.0
5	3	2	2	2	0	0	1	0	0	87600.0	120.0
5	3	2	3	1	2	0	0	0	0	175200.0	240.0
5	3	2	3	2	0	0	0	0	0	87600.0	120.0
5	3	4	2	1	2	4	0	0	1	219000.0	300.0
5	3	4	2	2	1	0	1	0	1	613200.0	840.0
5	3	5	2	2	0	0	0	0	0	87600.0	120.0
5	4	3	1	1	1	0	0	0	0	219000.0	300.0
5	4	3	1	2	0	0	0	0	1	87600.0	120.0
5	4	3	2	1	0	0	0	0	0	131400.0	180.0
5	4	4	1	2	0	0	0	0	0	43800.0	60.0
5	4	4	2	1	0	0	0	0	0	43800.0	60.0
5	4	5	2	2	0	0	0	0	0	43800.0	60.0

TABLE A-II

BWR VALVE FAILURE DATA FOR FAILURE MODES E, F, AND H

FACTORS				DEGRADED		INCIPIENT	
SYSTEM[a]	OTYPE[b]	VTYPE[c]	SIZE[d]	E	F	H	TIME
1	1	2	3	12	15	16	1208880.0
1	1	2	4	3	0	4	210240.0
1	1	3	3	4	3	12	840960.0
1	3	5	3	1	0	0	105120.0
2	1	2	2	0	0	0	525600.0
2	1	3	1	0	0	0	157680.0
2	1	3	2	0	0	0	473040.0
2	1	5	1	0	0	0	105120.0
2	1	5	2	0	0	0	157680.0
2	3	5	1	0	0	0	210240.0
2	3	5	2	0	0	0	262800.0
2	3	5	3	0	0	0	525600.0
2	5	5	2	0	0	0	157680.0
3	1	3	1	0	0	0	315360.0
3	1	3	2	1	0	0	262800.0
3	1	3	3	1	0	0	630720.0
3	1	6	3	0	0	0	105120.0
3	1	7	2	0	0	1	578160.0
3	1	7	3	0	0	0	315360.0
3	1	8	1	0	0	6	315360.0
3	3	1	2	0	0	0	262800.0
3	3	1	3	0	0	0	105120.0
3	3	5	1	0	0	2	210240.0
3	3	5	2	0	0	0	578160.0
3	3	5	3	4	2	1	1156320.0
3	3	6	1	0	0	0	157680.0
3	3	6	2	0	0	1	210240.0
3	5	8	2	0	0	1	105120.0
4	1	3	2	0	0	0	893520.0
4	1	3	3	0	0	0	315360.0
4	1	7	1	0	3	0	105120.0
4	3	5	2	8	0	0	262800.0
4	3	5	3	1	1	0	105120.0
4	3	6	2	2	3	0	210240.0
4	4	5	3	0	0	0	52560.0
5	1	2	2	4	2	33	1261440.0

[a] 1 - containment, 2 - nuclear, 3 - power conversion, 4 - safety, 5 - process auxiliary, 6 - plant auxiliary

[b] 1 - air, 2 - solenoid, 3 - motor driven, 4 - chain, 5 - manual

[c] 1 - angle, 2 - butterfly, 3 - check, 4 - diaphragm, 5 - gate, 6 - globe, 7 - relief/safety, 8 - plug

[d] 1 - $\leq$ 2 inches, 2 - 2 $<$ size $<$ 10 inches, 3 - 10 $\leq$ size $<$ 30 inches, 4 - $\leq$ 30 inches

TABLE A-II (cont)

FACTORS				DEGRADED		INCIPIENT	
SYSTEM[a]	OTYPE[b]	VTYPE[c]	SIZE[d]	E	F	H	TIME
5	1	2	3	0	0	7	315360.0
5	1	3	1	0	0	0	1314000.0
5	1	3	2	0	0	0	788400.0
5	1	3	3	0	0	0	157680.0
5	1	4	2	0	0	0	52560.0
5	1	5	2	0	0	0	52560.0
5	1	6	2	0	0	0	473040.0
5	2	4	2	0	0	0	52560.0
5	2	5	1	0	0	0	105120.0
5	3	2	3	2	0	0	210240.0
5	3	2	4	0	0	2	578160.0
5	3	5	2	0	0	0	157680.0
5	4	2	2	0	0	0	473040.0
5	4	2	3	0	0	0	473040.0
5	5	5	1	0	0	1	157680.0
6	1	3	2	0	0	0	210240.0
6	1	3	3	1	0	0	105120.0

TABLE A-III

BWR VALVE FAILURE DATA FOR FAILURE MODE G

FACTORS				INCIPIENT	
SYSTEM[a]	OTYPE[b]	VTYPE[c]	SIZE[d]	G	TIME
1	1	2	3	0	1208880.0
1	1	2	4	0	210240.0
1	1	3	3	5	840960.0
1	3	5	3	3	105120.0
2	1	2	2	0	525600.0
2	1	3	1	1	157680.0
2	1	3	2	0	473040.0
2	1	5	1	0	105120.0
2	1	5	2	0	157680.0
2	3	5	1	0	210240.0
2	3	5	2	4	262800.0
2	3	5	3	0	525600.0
2	5	5	2	0	157680.0
3	1	3	1	0	315360.0
3	1	3	2	0	262800.0
3	1	3	3	0	630720.0
3	1	6	3	1	105120.0
3	1	7	1	0	315360.0
3	3	1	2	1	262800.0
3	3	1	3	2	105120.0
3	3	5	1	2	210240.0
3	3	5	2	5	578160.0
3	3	5	3	28	1156320.0
3	3	6	1	4	157680.0
3	3	6	2	4	210240.0
3	5	7	2	0	105120.0
4	1	3	2	0	893520.0
4	1	3	3	0	315360.0
4	3	5	2	0	262800.0
4	3	5	3	0	105120.0
4	3	6	2	9	210240.0
4	4	5	3	0	52560.0
5	1	2	2	3	1261440.0
5	1	2	3	0	315360.0
5	1	3	1	1	1314000.0
5	1	3	2	0	788400.0

[a] 1 - containment, 2 - nuclear, 3 - power conversion, 4 - safety, 5 - process auxiliary, 6 - plant auxiliary

[b] 1 - air, 2 - solenoid, 3 - motor driven, 4 - chain, 5 - manual

[c] 1 - angle, 2 - butterfly, 3 - check, 4 - diaphragm, 5 - gate, 6 - globe, 7 - plug

[d] 1 - $\leq$ 2 inches, 2 - 2 $<$ size $<$ 10 inches, 3 - 10 $\leq$ size $<$ 30 inches, 4 - $\geq$ 30 inches

TABLE A-III (cont)

FACTORS				INCIPIENT	
SYSTEM[a]	OTYPE[b]	VTYPE[c]	SIZE[d]	G	TIME
5	1	3	3	0	157680.0
5	1	4	2	0	52560.0
5	1	5	2	0	52560.0
5	1	6	2	0	473040.0
5	2	4	2	0	52560.0
5	2	5	1	0	105120.0
5	3	2	3	1	210240.0
5	3	2	4	0	578160.0
5	3	5	2	0	157680.0
5	4	2	2	0	473040.0
5	4	2	3	0	473040.0
5	5	5	1	0	157680.0
6	1	3	2	0	210240.0
6	1	3	3	0	105120.0

TABLE A-IV

BWR VALVE FAILURE DATA FOR DEMAND-RELATED CATASTROPHIC FAILURES

FACTORS				CATASTROPHIC	
SYSTEM[a]	OTYPE[b]	VTYPE[c]	SIZE[d]	A	DEMAND
1	1	2	3	1	1656.0
1	1	2	4	0	288.0
1	3	5	3	0	144.0
2	1	2	2	3	720.0
2	1	5	1	0	144.0
2	1	5	2	0	216.0
2	3	5	1	0	288.0
2	3	5	2	1	360.0
2	3	5	3	0	720.0
2	5	5	2	0	216.0
3	1	3	1	0	432.0
3	1	6	3	0	144.0
3	1	7	2	0	792.0
3	1	7	3	0	432.0
3	3	1	2	1	360.0
3	3	1	3	0	144.0
3	3	5	1	2	288.0
3	3	5	2	0	792.0
3	3	5	3	4	1584.0
3	3	6	1	0	216.0
3	3	6	2	0	288.0
3	5	3	2	0	144.0
4	1	7	1	0	144.0
4	3	5	2	0	360.0
4	3	5	3	0	144.0
4	3	6	2	0	288.0
4	4	5	3	0	72.0
5	1	2	2	1	1728.0
5	1	2	3	0	432.0
5	1	4	2	0	72.0
5	1	5	2	0	72.0
5	1	6	2	1	648.0
5	2	4	2	0	72.0
5	2	5	1	0	144.0
5	3	2	3	0	288.0
5	3	2	4	6	792.0

[a] 1 - containment, 2 - nuclear, 3 - power conversion, 4 - safety, 5 - process auxiliary

[b] 1 - air, 2 - solenoid, 3 - motor driven, 4 - chain, 5 - manual

[c] 1 - angle, 2 - butterfly, 3 - plug, 4 - diaphragm, 5 - gate, 6 - globe, 7 - relief/safety

[d] 1 - ≤2 inches, 2 - 2 < size < 10 inches, 3 - 10 ≤ size < 30 inches, 4 - ≥ 30 inches

TABLE A-IV (cont)

FACTORS				CATASTROPHIC	
SYSTEM[a]	OTYPE[b]	VTYPE[c]	SIZE[d]	A	DEMAND
5	3	5	2	0	216.0
5	4	2	2	0	648.0
5	4	2	3	0	648.0
5	5	5	1	0	216.0

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NRCM 1102,
3201, 3202

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1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-4217
LA-10396-MS

2. TITLE AND SUBTITLE
A Statistical Analysis of Nuclear Power Plant Valve Failure-Rate Variability--Some Preliminary Results

3. LEAVE BLANK

4. DATE REPORT COMPLETED

MONTH	YEAR
March	1985

5. AUTHOR(S)
R. J. Beckman
H. F. Martz

6. DATE REPORT ISSUED

MONTH	YEAR
May	1985

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Los Alamos National Laboratory
Los Alamos, NM 87545

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER
A7225-5

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

11a. TYPE OF REPORT
Formal

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)
Valve failure data from the In-Plant Reliability Data System (IPRDS) are statistically analyzed using the Failure Rate Analysis Code (FRAC). Data from the five failure modes, four of which are time related and the other demand related, are analyzed to determine which of the factors--operating system, valve size, valve type, operating type, and operating mode--most affect valve failure rates. A separate analysis is given for each of two plants, a pressurized water reactor (PWR) and a boiling water reactor (BWR).

For both plants and each failure mode, multiplicative adjustments for the mean are obtained for categories, such as nuclear or containment systems, of the various factors. These multipliers indicate whether a particular category of a factor has a corresponding failure rate that is less than the average failure rate (a multiplier less than one) or greater than average (a multiplier greater than one).

Based on the multiplicative adjustments, ball valves are shown to be the most reliable valves for the PWR plant. Globe and gate valves have the highest failure rates for this plant. The average failure rate for the BWR plant is found to be half that of the PWR plant for three of the five failure modes studied.

In addition to the multipliers, point estimates and confidence intervals on the failure rates are given for selected valve factor combinations. These estimates and intervals are compared with several other estimates.

14. DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT
Unlimited

16. SECURITY CLASSIFICATION
(This page)
Unclassified
(This report)
Unclassified

17. NUMBER OF PAGES

18. PRICE

☆ U.S. GOVERNMENT PRINTING OFFICE 1985—576-034/20068

Available from

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Division of Technical Information and Document Control
US Nuclear Regulatory Commission
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