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

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CONTENTS

A STATISTICAL ANALYSIS OF NUCLEAR POWER PLANT PUMP FAILURE RATE VARIABILITY--SOME PRELIMINARY RESULTS

by

Harry F. Martz and David E. Whiteman

ABSTRACT

In-Plant Reliability Data System (IPRDS) pump failure data on over 60 selected pumps in four nuclear power plants are statistically analyzed using the Failure Rate Analysis Code (FRAC). A major purpose of the analysis is to determine which environmental, system, and operating factors adequately explain the variability in the failure data. Catastrophic, degraded, and incipient failure severity categories are considered for both demand-related and time-dependent failures.

For catastrophic demand-related pump failures, the variability is explained by the following factors listed in their order of importance: system application, pump driver, operating mode, reactor type, pump type, and unidentified plant-specific influences. Quantitative failure rate adjustments are provided for the effects of these factors.

In the case of catastrophic time-dependent pump failures, the failure rate variability is explained by three factors: reactor type, pump driver, and unidentified plant-specific influences.

Finally, point and confidence interval failure rate estimates are provided for each selected pump by considering the influential factors. Both types of estimates represent an improvement over the estimates computed exclusively from the data on each pump.

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1. INTRODUCTION AND EXECUTIVE SUMMARY

Estimates of the reliability of numerous pump components are used in probabilistic risk analysis (PRA) of nuclear power plants. The estimates are used in quantifying the system fault tree models that appear in the event trees for each postulated accident.

The purpose of this report is (1) to determine the environmental, system, and operating factors which best explain (in a statistical sense) the observed differences in a certain set of estimated pump failure rates and to quantify the effects that these factors have on the failure rate estimates, (2) to determine various statistical models using the factors found in (1) which can be used to calculate pump failure rate estimates, and (3) to provide point and confidence interval estimates of pump failure rates using the models determined in (2).

Following the Introduction and Executive Summary in Section 1, Section 2 describes the pump failure rate data used in the analysis. Section 3 presents the detailed results of the analysis, which are summarized in Section 1.3. Finally, Section 4 gives the failure rate estimates.

1.1 Scope

The pump failure rate information analyzed here is the set of preliminary data for a selected group of important pumps identified and considered in the In-Plant Reliability Data System (IPRDS) on the pump component.[1] Pump data from four nuclear power plants are analyzed. The data cover 23 functionally different pumps for each of two Pressurized Water Reactors (PWRs), and 21 and 17 functionally different pumps, respectively, for two Boiling Water Reactors (BWRs). Because the data in Ref. 1 are assumed to be of a preliminary nature, the analysis undertaken here is likewise of a preliminary nature.

Two types of failures are analyzed: demand-related and time-dependent failures. Each pump is classified into one of three operating modes according to its primary mode of operation:

Running: The primary state of the pump is the running or active mode, for example, the condensate feedwater pumps.

Alternating: The pump alternates between the running and standby operating mode, such as boric acid transfer pumps.

Standby: The pump is normally in the standby state, for example, the containment spray pumps.

Pumps in the running mode have a time-dependent failure rate, while those in the standby mode possess a demand-related failure rate. Those in the alternating mode have both time- and demand-related failure rates.

One of three failure severity categories is assigned to each pump failure based on six possible failure mode categories. The three severity categories are

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

Degraded: The pump operates at less than its specified performance level. For example, there is low flow ·m the pump.

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

The six failure mode categories are fails to start, fails while running, low output, vibration, leakage, and other. A catastrophic failure is reported for a pump which either fails to start (for demand-related failures) or fails while running (for time-dependent failures). A degraded failure is reported when a pump fails in the low output mode, and an incipient failure occurs for those pumps failing in the vibration, leakage, or other failure mode categories.

A variety of factors are reported for each pump in the data base and several of these are considered here. Such factors as pump identification number, functional name, system and operating characteristics (such as pump and driver type, horsepower, and differential head), reactor type, plant designator, etc., are reported. However, in some cases not all of this information is readily available from the plant records, and the corresponding data fields have been left blank. Of all the factors reported,[1] six factors are complete enough to be considered here. They are

Reactor Type: Two types of light water reactors: (1) PWR and (2) BWR

Plant: Four plants coded as (1) PWR No. 1, (2) PWR No. 2, (3) BWR No. 1, and (4) BWR No. 2

System: The IPRDS data base considers pumps in the following seven systems: (1) Nuclear, (2) Engineered Safety, (3) Containment, (4) Electrical, (5) Power Conversion, (6) Process Auxiliary, and (7) Plant Auxiliary (Section 2 provides a generic listing of the plant systems in each of these categories)

Operating Mode: Three dominant modes of pump operation: (1) Running, (2) Standby, and (3) Alternating

Pump Type: Two major pump types: (1) Positive Displacement and (2) Centrifugal

Pump Driver: Three types of pump drivers: (1) Motor, (2) Diesel, and (3) Turbine

For each failure severity category, the relationship is determined between each type of failure rate and the subset of the above factors found to be most statistically significant for explaining the variability in the failure rates. These relationships are used to calculate the numerical effect of each of the significant factors. The factors are also importance-ranked according to their effect on the failure rates.

1.2 Procedure

The Failure Rate Analysis Code (FRAC)[2] is used for the analysis. FRAC uses the well-established statistical methods of weighted least squares and weighted maximum likelihood to obtain the desired models based on the six factors previously discussed. The statistical significance level associated with a given model measures the ability of that model to explain the observed variability in the pump failure rate estimates. For a given failure rate type and severity category, finding the model having the smallest significance level, or P-Value, within the class of all feasible models is desirable. Such a model is subsequently identified and labeled the Most Statistically Significant (MSS) model. Although other models may do nearly as well in explaining the variability, none are better than the MSS model. The MSS model is considered here to be the best model, and the corresponding conclusions and estimates are based on this model.

In the past it has been customary to examine the effect of multiple factors on a failure rate one at a time. This is an inefficient method of analysis that does not lend itself to convenient investigation of interaction effects and may also indicate spurious effects when no such effects are present. Also, in such an analysis, often either failure rate estimates are given for each factor combination appearing in the data base with little or no data pooling or estimates are based on pooled data with little or no statistical assurance that such pooling is justified. In the case of little or no pooling, the estimates may be inefficient, while in the case of pooling, the estimates may be inappropriate or incorrect. For example, suppose that the effect of pump size on the failure rate is of interest. If data are pooled into each of several size categories, any apparent size effect may in fact be due to other factors which coincidentally correspond to the size categories. Such confounding effects can often result in confusing, and sometimes contradictory, reports regarding the factors that affect pump failure rates. This potentially inefficient and error-prone situation is avoided here by simultaneous consideration of all the factors in a statistical analysis of variance framework using FRAC. Because all the pump failure data are combined in the analysis, the point and interval estimates are expected to be superior to single-cell estimates such as reported by Drago et al.[1] This superiority is a direct consequence of the efficient FRAC method of analysis which permits all of the data to be simultaneously utilized. The FRAC model is briefly described in Section 3. Finally, FRAC pools data across one or more factors only if those factors have no clear, statistically discernible effect on the pump failure rate.

1.3 Conclusions

The following conclusions pertain to the ability of the six factors discussed in Section 1.1 to statistically account for and explain the observed variability in pump failure rates in the IPRDS pump failure data base.

Table I presents the MSS factors obtained from the FRAC analyses that explain the variability for both demand- and time-related catastrophic, degraded, and incipient failures. The factors are listed in their order of importance in explaining the variation. The level of statistical significance (the P-Value) associated with each set of factors is also given. Recall that each of these

P-Values is the smallest value within the class of all feasible combinations of the six main factors.

Table I also gives the percentage of the total pump variation that is explained by each of these MSS factors. In the case of both demand- and time-related catastrophic failures, significant plant-to-plant variation was found to be present; thus, a random factor, Plant, is included in the set of MSS factors. This factor accounts for those unidentifiable plant-to-plant differences in the pump failure rate not explainable by the other five factors.

In addition, Table I presents the best and worst values, in regard to the pump failure rate, for each fixed MSS factor. The actual quantitative adjustments corresponding to these best and worst case conditions, as well as all other remaining intermediate conditions, are given in Section 3 and the appendices.

The system application of a pump is an important factor that explains the variation in demand-related pump failure rates with Engineered Safety, Power Conversion, and Electrical systems projected to yield the smallest failure rates. The largest failure rates are expected to occur for Plant Auxiliary and Nuclear system applications. The pump driver is also an important factor. Together these two factors account for over 50% of the explainable catastrophic demand-related failure rate variability and 100% of the explainable degraded variability.

Reactor type is an important factor that explains the variation in time-dependent pump failure rates, with BWRs clearly projected to have the smallest failure rates. Pump driver is also an important explanatory factor for catastrophic and incipient time-dependent failure rate differences, with motor-driven pumps having the best projected rate of failure. Although the system application is by far the most important factor for the category of degraded pumps, it is not nearly as important for catastrophic or incipient time-dependent failures as it is for demand-related failures.

Finally, there is more unexplained variation in degraded pump failures than in either catastrophic or incipient failures. This is clear from the small P-Values for both the catastrophic and incipient cases.

TABLE I

MSS FACTORS AND THE PERCENTAGE OF PUMP FAILURE RATE VARIATION EXPLAINED BY EACH FIXED FACTOR

Failure Type	Failure Severity	P-Value	MSS Factor	Pump Failure Rate		Percentage of Variation Explained
				Best	Worst	
Demand-Related	Catastrophic	0.28×10^{-8}	System	Eng. Safety	Plant Aux.	34
			Pump Driver	Motor	Turbine	21
			Operating Mode	Alternating	Standby	20
			Reactor Type	BWR	PWR	13
			Pump Type	Pos. Disp.	Centrifugal	12
			Plant[a]	--	--	--
	Degraded	0.17×10^{-2}	System	Power Conv.	Nuclear	73
			Pump Driver	Turbine	Diesel	27
	Incipient	0.55×10^{-8}	System	Electrical	Plant Aux.	81
			Reactor Type	BWR	PWR	19
Time-Dependent	Catastrophic	0.96×10^{-7}	Reactor Type	BWR	PWR	53
			Pump Driver	Motor	Turbine	47
			Plant[a]	--	--	--
	Degraded	0.21×10^{-2}	System	Eng. Safety	Power Conv.	82
			Operating Mode	Running	Alternating	12
			Reactor Type	BWR	PWR	6
	Incipient	0.41×10^{-7}	Reactor Type	BWR	PWR	61
			Pump Driver	Motor	Turbine	39

[a]Random factor.

2. IPRDS PUMP DATA BASE

The IPRDS pump data base includes more than 4 000 pump maintenance records on over 1 500 pumps for four nuclear power generating plants. These records span more than 27 plant-years of operation. Background information on the development of the IPRDS is given by Drago et al.[3] The pump population data are taken directly from the plant equipment lists, and the failure data are taken from the maintenance records.

The pump boundary considers a "super" pump or pumping function. In addition to those failures of the pump itself, such as the pump impeller, shaft, or motor, local failures such as switches, local instrumentation, and control circuitry are also considered to be within the pump boundary. However, command faults such as loss of steam are not included in the pump boundary. The rationale for this approach is given in Drago et al.[1]

From the population lists of pumps in the four plants, a set of over 60 important pumps was selected for reliability analysis by Drago et al.[1] This is the data set analyzed here. Tables II-V identify the selected pumps by plant. The entries in the column labeled "Population" are the number of pumps in the plant of that type. Definitions of the system codes in Tables II-V are given in Table VI.

The time-dependent and demand-related IPRDS pump failure data corresponding to Tables II-V are given in Appendix A. For simplicity, the following abbreviated names are used throughout this report for the six main factors listed in Section 1.1:

RTYPE -- Reactor Type

PLANT -- Plant

SYSTEM -- System

OPMODE -- Operating Mode

PTYPE -- Pump Type

DRIVER -- Pump Driver

TABLE II

SELECTED PUMPS FROM PLANT 1: PWR

Functional Name	System Code	Pump Type[a,b]	Driver Type[c-e]	Population
Auxiliary feedwater (diesel)	S05	C	D	1
Auxiliary feedwater (turbine)	S05	C	T	1
Boric acid transfer	N09	C	M	2
Boron injection recirculation	N09	C	M	2
Centrifugal charging	N09	C	M	2
Circulating water	P06	C	M	2
Component-cooling water	W03	C	M	3
Condensate	P04	C	M	2
Containment spray	C10	C	M	2
Diesel fuel oil transfer	E04	C	M	2
Fire pump (motor)	X02	C	M	1
Fire pump (diesel)	X02	C	D	1
Fire system jockey pump	X02	C	M	1
F.W. pump turbine emergency lube oil	P05	PD	M	2
F.W. pump turbine lube oil transfer	P05	PD	M	1
F.W. pump turbine main lube oil	P05	PD	M	2
Positive displacement charging	N09	PD	M	1
Reactor coolant	N04	C	M	4
Residual heat removal	N08	C	M	2
Safety injection	S03	C	M	2
Service water	W04	C	M	3
Service water booster	W04	C	M	4
Steam generator feed F.W.	P05	C	T	2

[a]C = centrifugal.
[b]PD = positive displacement.
[c]D = diesel.
[d]M = motor.
[e]T = turbine.

TABLE III

SELECTED PUMPS FROM PLANT 2: PWR

Functional Name	System Code	Pump Type	Driver Type	Population
Auxiliary feedwater (motor)	S05	C	M	2
Auxiliary feedwater (turbine)	S05	C	T	1
Boric acid transfer	N09	C	M	2
Boron injection recirculation	S03	C	M	2
Charging/high-head safety injection	N09	C	M	3
Chemical addition (continuous spray)	C10	C	M	1
Circulating water	P06	C	M	4
Component-cooling water	W03	C	M	3
Condensate	P04	C	M	2
Diesel-generator fuel oil transfer	E04	PD	M	4
Diesel-generator oil circulation	E04	C	M	2
Filtered seal water	W04	C	M	2
Fire pump (motor)	X02	PD	M	1
Fire pump (diesel)	X02	C	D	1
Fuel oil transfer	X02	PD	M	1
Low-head safety injection	S03	C	M	2
Inside recirculation spray	C10	C	M	2
Outside recirculation spray	C10	C	M	2
Quench spray	C10	C	M	2
Reactor coolant	N04	C	M	3
Residual heat removal	N08	C	M	2
Service water	W04	C	M	3
Steam generator feed	P05	C	M	2

TABLE IV

SELECTED PUMPS FROM PLANT 3: BWR

Functional Name	System Code	Pump Type	Driver Type	Population
Condensate	P04	C	M	9
Condensate booster	P04	C	M	9
Condenser circulating	P06	C	M	9
Control rod drive	N02	C	M	5
Core spray	S03	C	M	12
Engine-driven fuel	E04	C	D	12
Fire	X02	C	3M,D	4
High-pressure coolant injection (HPCI)	S03	C	T	3
HPCI booster	S03	C	T	3
Lube oil transfer	E04	C	M	1
Raw cooling water	W03	C	M	12
Raw cooling water booster	W03	C	M	4
Reactor building closed cooling water	W03	C	M	9
Reactor core isolation cooling (RCIC)	S01	C	T	3
Reactor feedwater	P05	C	T	9
Reactor recirculating	N04	C	M	6
Residual heat removal	N08	C	M	12
Residual heat removal service water	W04	C	M	12
Seal water injection to F.W. pump	P05	C	M	6
Standby liquid control	N05	PD	M	6
Transfer pump	E04	C	M	22

TABLE V

SELECTED PUMPS FROM PLANT 4: BWR

Functional Name	System Code	Pump Type	Driver Type	Population
Circulating water	P06	C	M	4
Condensate	P04	C	M	3
Containment spray	C10	C	M	4
Control rod drive	N02	C	M	2
Core spray	S03	C	M	4
Core spray booster	S03	C	M	4
Diesel generator transfer	E04	C	M	4
Emergency diesel generator fuel	E04	PD	D	2
Emergency service water	W04	C	M	4
Fire (diesel)	X02	C	D	2
Fire jockey pump	X02	C	M	1
Reactor building closed cooling water	W03	C	M	2
Reactor feedwater	P05	C	M	3
Reactor recirculating	N04	C	M	5
Residual heat removal	N08	C	M	3
Service water	W04	C	M	2
Liquid poison (standby liquid control)	N05	PD	M	2

TABLE VI

IPRD 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 cleanup system	N09	Chemical and volume control system (CVCS)

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 shutdown system	S04	Remote shutdown system
		S05	Auxiliary feedwater system

TABLE VI (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	Standby 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 room ventilation system

Electrical Systems-E

BWR		PWR	
E01	Main power system		• plant instrument ac power subsystem
E01.A	Protective relaying and controls	E04	Emergency power system
E02	Plant ac distribution system	E04.A	Diesel-generator fuel oil subsystem
E02.A	Essential power system		
E02.B	Nonessential power system	E04.B	Diesel-generator cooling water subsystem
E02.C	High-pressure core spray power system		
E02.D	Protective relaying and controls	E04.C	Diesel-generator air subsystem
E03	Instrumentation and control systems	E04.D	Diesel-generator power lubrication oil subsystem
E03.A	dc power system		
	• vital dc power subsystem	E05	Plant lighting system
	• plant dc power subsystem	E05.A	Essential lighting
E03.B	Instrument ac power system	E05.B	Nonessential lighting
	• vital instrument ac power subsystem	E06	Plant computer
		E03.B	Instrument power system
		E07	Switchyard
		E07.A	dc control power system
		E07.B	Protective relaying

TABLE VI (cont)

Power Conversion Systems-P

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

Process Auxiliary Systems-W

BWR		PWR	
W01	Radioactive waste system	W04.B	Station service water system • essential service water system • nonessential service water system
W01.A	Gaseous radwaste system • offgas subsystem (BWR)	W04.C	Chilled water system
W01.B	Liquid radwaste system	W05	Refueling system
W01.C	Solid radwaste system	W06	Spent fuel storage system
W02	Radiation monitoring system	W06.A	Fuel-pool-cooling and clean-up systems
W02.A	Plant area radiation monitors	W07	Compressed air system
W02.B	Environmental radiation monitors	W07.A	Service air system
W02.C	Process radiation monitors	W07.B	Instrument air system
W03	Cooling water systems	W08	Process sampling system
W03.A	Reactor building cooling water system	W09	Plant gas system
W03.B	Turbine building cooling water system	W09.A	Nitrogen system
W04	Service water systems	W09.B	Hydrogen system
W04.A	Demineralized makeup water system		

Plant Auxiliary Systems-X

BWR		PWR	
X01	Potable and sanitary water system	X05.C	Diesel building ventilation system
X02	Fire protection system	X05.D	Auxiliary building ventilation system
X02.A	Water system	X05.E	Fuel building ventilation system
X02.B	Carbon dioxide system	X06	Nonradioactive waste system
X03	Communications system	X06.A	Gaseous waste subsystem
X04	Security system	X06.B	Liquid waste subsystem
X05	Heating, ventilating, and air conditioning systems	X06.C	Solid waste subsystem
X05.A	Control room habitability system		
X05.B	Turbine building ventilation system		

3. PUMP FAILURE RATE ANALYSIS

A short summary of the FRAC methodology is now given for background information. A complete description is provided by Martz, Beckman, and McInteer.[2]

A major assumption in the FRAC method is that all failure rates are constant during the time period for which the failure data have been collected. Thus, for any given pump (pump s for example), the number of failures of a given severity in time T_s follows a Poisson distribution with parameter $\lambda_s T_s$, where λ_s is the constant pump failure rate of interest, which is to be analyzed and estimated.

Suppose further that the true underlying failure rate λ_s is a function of K factors $F_1, F_2, \ldots, F_k$. The levels or values of factor F_j are denoted as $1, 2, \ldots, m_j$. For example, if F_1 denotes RTYPE, then F_1 has two levels: 1 for PWRs and 2 for BWRs. We denote the specific levels of the K factors associated with the sth pump failure data set in the data base (that is, the sth cell) as the set of pairs of indices $S = \{(1,s(1)),(2,s(2)),\ldots,(K,s(K))\}$, where s(j) is an integer from the set $\{1,2,\ldots,m_j\}$. For example, if K = 3 then $S = \{(1,2),(2,3),(3,1)\}$ indicates that F_1 is at coded level 2, F_2 is at coded level 3, and F_3 is at coded level 1 for that cell.

The particular model adopted in FRAC for the failure rate λ_s associated with pump s 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 on the average failure rate λ_g. The A(j,s(j)) terms are thus multiplicative "adjustments" which account for the effect that factor F_j at level s(j) has on the average failure rate λ_g. The average failure rate λ_g acts as a constant term in the model and is the geometric average of all the pump failure rates in the data base.

The factors F_j may be either main factors, such as those listed in Section 1.1, or interactions of two or more main factors. However, no interactions are examined in this preliminary report because the number of pumps in the data base is insufficient to consider such interactions. The factors F_j may also be either fixed (that is, nonrandom) factors or random variables. If F_j is a random factor, then log A(j,s(j)) is assumed to be the value of a normally distributed random variable with mean 0 and variance $\sigma_j^2/E(\lambda_s)T_s$; thus, A(j,s(j)) has a lognormal distribution with median one. In the FRAC analysis here, only the main factor PLANT is considered to be a random factor. The main reason for this is that the actual identity of each of the four plants represented in the data base is proprietary information and thus any PLANT effects cannot be attributed to specific plants. Therefore, any observed plant-to-plant differences for the four plants considered are interpreted as random plant population variability effects. If $\sigma_j^2 = 0$, then there is no PLANT effect on a given pump failure rate and A(j,s(j)) = 1 for all plants. However, if $\sigma_j^2 > 0$, then the larger the value of σ_j^2, the greater the plant-to-plant contribution to the pump failure rate variability. The random factor PLANT thus represents the plant population variability effect on the pump failure rate.

3.1 Selecting the Best Model

FRAC uses the methods of weighted least squares and weighted maximum likelihood to arrive at estimates of the fixed effects A(j,s(j)) and the variance components σ_j^2 of the random factors. A chi-square statistic is computed and used to statistically assess the quality of fit of a given model to the observed pump failure rate data. For each model examined, the P-Value associated with the chi-square statistic is computed. This value is the probability of observing an associated chi-square statistic at least as large as the computed value by pure chance alone when only a constant term λ_g is in the model. For example, if the P-Value for a given model is 0.04, then the factors in the model (other than the constant term) are statistically able to explain the observed failure rate variability at the 4% level of significance. The smaller the P-Value, the more statistically significant the model. In other words, the smaller the P-Value, the better the set of factors in the given model can explain the observed variability in pump failure rates.

As discussed in Section 1.2, the class of models consisting of all feasible combinations of the six main factors given in Section 1.1 is considered. The model having the smallest P-Value within this class is labeled the Most Statistically Significant (MSS) model. This model is considered to be the best model for explaining the variability in the IPRDS pump failure rate data. All subsequent results, conclusions, and estimates are based on such MSS models.

Once the MSS model has been identified, the fixed factors in the model are ranked according to their overall effect in explaining the variability. The procedure is as follows: for a given fixed factor F_j, the ratio $R_j = \max_{s(j)} A(j,s(j))/\min_{s(j)} A(j,s(j))$ is computed. This ratio R_j measures the overall effect that F_j has on the average pump failure rate λ_g. The factors appearing in the MSS model are then ranked as follows: the factor having the largest R_j value is considered to be the most influential factor, the factor having the second largest R_j value is second most influential, and so on.

3.2 Demand-Related Failure Analysis

Recall from Section 1.1 that pumps which operate in either a standby or an alternating mode have an associated demand-related failure rate. We consider the catastrophic failure to start per demand as well as degraded and incipient failure rates per demand.

3.2.1 Catastrophic Failures.

Table VII gives the P-Values for all feasible demand-related catastrophic FRAC failure rate models based on the six main factors. Because PLANT is nested within RTYPE, PLANT cannot appear in the model unless RTYPE is also present. The MSS model contains all six factors, and this model is highly statistically significant at the 0.28×10^{-8} level of significance. The outlined arrows in the table indicate the MSS model for a given number of factors, while the solid arrow indicates the overall MSS model.

Table VIII gives the estimated effects (the multiplicative "adjustments") for each of the factors at each possible level in the MSS model. The values of R_j are also given for each of the fixed factors, and the fixed factors in Table VIII are listed in their decreasing order of influence according to these values. The entries in parentheses in Table VIII are the estimated standard deviations associated with the estimated adjustments and variance components. The rather large standard deviations for some factor levels are the result of the relatively small quantity of data currently in the IPRDS pump failure data base for the selected group of pumps considered here.

The overall average pump failure rate estimate is 8.17×10^{-3}. This average value is roughly a factor of 8 larger than the commonly used WASH-1400 (Ref. 4) value of 10^{-3} per demand.

The factor SYSTEM is the most influential factor, having an overall range of effect of 2.79/0.38 = 7.34 on the average pump failure rate estimate. Plant Engineered Safety systems are estimated to have the smallest pump failure rates (an adjustment of 0.38), while pumps in Plant Auxiliary systems are estimated to have the largest failure rates (an adjustment of 2.79). Similarly, DRIVER is the second most influential factor; OPMODE is third; and so on.

The random factor PLANT is also in the MSS model. This means that there is statistically significant variability in pump failure rates between the two plants for each type of reactor which is not completely explained by the other five factors. However, it is not ranked because it is a random factor. The PLANT variance component in Table VIII will be reflected in the confidence interval estimates given in Section 4.

Table VIII can be used as follows: a centrifugally designed, standby, diesel-operated auxiliary feedwater pump in a PWR has an estimated catastrophic failure rate per demand of

$$8.17 \times 10^{-3}(0.38)(0.71)(2.06)(1.67)(1.63) = 1.24 \times 10^{-2} \text{ f/d} \quad .$$

In performing a PRA the actual level of one or more of the factors in Table VIII may be either unknown or undetermined at the time the PRA is performed. In such case the corresponding factor adjustments could either simply be ignored, because the geometric mean of the adjustments for each fixed factor has a nominal value constrained to be equal to one, or the extreme adjustments corresponding to the unknown fixed factors could be used to establish a range of uncertainty due to the unknown factors.

Table IX gives the best and worst case catastrophic demand-related pump failure rate estimates based on the FRAC MSS model in Table VIII. There are approximately three orders of magnitude between the best and worst case estimates that are explained by the FRAC MSS model. This compares favorably with approximately 2.9 orders of magnitude between the largest and smallest failure rate estimates in the IPRDS demand-related data base in Appendix A. The observed range is expected to be smaller because the data extremes are unlikely to be the absolute best and worst case conditions, which may or may not represent feasible operating conditions.

3.2.2 Degraded Failures. Table B-I in Appendix B gives the P-Values for all feasible degraded FRAC failure rate models based on the six main factors. The dashes (--) in Table B-I indicate those models in which it is not possible to consider all the indicated factors, primarily the result of "multi-collinearity" between the factors. Such models are thus infeasible. In such cases FRAC "zeros out" one or more of the collinear factors, and the corresponding model reduces to one of the lower order models in the table. The MSS model contains the two factors SYSTEM and DRIVER and is highly significant at the 1.67×10^{-3} level of significance.

Table B-II gives the multiplicative adjustments for each of the two factors in the MSS model. Analogous to Table VIII, Table B-II lists the factors in their decreasing order of influence according to the value of R_j. SYSTEM is the most influential factor with a range of 28, nearly three times that of the remaining factor, DRIVER. Pumps in Nuclear systems are expected to have the largest degraded demand-related failure rates, while pumps in Power Conversion systems are expected to have the smallest failure rates.

Table B-III gives the best and worst case failure rate estimates based on the FRAC model in Table B-II. There are approximately 3.5 orders of magnitude between the best and worst case estimates that are accounted for by the FRAC MSS degraded demand-related pump failure rate model.

3.2.3 Incipient Failures. Tables B-IV through B-VI give the results of the pump demand-related FRAC failure rate analysis for incipient failures. Table B IV gives the P-Values for all feasible FRAC models using the six main factors. The MSS model contains the two factors SYSTEM and RTYPE and is highly significant at the 5.55×10^{-9} level of significance.

Table B-V gives the multiplicative adjustments. The factor SYSTEM is the most influential factor with a range of effect slightly over an order of magnitude, while RTYPE has a range of 2.90. Because incipient failures are often precursors of either catastrophic or degraded failures, incipient pump failures in Plant Auxiliary, Nuclear, Process Auxiliary, and Engineered Safety systems should be carefully monitored as possible precursors of more serious pump failures which may jeopardize plant safety.

Table B-VI gives the best and worst case FRAC estimates using the model in Table V. There are roughly 1.6 orders of magnitude between the best and worst case estimates that are explainable by the FRAC MSS model.

3.3 Time-Dependent Failure Analysis

Recall that pumps which operate in either a running or alternating mode have an associated time-related failure rate. We consider the catastrophic failure rate per operating hour as well as the degraded and incipient failure rates per hour of operation.

3.3.1 Catastrophic Failures. Table X gives the P-Values for all feasible time-dependent catastrophic FRAC failure rate models. The MSS model contains only the two factors RTYPE and DRIVER and is highly significant at the 9.6×10^{-8} level.

The estimate of the average pump failure rate λ_g is 8.91×10^{-5} per operating hour and is roughly three times larger than the corresponding WASH-1400 (Ref. 4) value of 3×10^{-5} per operating hour.

Table XI gives the multiplicative adjustments for the FRAC MSS model. The range of effect of both factors is approximately four, which indicates that there is less variability in the catastrophic time-dependent pump failure rate data base than in the demand-related data base. Also, the FRAC MSS model in Table XI explains less variability than the model in Table VIII as demonstrated by the rather large error variance component in Table XI. This may also be seen in Table XII in which only 1.3 orders of magnitude separate the best and worst case estimates produced by the FRAC MSS model. Recall that in the case of catastrophic demand-related estimates, this difference was over three orders of magnitude.

3.3.2 Degraded Failures. Table C-I in Appendix C gives the P-Values for all feasible time-dependent degraded FRAC failure rate models. The MSS model contains three factors, SYSTEM, OPMODE, and RTYPE, and this model is statistically significant at the 0.0021 level of significance.

Table C-II gives the multiplicative failure rate adjustments for the MSS model. SYSTEM is the most important factor, having a range of effect of 33.40. This range is nearly 7 times that of the second most important factor, OPMODE, and nearly 15 times that of the third most influential factor, RTYPE.

Table C-III gives the best and worst case FRAC estimates based on the MSS model in Table C-II. The FRAC MSS model yields an overall range of variability of approximately 2.6 orders of magnitude between the best and worst case estimates.

3.3.3 Incipient Failures. Table C-IV gives the P-Values for all the feasible FRAC models based on the six main factors. The MSS model contains the two factors, RTYPE and DRIVER.

Table C-V gives the estimated failure rate adjustments for the MSS model. Note that neither RTYPE nor DRIVER has a large range of effect on the incipient time-dependent pump failure rates. Although RTYPE has the larger R_j value, it is only slightly more influential than DRIVER.

Table C-VI gives the best and worst case estimates using the FRAC MSS model in Table C-V. Only a 0.9 order of magnitude separates these estimates. Incipient failures in PWR turbine driven pumps should be carefully monitored as possible precursors of either catastrophic or degraded failures that may jeopardize plant safety.

TABLE VII

CATASTROPHIC DEMAND-RELATED FRAC FAILURE RATE MODEL ANALYSIS

One-Factor Models	P-Values
RTYPE	0.2338×10^{-2}
SYSTEM	0.1164×10^{-3}
OPMODE	0.1510×10^{-2}
PTYPE	0.4767×10^{0}
DRIVER	0.4431×10^{-2}

Two-Factor Models	P-Values
RTYPE, PLANT	0.7798×10^{-2}
RTYPE, SYSTEM	0.4179×10^{-5}
RTYPE, OPMODE	0.1999×10^{-4}
RTYPE, PTYPE	0.7810×10^{-2}
RTYPE, DRIVER	0.2644×10^{-3}
SYSTEM, OPMODE	0.1304×10^{-4}
SYSTEM, PTYPE	0.2316×10^{-3}
SYSTEM, DRIVER	0.4966×10^{-4}
OPMODE, DRIVER	0.7896×10^{-3}
OPMODE, PTYPE	0.2199×10^{-2}
PTYPE, DRIVER	0.1178×10^{-1}

TABLE VII (cont)

Three-Factor Models	P-Values
RTYPE, PLANT, SYSTEM	0.3305×10^{-5}
RTYPE, PLANT, OPMODE	0.4520×10^{-4}
RTYPE, PLANT, PTYPE	0.1504×10^{-1}
RTYPE, PLANT, DRIVER	0.2487×10^{-3}
RTYPE, SYSTEM, OPMODE	0.7428×10^{-7}
RTYPE, SYSTEM, PTYPE	0.1029×10^{-4}
RTYPE, SYSTEM, DRIVER	0.6813×10^{-6}
RTYPE, PTYPE, SYSTEM	0.7312×10^{-3}
PTYPE, SYSTEM, OPMODE	0.7840×10^{-5}
DRIVER, OPMODE, SYSTEM	0.5338×10^{-5}
OPMODE, PTYPE, DRIVER	0.1201×10^{-2}
RTYPE, PTYPE, OPMODE	0.2536×10^{-4}
RTYPE, DRIVER, OPMODE	0.2293×10^{-4}
SYSTEM, DRIVER, PTYPE	0.1000×10^{-3}

Four-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE	0.1105×10^{-6}
RTYPE, PLANT, SYSTEM, PTYPE	0.7688×10^{-5}
RTYPE, PLANT, SYSTEM, DRIVER	0.4720×10^{-6}
RTYPE, PLANT, OPMODE, PTYPE	0.2641×10^{-4}
RTYPE, PLANT, OPMODE, DRIVER	0.5359×10^{-4}
RTYPE, PLANT, PTYPE, DRIVER	0.6670×10^{-3}
SYSTEM, RTYPE, DRIVER, OPMODE	0.7980×10^{-8}
RTYPE, PTYPE, DRIVER, SYSTEM	0.1697×10^{-5}
PTYPE, SYSTEM, OPMODE, RTYPE	0.5595×10^{-7}
DRIVER, OPMODE, RTYPE, PTYPE	0.3529×10^{-4}
OPMODE, PTYPE, DRIVER, SYSTEM	0.3647×10^{-5}

Five-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE, PTYPE	0.2011×10^{-7}
RTYPE, PLANT, SYSTEM, OPMODE, DRIVER	0.1140×10^{-7}
RTYPE, PLANT, SYSTEM, DRIVER, PTYPE	0.1094×10^{-5}
RTYPE, PLANT, OPMODE, PTYPE, DRIVER	0.5185×10^{-4}
RTYPE, SYSTEM, PTYPE, DRIVER, OPMODE	0.6403×10^{-8}

Six-Factor Model	P-Values
RTYPE, PLANT, SYSTEM OPMODE, PTYPE, DRIVER	0.2784×10^{-8}

TABLE VIII

CATASTROPHIC DEMAND-RELATED MSS FRAC MODEL

Average Failure Rate Estimate--8.17×10^{-3} (2.60×10^{-3})

Fixed Factors

Level of Influence	Factor	Level	Description	R_j	Failure Rate Adjustment
1	SYSTEM	1	Nuclear	7.34	2.66 (0.636)
		2	Engineered Safety		0.38 (0.131)
		3	Containment		0.64 (0.228)
		4	Electrical		0.53 (0.177)
		5	Power Conversion		0.57 (0.397)
		6	Process Auxiliary		1.84 (0.484)
		7	Plant Auxiliary		2.79 (0.718)
2	DRIVER	1	Motor	4.48	0.56 (0.114)
		2	Diesel		0.71 (0.189)
		3	Turbine		2.51 (0.849)
3	OPMODE	1	Standby	4.20	2.06 (0.302)
		2	Alternating		0.49 (0.071)
4	RTYPE	1	PWR	2.78	1.67 (0.298)
		2	BWR		0.60 (0.107)
5	PTYPE	1	Positive Displacement	2.67	0.61 (0.117)
		2	Centrifugal		1.63 (0.312)

Random Factors

Factor	Variance Component
PLANT	0.882 (0.0854)
ERROR	0.586 (0.1061)

TABLE IX

BEST AND WORST CASE CATASTROPHIC DEMAND-RELATED FRAC PUMP FAILURE RATE ESTIMATES

CASE	SYSTEM	DRIVER	OPMODE	RTYPE	PTYPE	ESTIMATE
Best	Eng. Safety	Motor	Alternating	BWR	Pos. Displacement	3.09×10^{-4}/d
Worst	Plant Aux.	Turbine	Standby	PWR	Centrifugal	3.21×10^{-1}/d

Note: $3.21 \times 10^{-1}/3.09 \times 10^{-4} = 1039 \approx 3.0$ orders of magnitude between the best and worst case estimates.

TABLE X

CATASTROPHIC TIME-DEPENDENT FRAC FAILURE RATE MODEL ANALYSIS

One-Factor Models	P-Values
RTYPE	0.8883×10^{-4}
SYSTEM	0.7802×10^{-2}
OPMODE	0.1379×10^{0}
PTYPE	0.5759×10^{0}
DRIVER	0.9651×10^{-1}

Two-Factor Models	P-Values
RTYPE, PLANT	0.1377×10^{-3}
RTYPE, SYSTEM	0.3175×10^{-4}
RTYPE, OPMODE	0.1694×10^{-3}
RTYPE, PTYPE	0.2361×10^{-3}
RTYPE, DRIVER	0.5282×10^{-5}
SYSTEM, OPMODE	0.1348×10^{-1}
SYSTEM, PTYPE	0.1795×10^{-1}
SYSTEM, DRIVER	0.1583×10^{-1}
OPMODE, DRIVER	0.1869×10^{0}
OPMODE, PTYPE	0.2539×10^{0}
PTYPE, DRIVER	0.2288×10^{0}

TABLE X (cont)

Three-Factor Models	P-Values
RTYPE, PLANT, SYSTEM	0.4424×10^{-4}
RTYPE, PLANT, OPMODE	0.1319×10^{-3}
RTYPE, PLANT, PTYPE	0.3063×10^{-3}
RTYPE, PLANT, DRIVER	0.9622×10^{-7}
RTYPE, SYSTEM, OPMODE	0.3437×10^{-4}
RTYPE, SYSTEM, PTYPE	0.5850×10^{-4}
RTYPE, SYSTEM, DRIVER	0.1461×10^{-4}
RTYPE, PTYPE, SYSTEM	0.1166×10^{-4}
PTYPE, SYSTEM, OPMODE	0.2904×10^{-1}
DRIVER, OPMODE, SYSTEM	0.2355×10^{-1}
OPMODE, PTYPE, DRIVER	0.2985×10^{0}
RTYPE, PTYPE, OPMODE	0.2538×10^{-3}
RTYPE, DRIVER, OPMODE	0.2253×10^{-4}
SYSTEM, DRIVER, PTYPE	0.3206×10^{-1}

Four-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE	0.4646×10^{-4}
RTYPE, PLANT, SYSTEM, PTYPE	0.8078×10^{-4}
RTYPE, PLANT, SYSTEM, DRIVER	0.1468×10^{-5}
RTYPE, PLANT, OPMODE, PTYPE	0.2085×10^{-3}
RTYPE, PLANT, OPMODE, DRIVER	0.3374×10^{-6}
RTYPE, PLANT, PTYPE, DRIVER	0.2880×10^{-6}
SYSTEM, RTYPE, DRIVER, OPMODE	0.1008×10^{-4}
RTYPE, PTYPE, DRIVER, SYSTEM	0.2474×10^{-4}
PTYPE, SYSTEM, OPMODE, RTYPE	0.8019×10^{-4}
DRIVER, OPMODE, RTYPE, PTYPE	0.4021×10^{-4}
OPMODE, PTYPE, DRIVER, SYSTEM	0.4615×10^{-1}

Five-Factor Models	P-Value
RTYPE, PLANT, SYSTEM, OPMODE, PTYPE	0.1044×10^{-3}
RTYPE, PLANT, SYSTEM, OPMODE, DRIVER	0.6739×10^{-6}
RTYPE, PLANT, SYSTEM, DRIVER, PTYPE	0.3154×10^{-5}
RTYPE, PLANT, OPMODE, PTYPE, DRIVER	0.9006×10^{-6}
RTYPE, SYSTEM, PTYPE, DRIVER, OPMODE	0.2370×10^{-4}

Six-Factor Model	P-Value
RTYPE, PLANT, OPMODE SYSTEM, PTYPE, DRIVER	0.1735×10^{-5}

TABLE XI

CATASTROPHIC TIME-DEPENDENT MSS FRAC MODEL

Average Failure Rate Estimate--8.91×10^{-5} (2.63×10^{-5})

Fixed Factors

Level of Influence	Factor	Level	Description	R_j	Failure Rate Adjustment
1	RTYPE	1	PWR	4.57	2.15 (0.608)
		2	BWR		0.47 (0.132)
2	DRIVER	1	Motor	3.98	0.50 (0.071)
		2	Turbine		1.99 (0.278)

Random Factors

Factor	Variance Component
PLANT	0.269 (0.225)
ERROR	1.047 (0.608)

TABLE XII

BEST AND WORST CASE CATASTROPHIC TIME-DEPENDENT FRAC PUMP FAILURE RATE ESTIMATES

Case	RTYPE	DRIVER	Estimate
Best	BWR	Motor	2.09×10^{-5}/h
Worst	PWR	Turbine	3.81×10^{-4}/h

Note: $3.81 \times 10^{-4}/2.09 \times 10^{-5} = 18.23 \simeq 1.3$ orders of magnitude between the best and worst case estimates.

4. PUMP FAILURE RATE ESTIMATES

Point estimates of pump failure rates are calculated directly from the estimated FRAC MSS models, such as in Tables VIII and XI. Confidence interval estimates are computed using the FRAC procedure and equations given in Martz, Beckman, and McInteer.[2] Estimates are given for each of the pump failure data entries in the data bases in Appendix A. Ninety-five percent confidence interval estimates are given in which the lower and upper interval endpoints correspond to the lower 2.5% and upper 97.5% confidence limits, respectively, on the corresponding true (but unknown) underlying pump failure rate.

For convenience, the following coded abbreviations are used in the tables which follow:

RTYPE

P = PWR
B = BWR

PLANT

1 = Plant 1 (PWR)
2 = Plant 2 (PWR)
3 = Plant 3 (BWR)
4 = Plant 4 (BWR)

OPMODE

S = Standby
A = Alternating
R = Running

DRIVER

M = Motor
D = Diesel
T = Turbine

PTYPE

PD = Positive Displacement
C = Centrifugal

Tables XIII-XV give the point and 95% confidence interval estimates of the demand-related pump failure rates for catastrophic, degraded, and incipient failure severity categories for each pump in Table A-II. The point estimates are the "recommended" values, while the lower and upper interval endpoints are considered to be the "low" and "high" values, respectively. The SYSTEM codes are defined in Table VI. The estimates are given as failures per demand. Different failure rate estimates are obtained only for different levels or values of the MSS factors, as these are the only factors that appear in the corresponding MSS models.

Consider the first entry in Table XIII, the catastrophic failure rate per demand for a PWR centrifugally designed, diesel-operated, standby auxiliary feedwater pump. The point estimate is 1.25×10^{-2} per demand. The corresponding single-cell point estimate based on one catastrophic failure in 60 demands is $1/60 = 1.67 \times 10^{-2}$. The FRAC MSS model estimate is thus roughly 75% as large as the simple single-cell estimate. This reduction is the result of considering additional failure data for the other pumps in the data base via the FRAC MSS model. Now consider the 95% confidence interval estimate. The FRAC estimate is $(4.78 \times 10^{-3}, 3.27 \times 10^{-2})$, and the corresponding single-cell estimate based on the chi-square distribution, such as given by Drago et al.,[1] is $(4.25 \times 10^{-4}, 9.29 \times 10^{-2})$. The FRAC interval estimate is roughly 32 times narrower than the single-cell estimate. This reduction in uncertainty is also the result of the pooled utilization of all the pump failure data via the FRAC MSS model.

Similarly, Tables XVI-XVIII give the estimates of the time-dependent pump failure rates for each pump entry in Table A-IV.

TABLE XIII

CATASTROPHIC DEMAND-RELATED FRAC PUMP FAILURE RATE ESTIMATES PER DEMAND

1	AUX FW	P	1	S	D	C	S05	0.1249E-01	(0.4777E-02,0.3265E-01)
2	AUX FW	P	1	S	T	C	S05	0.4387E-01	(0.1951E-01,0.9866E-01)
3	BORIC ACID TRANSFER	P	1	A	M	C	N09	0.1603E-01	(0.8863E-02,0.2898E-01)
4	BORON INJECTION RECIRCULATION	P	1	A	M	C	N09	0.1603E-01	(0.8863E-02,0.2898E-01)
5	CENTRIFUGAL CHARGING	P	1	S	M	C	N09	0.6818E-01	(0.3318E-01,0.1401E+00)
6	COMPONENT-COOLING WATER	P	1	A	M	C	W03	0.1105E-01	(0.5673E-02,0.2154E-01)
7	CONTAINMENT SPRAY	P	1	S	M	C	C10	0.1648E-01	(0.7326E-02,0.3709E-01)
8	DIESEL FUEL OIL TRANSFER	P	1	S	M	C	E04	0.1359E-01	(0.5828E-02,0.3169E-01)
9	FIRE	P	1	S	M	C	X02	0.7138E-01	(0.3710E-01,0.1373E+00)
10	FIRE	P	1	S	D	C	X02	0.9138E-01	(0.4734E-01,0.1764E+00)
11	FIRE JOCKEY	P	1	S	M	C	X02	0.7138E-01	(0.3710E-01,0.1373E+00)
12	FW TURBINE EMER LUBE OIL	P	1	S	M	PD	P05	0.5434E-02	(0.1108E-02,0.2666E-01)
13	FW TURBINE LUBE OIL TRANSFER	P	1	S	M	PD	P05	0.5434E-02	(0.1108E-02,0.2666E-01)
14	RESIDUAL HEAT REMOVAL	P	1	A	M	C	N08	0.1603E-01	(0.8863E-02,0.2898E-01)
15	SAFETY INJECTION	P	1	S	M	C	S03	0.9756E-02	(0.4201E-02,0.2266E-01)
16	SERVICE WATER	P	1	A	M	C	W04	0.1105E-01	(0.5673E-02,0.2154E-01)
17	SERVICE WATER BOOSTER	P	1	A	M	C	W04	0.1105E-01	(0.5673E-02,0.2154E-01)
18	AUX FW	P	2	S	M	C	S05	0.9756E-02	(0.4201E-02,0.2266E-01)
19	AUX FW	P	2	S	T	C	S05	0.4387E-01	(0.1951E-01,0.9866E-01)
20	BORIC ACID TRANSFER	P	2	A	M	C	N09	0.1603E-01	(0.8863E-02,0.2898E-01)
21	BORON INJECTION RECIRCULATION	P	2	A	M	C	S03	0.2293E-02	(0.8713E-03,0.6037E-02)
22	CHARGING/HIGH-HEAD SAFETY INJECTION	P	2	A	M	C	N09	0.1603E-01	(0.8863E-02,0.2898E-01)
23	CHEMICAL ADDITION (CONTAINMENT SPRAY)	P	2	S	M	C	C10	0.1648E-01	(0.7326E-02,0.3709E-01)
24	COMPONENT-COOLING WATER	P	2	A	M	C	W03	0.1105E-01	(0.5673E-02,0.2154E-01)
25	DIESEL-GENERATOR FUEL OIL TRANSFER	P	2	S	M	PD	E04	0.5088E-02	(0.1851E-02,0.1399E-01)
26	DIESEL-GENERATOR OIL CIRCULATION	P	2	S	M	PD	E04	0.5088E-02	(0.1851E-02,0.1399E-01)
27	FILTERED SEAL WATER	P	2	A	M	C	W04	0.1105E-01	(0.5673E-02,0.2154E-01)
28	FIRE	P	2	S	M	PD	X02	0.2673E-01	(0.1039E-01,0.6873E-01)
29	FIRE	P	2	S	D	C	X02	0.9138E-01	(0.4734E-01,0.1764E+00)
30	FUEL OIL TRANSFER	P	2	S	M	PD	X02	0.2673E-01	(0.1039E-01,0.6873E-01)
31	LOW-HEAD SAFETY INJECTION	P	2	S	M	C	S03	0.9756E-02	(0.4201E-02,0.2266E-01)
32	INSIDE RECIRCULATION SPRAY	P	2	S	M	C	C10	0.1648E-01	(0.7326E-02,0.3709E-01)
33	OUTSIDE RECIRCULATION SPRAY	P	2	S	M	C	C10	0.1648E-01	(0.7326E-02,0.3709E-01)
34	QUENCH SPRAY	P	2	S	M	C	C10	0.1648E-01	(0.7326E-02,0.3709E-01)
35	RESIDUAL HEAT REMOVAL	P	2	A	M	C	N08	0.1603E-01	(0.8863E-02,0.2898E-01)
36	SERVICE WATER	P	2	A	M	C	W04	0.1105E-01	(0.5673E-02,0.2154E-01)
37	CONTROL ROD DRIVE	B	3	A	M	C	N02	0.5759E-02	(0.3041E-02,0.1091E-01)
38	CORE SPRAY	B	3	S	M	C	S03	0.3505E-02	(0.1498E-02,0.8202E-02)
39	ENGINE-DRIVEN FUEL	B	3	S	D	C	E04	0.6251E-02	(0.2354E-02,0.1660E-01)
40	FIRE	B	3	S	M	C	X02	0.2565E-01	(0.1342E-01,0.4902E-01)
41	HIGH-PRESSURE COOLANT INJECTION	B	3	S	T	C	S03	0.1576E-01	(0.7307E-02,0.3400E-01)
42	HPCI BOOSTER	B	3	S	T	C	S03	0.1576E-01	(0.7307E-02,0.3400E-01)
43	LUBE OIL TRANSFER	B	3	S	M	C	E04	0.4883E-02	(0.2098E-02,0.1136E-01)
44	RAW COOLING WATER	B	3	A	M	C	W03	0.3972E-02	(0.2169E-02,0.7275E-02)
45	RAW COOLING WATER BOOSTER	B	3	A	M	C	W03	0.3972E-02	(0.2169E-02,0.7275E-02)
46	REACTOR BUILDING CLOSED COOLING	B	3	A	M	C	W03	0.3972E-02	(0.2169E-02,0.7275E-02)
47	REACTOR CORE ISOLATION COOLING	B	3	S	T	C	S01	0.1576E-01	(0.7307E-02,0.3400E-01)
48	RESIDUAL HEAT REMOVAL	B	3	A	M	C	N08	0.5759E-02	(0.3041E-02,0.1091E-01)
49	RHR SERVICE WATER	B	3	A	M	C	W04	0.3972E-02	(0.2169E-02,0.7275E-02)
50	SEAL WATER INJECTION TO FW	B	3	A	M	C	P05	0.1226E-02	(0.2288E-03,0.6569E-02)
51	LIQUID CONTROL	B	3	S	M	PD	N05	0.9172E-02	(0.4112E-02,0.2046E-01)
52	TRANSFER	B	3	S	M	C	E04	0.4883E-02	(0.2098E-02,0.1136E-01)
53	CONTAINMENT SPRAY	B	4	S	M	C	C10	0.5923E-02	(0.2593E-02,0.1353E-01)
54	CONTROL ROD DRIVE	B	4	A	M	C	N02	0.5759E-02	(0.3041E-02,0.1091E-01)
55	CORE SPRAY	B	4	S	M	C	S03	0.3505E-02	(0.1498E-02,0.8202E-02)
56	CORE SPRAY BOOSTER	B	4	S	M	C	S03	0.3505E-02	(0.1498E-02,0.8202E-02)
57	DIESEL-GENERATOR TRANSFER	B	4	S	D	C	E04	0.6251E-02	(0.2354E-02,0.1660E-01)
58	EMER DIESEL-GENERATOR FUEL	B	4	S	D	PD	E04	0.2341E-02	(0.7343E-03,0.7461E-02)
59	EMER SERVICE WATER	B	4	S	M	C	W04	0.1690E-01	(0.8691E-02,0.3285E-01)
60	FIRE	B	4	S	D	C	X02	0.3283E-01	(0.1628E-01,0.6622E-01)
61	FIRE JOCKEY	B	4	S	M	C	X02	0.2565E-01	(0.1342E-01,0.4902E-01)
62	REACTOR BUILDING CLOSED COOLING	B	4	A	M	C	W03	0.3972E-02	(0.2169E-02,0.7275E-02)
63	RESIDUAL HEAT REMOVAL	B	4	A	M	C	N08	0.5759E-02	(0.3041E-02,0.1091E-01)
64	SERVICE WATER	B	4	A	M	C	W04	0.3972E-02	(0.2169E-02,0.7275E-02)
65	LIQUID CONTROL (POISON)	B	4	S	M	PD	N05	0.9172E-02	(0.4112E-02,0.2046E-01)

TABLE XIV

DEGRADED DEMAND-RELATED FRAC PUMP FAILURE RATE ESTIMATES PER DEMAND

1	AUX FW	P	1	S	D	C	S05	0.1478E+00	(0.6088E-01,0.3587E+00)
2	AUX FW	P	1	S	T	C	S05	0.1414E-01	(0.2800E-02,0.7141E-01)
3	BORIC ACID TRANSFER	P	1	A	M	C	N09	0.7459E-01	(0.4570E-01,0.1217E+00)
4	BORON INJECTION RECIRCULATION	P	1	A	M	C	N09	0.7459E-01	(0.4570E-01,0.1217E+00)
5	CENTRIFUGAL CHARGING	P	1	S	M	C	N09	0.7459E-01	(0.4570E-01,0.1217E+00)
6	COMPONENT-COOLING WATER	P	1	A	M	C	W03	0.3135E-01	(0.1905E-01,0.5158E-01)
7	CONTAINMENT SPRAY	P	1	S	M	C	C10	0.5800E-02	(0.4888E-03,0.6882E-01)
8	DIESEL FUEL OIL TRANSFER	P	1	S	M	C	E04	0.5120E-02	(0.1067E-02,0.2458E-01)
9	FIRE	P	1	S	M	C	X02	0.1955E-01	(0.6145E-02,0.6222E-01)
10	FIRE	P	1	S	D	C	X02	0.6457E-01	(0.1338E-01,0.3116E+00)
11	FIRE JOCKEY	P	1	S	M	C	X02	0.1955E-01	(0.6145E-02,0.6222E-01)
12	FW TURBINE EMER LUBE OIL	P	1	S	M	PD	P05	0.2705E-02	(0.8181E-04,0.8941E-01)
13	FW TURBINE LUBE OIL TRANSFER	P	1	S	M	PD	P05	0.2705E-02	(0.8181E-04,0.8941E-01)
14	RESIDUAL HEAT REMOVAL	P	1	A	M	C	N08	0.7459E-01	(0.4570E-01,0.1217E+00)
15	SAFETY INJECTION	P	1	S	M	C	S03	0.4475E-01	(0.1027E-01,0.1949E+00)
16	SERVICE WATER	P	1	A	M	C	W04	0.3135E-01	(0.1905E-01,0.5158E-01)
17	SERVICE WATER BOOSTER	P	1	A	M	C	W04	0.3135E-01	(0.1905E-01,0.5158E-01)
18	AUX FW	P	2	S	M	C	S05	0.4475E-01	(0.1027E-01,0.1949E+00)
19	AUX FW	P	2	S	T	C	S05	0.1414E-01	(0.2800E-02,0.7141E-01)
20	BORIC ACID TRANSFER	P	2	A	M	C	N09	0.7459E-01	(0.4570E-01,0.1217E+00)
21	BORON INJECTION RECIRCULATION	P	2	A	M	C	S03	0.4475E-01	(0.1027E-01,0.1949E+00)
22	CHARGING/HIGH-HEAD SAFETY INJECTION	P	2	A	M	C	N09	0.7459E-01	(0.4570E-01,0.1217E+00)
23	CHEMICAL ADDITION (CONTAINMENT SPRAY)	P	2	S	M	C	C10	0.5800E-02	(0.4888E-03,0.6882E-01)
24	COMPONENT-COOLING WATER	P	2	A	M	C	W03	0.3135E-01	(0.1905E-01,0.5158E-01)
25	DIESEL-GENERATOR FUEL OIL TRANSFER	P	2	S	M	PD	E04	0.5120E-02	(0.1067E-02,0.2458E-01)
26	DIESEL-GENERATOR OIL CIRCULATION	P	2	S	M	PD	E04	0.5120E-02	(0.1067E-02,0.2458E-01)
27	FILTERED SEAL WATER	P	2	A	M	C	W04	0.3135E-01	(0.1905E-01,0.5158E-01)
28	FIRE	P	2	S	M	PD	X02	0.1955E-01	(0.6145E-02,0.6222E-01)
29	FIRE	P	2	S	D	C	X02	0.6457E-01	(0.1338E-01,0.3116E+00)
30	FUEL OIL TRANSFER	P	2	S	M	PD	X02	0.1955E-01	(0.6145E-02,0.6222E-01)
31	LOW-HEAD SAFETY INJECTION	P	2	S	M	C	S03	0.4475E-01	(0.1027E-01,0.1949E+00)
32	INSIDE RECIRCULATION SPRAY	P	2	S	M	C	C10	0.5800E-02	(0.4888E-03,0.6882E-01)
33	OUTSIDE RECIRCULATION SPRAY	P	2	S	M	C	C10	0.5800E-02	(0.4888E-03,0.6882E-01)
34	QUENCH SPRAY	P	2	S	M	C	C10	0.5800E-02	(0.4888E-03,0.6882E-01)
35	RESIDUAL HEAT REMOVAL	P	2	A	M	C	N08	0.7459E-01	(0.4570E-01,0.1217E+00)
36	SERVICE WATER	P	2	A	M	C	W04	0.3135E-01	(0.1905E-01,0.5158E-01)
37	CONTROL ROD DRIVE	B	3	A	M	C	N02	0.7459E-01	(0.4570E-01,0.1217E+00)
38	CORE SPRAY	B	3	S	M	C	S03	0.4475E-01	(0.1027E-01,0.1949E+00)
39	ENGINE-DRIVEN FUEL	B	3	S	D	C	E04	0.1691E-01	(0.3272E-02,0.8737E-01)
40	FIRE	B	3	S	M	C	X02	0.1955E-01	(0.6145E-02,0.6222E-01)
41	HIGH-PRESSURE COOLANT INJECTION	B	3	S	T	C	S03	0.1414E-01	(0.2800E-02,0.7141E-01)
42	HPCI BOOSTER	B	3	S	T	C	S03	0.1414E-01	(0.2800E-02,0.7141E-01)
43	LUBE OIL TRANSFER	B	3	S	M	C	E04	0.5120E-02	(0.1067E-02,0.2458E-01)
44	RAW COOLING WATER	B	3	A	M	C	W03	0.3135E-01	(0.1905E-01,0.5158E-01)
45	RAW COOLING WATER BOOSTER	B	3	A	M	C	W03	0.3135E-01	(0.1905E-01,0.5158E-01)
46	REACTOR BUILDING CLOSED COOLING	B	3	A	M	C	W03	0.3135E-01	(0.1905E-01,0.5158E-01)
47	REACTOR CORE ISOLATION COOLING	B	3	S	T	C	S01	0.1414E-01	(0.2800E-02,0.7141E-01)
48	RESIDUAL HEAT REMOVAL	B	3	A	M	C	N08	0.7459E-01	(0.4570E-01,0.1217E+00)
49	RHR SERVICE WATER	B	3	A	M	C	W04	0.3135E-01	(0.1905E-01,0.5158E-01)
50	SEAL WATER INJECTION TO FW	B	3	A	M	C	P05	0.2705E-02	(0.8181E-04,0.8941E-01)
51	LIQUID CONTROL	B	3	S	M	PD	N05	0.7459E-01	(0.4570E-01,0.1217E+00)
52	TRANSFER	B	3	S	M	C	E04	0.5120E-02	(0.1067E-02,0.2458E-01)
53	CONTAINMENT SPRAY	B	4	S	M	C	C10	0.5800E-02	(0.4888E-03,0.6882E-01)
54	CONTROL ROD DRIVE	B	4	A	M	C	N02	0.7459E-01	(0.4570E-01,0.1217E+00)
55	CORE SPRAY	B	4	S	M	C	S03	0.4475E-01	(0.1027E-01,0.1949E+00)
56	CORE SPRAY BOOSTER	B	4	S	M	C	S03	0.4475E-01	(0.1027E-01,0.1949E+00)
57	DIESEL-GENERATOR TRANSFER	B	4	S	D	C	E04	0.1691E-01	(0.3272E-02,0.8737E-01)
58	EMER DIESEL-GENERATOR FUEL	B	4	S	D	PD	E04	0.1691E-01	(0.3272E-02,0.8737E-01)
59	EMER SERVICE WATER	B	4	S	M	C	W04	0.3135E-01	(0.1905E-01,0.5158E-01)
60	FIRE	B	4	S	D	C	X02	0.6457E-01	(0.1338E-01,0.3116E+00)
61	FIRE JOCKEY	B	4	S	M	C	X02	0.1955E-01	(0.6145E-02,0.6222E-01)
62	REACTOR BUILDING CLOSED COOLING	B	4	A	M	C	W03	0.3135E-01	(0.1905E-01,0.5158E-01)
63	RESIDUAL HEAT REMOVAL	B	4	A	M	C	N08	0.7459E-01	(0.4570E-01,0.1217E+00)
64	SERVICE WATER	B	4	A	M	C	W04	0.3135E-01	(0.1905E-01,0.5158E-01)
65	LIQUID CONTROL (POISON)	B	4	S	M	PD	N05	0.7459E-01	(0.4570E-01,0.1217E+00)

TABLE XV

INCIPIENT DEMAND-RELATED FRAC PUMP FAILURE RATE ESTIMATES PER DEMAND

1	AUX FW	P	1	S	D	C	S05	0.1032E+00	(0.6629E-01,0.1606E+00)
2	AUX FW	P	1	S	T	C	S05	0.1032E+00	(0.6629E-01,0.1606E+00)
3	BORIC ACID TRANSFER	P	1	A	M	C	N09	0.1438E+00	(0.1030E+00,0.2008E+00)
4	BORON INJECTION RECIRCULATION	P	1	A	M	C	N09	0.1438E+00	(0.1030E+00,0.2008E+00)
5	CENTRIFUGAL CHARGING	P	1	S	M	C	N09	0.1438E+00	(0.1030E+00,0.2008E+00)
6	COMPONENT-COOLING WATER	P	1	A	M	C	W03	0.1317E+00	(0.9143E-01,0.1897E+00)
7	CONTAINMENT SPRAY	P	1	S	M	C	C10	0.4041E-01	(0.1428E-01,0.1143E+00)
8	DIESEL FUEL OIL TRANSFER	P	1	S	M	C	E04	0.2032E-01	(0.5330E-02,0.7748E-01)
9	FIRE	P	1	S	M	C	X02	0.2547E+00	(0.1593E+00,0.4072E+00)
10	FIRE	P	1	S	D	C	X02	0.2547E+00	(0.1593E+00,0.4072E+00)
11	FIRE JOCKEY	P	1	S	M	C	X02	0.2547E+00	(0.1593E+00,0.4072E+00)
12	FW TURBINE EMER LUBE OIL	P	1	S	M	PD	P05	0.2119E-01	(0.3790E-02,0.1185E+00)
13	FW TURBINE LUBE OIL TRANSFER	P	1	S	M	PD	P05	0.2119E-01	(0.3790E-02,0.1185E+00)
14	RESIDUAL HEAT REMOVAL	P	1	A	M	C	N08	0.1438E+00	(0.1030E+00,0.2008E+00)
15	SAFETY INJECTION	P	1	S	M	C	S03	0.1032E+00	(0.6629E-01,0.1606E+00)
16	SERVICE WATER	P	1	A	M	C	W04	0.1317E+00	(0.9143E-01,0.1897E+00)
17	SERVICE WATER BOOSTER	P	1	A	M	C	W04	0.1317E+00	(0.9143E-01,0.1897E+00)
18	AUX FW	P	2	S	M	C	S05	0.1032E+00	(0.6629E-01,0.1606E+00)
19	AUX FW	P	2	S	T	C	S05	0.1032E+00	(0.6629E-01,0.1606E+00)
20	BORIC ACID TRANSFER	P	2	A	M	C	N09	0.1438E+00	(0.1030E+00,0.2008E+00)
21	BORON INJECTION RECIRCULATION	P	2	A	M	C	S03	0.1032E+00	(0.6629E-01,0.1606E+00)
22	CHARGING/HIGH-HEAD SAFETY INJECTION	P	2	A	M	C	N09	0.1438E+00	(0.1030E+00,0.2008E+00)
23	CHEMICAL ADDITION (CONTAINMENT SPRAY)	P	2	S	M	C	C10	0.4041E-01	(0.1428E-01,0.1143E+00)
24	COMPONENT-COOLING WATER	P	2	A	M	C	W03	0.1317E+00	(0.9143E-01,0.1897E+00)
25	DIESEL-GENERATOR FUEL OIL TRANSFER	P	2	S	M	PD	E04	0.2032E-01	(0.5330E-02,0.7748E-01)
26	DIESEL-GENERATOR OIL CIRCULATION	P	2	S	M	PD	E04	0.2032E-01	(0.5330E-02,0.7748E-01)
27	FILTERED SEAL WATER	P	2	A	M	C	W04	0.1317E+00	(0.9143E-01,0.1897E+00)
28	FIRE	P	2	S	M	PD	X02	0.2547E+00	(0.1593E+00,0.4072E+00)
29	FIRE	P	2	S	D	C	X02	0.2547E+00	(0.1593E+00,0.4072E+00)
30	FUEL OIL TRANSFER	P	2	S	M	PD	X02	0.2547E+00	(0.1593E+00,0.4072E+00)
31	LOW-HEAD SAFETY INJECTION	P	2	S	M	C	S03	0.1032E+00	(0.6629E-01,0.1606E+00)
32	INSIDE RECIRCULATION SPRAY	P	2	S	M	C	C10	0.4041E-01	(0.1428E-01,0.1143E+00)
33	OUTSIDE RECIRCULATION SPRAY	P	2	S	M	C	C10	0.4041E-01	(0.1428E-01,0.1143E+00)
34	QUENCH SPRAY	P	2	S	M	C	C10	0.4041E-01	(0.1428E-01,0.1143E+00)
35	RESIDUAL HEAT REMOVAL	P	2	A	M	C	N08	0.1438E+00	(0.1030E+00,0.2008E+00)
36	SERVICE WATER	P	2	A	M	C	W04	0.1317E+00	(0.9143E-01,0.1897E+00)
37	CONTROL ROD DRIVE	B	3	A	M	C	N02	0.4942E-01	(0.3356E-01,0.7278E-01)
38	CORE SPRAY	B	3	S	M	C	S03	0.3546E-01	(0.2199E-01,0.5718E-01)
39	ENGINE-DRIVEN FUEL	B	3	S	D	C	E04	0.6985E-02	(0.1881E-02,0.2594E-01)
40	FIRE	B	3	S	M	C	X02	0.8753E-01	(0.5165E-01,0.1483E+00)
41	HIGH-PRESSURE COOLANT INJECTION	B	3	S	T	C	S03	0.3546E-01	(0.2199E-01,0.5718E-01)
42	HPCI BOOSTER	B	3	S	T	C	S03	0.3546E-01	(0.2199E-01,0.5718E-01)
43	LUBE OIL TRANSFER	B	3	S	M	C	E04	0.6985E-02	(0.1881E-02,0.2594E-01)
44	RAW COOLING WATER	B	3	A	M	C	W03	0.4526E-01	(0.3326E-01,0.6160E-01)
45	RAW COOLING WATER BOOSTER	B	3	A	M	C	W03	0.4526E-01	(0.3326E-01,0.6160E-01)
46	REACTOR BUILDING CLOSED COOLING	B	3	A	M	C	W03	0.4526E-01	(0.3326E-01,0.6160E-01)
47	REACTOR CORE ISOLATION COOLING	B	3	S	T	C	S01	0.3546E-01	(0.2199E-01,0.5718E-01)
48	RESIDUAL HEAT REMOVAL	B	3	A	M	C	N08	0.4942E-01	(0.3356E-01,0.7278E-01)
49	RHR SERVICE WATER	B	3	A	M	C	W04	0.4526E-01	(0.3326E-01,0.6160E-01)
50	SEAL WATER INJECTION TO FW	B	3	A	M	C	P05	0.7285E-02	(0.1321E-02,0.4016E-01)
51	LIQUID CONTROL	B	3	S	M	PD	N05	0.4942E-01	(0.3356E-01,0.7278E-01)
52	TRANSFER	B	3	S	M	C	E04	0.6985E-02	(0.1881E-02,0.2594E-01)
53	CONTAINMENT SPRAY	B	4	S	M	C	C10	0.1389E-01	(0.4718E-02,0.4089E-01)
54	CONTROL ROD DRIVE	B	4	A	M	C	N02	0.4942E-01	(0.3356E-01,0.7278E-01)
55	CORE SPRAY	B	4	S	M	C	S03	0.3546E-01	(0.2199E-01,0.5718E-01)
56	CORE SPRAY BOOSTER	B	4	S	M	C	S03	0.3546E-01	(0.2199E-01,0.5718E-01)
57	DIESEL-GENERATOR TRANSFER	B	4	S	D	C	E04	0.6985E-02	(0.1881E-02,0.2594E-01)
58	EMER DIESEL-GENERATOR FUEL	B	4	S	D	PD	E04	0.6985E-02	(0.1881E-02,0.2594E-01)
59	EMER SERVICE WATER	B	4	S	M	C	W04	0.4526E-01	(0.3326E-01,0.6160E-01)
60	FIRE	B	4	S	D	C	X02	0.8753E-01	(0.5165E-01,0.1483E+00)
61	FIRE JOCKEY	B	4	S	M	C	X02	0.8753E-01	(0.5165E-01,0.1483E+00)
62	REACTOR BUILDING CLOSED COOLING	B	4	A	M	C	W03	0.4526E-01	(0.3326E-01,0.6160E-01)
63	RESIDUAL HEAT REMOVAL	B	4	A	M	C	N08	0.4942E-01	(0.3356E-01,0.7278E-01)
64	SERVICE WATER	B	4	A	M	C	W04	0.4526E-01	(0.3326E-01,0.6160E-01)
65	LIQUID CONTROL (POISON)	B	4	S	M	PD	N05	0.4942E-01	(0.3356E-01,0.7278E-01)

TABLE XVI

CATASTROPHIC TIME-DEPENDENT FRAC PUMP FAILURE RATE ESTIMATES PER OPERATING HOUR

1	BORIC ACID TRANSFER	P	1	A	M	C	NO9	0.9645E-04	(0.4440E-04,0.2095E-03)
2	BORON INJECTION RECIRCULATION	P	1	A	M	C	NO9	0.9645E-04	(0.4440E-04,0.2095E-03)
3	CIRCULATING WATER	P	1	R	M	C	PO6	0.9645E-04	(0.4440E-04,0.2095E-03)
4	COMPONENT-COOLING WATER	P	1	A	M	C	WO3	0.9645E-04	(0.4440E-04,0.2095E-03)
5	CONDENSATE	P	1	R	M	C	PO4	0.9645E-04	(0.4440E-04,0.2095E-03)
6	FW TURBINE MAIN LUBE OIL	P	1	R	M	PD	PO5	0.9645E-04	(0.4440E-04,0.2095E-03)
7	CHARGING	P	1	R	M	PD	NO9	0.9645E-04	(0.4440E-04,0.2095E-03)
8	REACTOR COOLANT	P	1	R	M	C	NO4	0.9645E-04	(0.4440E-04,0.2095E-03)
9	RESIDUAL HEAT REMOVAL	P	1	A	M	C	NO8	0.9645E-04	(0.4440E-04,0.2095E-03)
10	SERVICE WATER	P	1	A	M	C	WO4	0.9645E-04	(0.4440E-04,0.2095E-03)
11	SERVICE WATER BOOSTER	P	1	A	M	C	WO4	0.9645E-04	(0.4440E-04,0.2095E-03)
12	STEAM GENERATOR FEED	P	1	R	T	C	PO5	0.3803E-03	(0.1539E-03,0.9398E-03)
13	BORIC ACID TRANSFER	P	2	A	M	C	NO9	0.9645E-04	(0.4440E-04,0.2095E-03)
14	BORON INJECTION RECIRCULATION	P	2	A	M	C	SO3	0.9645E-04	(0.4440E-04,0.2095E-03)
15	CHARGING/HIGH-HEAD SAFETY INJECTION	P	2	A	M	C	NO9	0.9645E-04	(0.4440E-04,0.2095E-03)
16	CIRCULATING WATER	P	2	R	M	C	PO6	0.9645E-04	(0.4440E-04,0.2095E-03)
17	COMPONENT-COOLING WATER	P	2	A	M	C	WO3	0.9645E-04	(0.4440E-04,0.2095E-03)
18	CONDENSATE	P	2	R	M	C	PO4	0.9645E-04	(0.4440E-04,0.2095E-03)
19	FILTERED SEAL WATER	P	2	A	M	C	WO4	0.9645E-04	(0.4440E-04,0.2095E-03)
20	REACTOR COOLANT	P	2	R	M	C	NO4	0.9645E-04	(0.4440E-04,0.2095E-03)
21	RESIDUAL HEAT REMOVAL	P	2	A	M	C	NO8	0.9645E-04	(0.4440E-04,0.2095E-03)
22	SERVICE WATER	P	2	A	M	C	WO4	0.9645E-04	(0.4440E-04,0.2095E-03)
23	STEAM GENERATOR FEED	P	2	R	M	C	PO5	0.9645E-04	(0.4440E-04,0.2095E-03)
24	CONDENSATE	B	3	R	M	C	PO4	0.2089E-04	(0.9337E-05,0.4672E-04)
25	CONDENSATE BOOSTER	B	3	R	M	C	PO4	0.2089E-04	(0.9337E-05,0.4672E-04)
26	CONDENSER CIRCULATING	B	3	R	M	C	PO6	0.2089E-04	(0.9337E-05,0.4672E-04)
27	CONTROL ROD DRIVE	B	3	A	M	C	NO2	0.2089E-04	(0.9337E-05,0.4672E-04)
28	RAW COOLING WATER	B	3	A	M	C	WO3	0.2089E-04	(0.9337E-05,0.4672E-04)
29	RAW COOLING WATER BOOSTER	B	3	A	M	C	WO3	0.2089E-04	(0.9337E-05,0.4672E-04)
30	REACTOR BUILDING CLOSED COOLING	B	3	A	M	C	WO3	0.2089E-04	(0.9337E-05,0.4672E-04)
31	REACTOR FW	B	3	R	T	C	PO5	0.8234E-04	(0.3361E-04,0.2017E-03)
32	REACTOR RECIRCULATING	B	3	R	M	C	NO4	0.2089E-04	(0.9337E-05,0.4672E-04)
33	RESIDUAL HEAT REMOVAL	B	3	A	M	C	NO8	0.2089E-04	(0.9337E-05,0.4672E-04)
34	RHR SERVICE WATER	B	3	A	M	C	WO4	0.2089E-04	(0.9337E-05,0.4672E-04)
35	SEAL WATER INJECTION TO FW	B	3	A	M	C	PO5	0.2089E-04	(0.9337E-05,0.4672E-04)
36	CIRCULATION	B	4	R	M	C	PO6	0.2089E-04	(0.9337E-05,0.4672E-04)
37	CONDENSATE	B	4	R	M	C	PO4	0.2089E-04	(0.9337E-05,0.4672E-04)
38	CONTROL ROD DRIVE	B	4	A	M	C	NO2	0.2089E-04	(0.9337E-05,0.4672E-04)
39	REACTOR BUILDING CLOSED COOLING	B	4	A	M	C	WO3	0.2089E-04	(0.9337E-05,0.4672E-04)
40	REACTOR FW	B	4	R	M	C	PO5	0.2089E-04	(0.9337E-05,0.4672E-04)
41	REACTOR RECIRCULATING	B	4	R	M	C	NO4	0.2089E-04	(0.9337E-05,0.4672E-04)
42	RESIDUAL HEAT REMOVAL	B	4	A	M	C	NO8	0.2089E-04	(0.9337E-05,0.4672E-04)
43	SERVICE WATER	B	4	A	M	C	WO4	0.2089E-04	(0.9337E-05,0.4672E-04)

TABLE XVII

DEGRADED TIME-DEPENDENT FRAC PUMP FAILURE RATE ESTIMATES PER OPERATING HOUR

1	BORIC ACID TRANSFER	P	1	A	M	C	NO9	0.4356E-03	(0.2062E-03,0.9203E-03)
2	BORON INJECTION RECIRCULATION	P	1	A	M	C	NO9	0.4356E-03	(0.2062E-03,0.9203E-03)
3	CIRCULATING WATER	P	1	R	M	C	PO6	0.1592E-03	(0.9295E-04,0.2726E-03)
4	COMPONENT-COOLING WATER	P	1	A	M	C	WO3	0.7349E-04	(0.3480E-04,0.1552E-03)
5	CONDENSATE	P	1	R	M	C	PO4	0.1592E-03	(0.9295E-04,0.2726E-03)
6	FW TURBINE MAIN LUBE OIL	P	1	R	M	PD	PO5	0.1592E-03	(0.9295E-04,0.2726E-03)
7	CHARGING	P	1	R	M	PD	NO9	0.8845E-04	(0.3044E-04,0.2571E-03)
8	REACTOR COOLANT	P	1	R	M	C	NO4	0.8845E-04	(0.3044E-04,0.2571E-03)
9	RESIDUAL HEAT REMOVAL	P	1	A	M	C	NO8	0.4356E-03	(0.2062E-03,0.9203E-03)
10	SERVICE WATER	P	1	A	M	C	WO4	0.7349E-04	(0.3480E-04,0.1552E-03)
11	SERVICE WATER BOOSTER	P	1	A	M	C	WO4	0.7349E-04	(0.3480E-04,0.1552E-03)
12	STEAM GENERATOR FEED	P	1	R	T	C	PO5	0.1592E-03	(0.9295E-04,0.2726E-03)
13	BORIC ACID TRANSFER	P	2	A	M	C	NO9	0.4356E-03	(0.2062E-03,0.9203E-03)
14	BORON INJECTION RECIRCULATION	P	2	A	M	C	SO3	0.2381E-04	(0.4078E-07,0.1390E-01)
15	CHARGING/HIGH-HEAD SAFETY INJECTION	P	2	A	M	C	NO9	0.4356E-03	(0.2062E-03,0.9203E-03)
16	CIRCULATING WATER	P	2	R	M	C	PO6	0.1592E-03	(0.9295E-04,0.2726E-03)
17	COMPONENT-COOLING WATER	P	2	A	M	C	WO3	0.7349E-04	(0.3480E-04,0.1552E-03)
18	CONDENSATE	P	2	R	M	C	PO4	0.1592E-03	(0.9295E-04,0.2726E-03)
19	FILTERED SEAL WATER	P	2	A	M	C	WO4	0.7349E-04	(0.3480E-04,0.1552E-03)
20	REACTOR COOLANT	P	2	R	M	C	NO4	0.8845E-04	(0.3044E-04,0.2571E-03)
21	RESIDUAL HEAT REMOVAL	P	2	A	M	C	NO8	0.4356E-03	(0.2062E-03,0.9203E-03)
22	SERVICE WATER	P	2	A	M	C	WO4	0.7349E-04	(0.3480E-04,0.1552E-03)
23	STEAM GENERATOR FEED	P	2	R	M	C	PO5	0.1592E-03	(0.9295E-04,0.2726E-03)
24	CONDENSATE	B	3	R	M	C	PO4	0.7084E-04	(0.3934E-04,0.1276E-03)
25	CONDENSATE BOOSTER	B	3	R	M	C	PO4	0.7084E-04	(0.3934E-04,0.1276E-03)
26	CONDENSER CIRCULATING	B	3	R	M	C	PO6	0.7084E-04	(0.3934E-04,0.1276E-03)
27	CONTROL ROD DRIVE	B	3	A	M	C	NO2	0.1939E-03	(0.1112E-03,0.3382E-03)
28	RAW COOLING WATER	B	3	A	M	C	WO3	0.3271E-04	(0.1539E-04,0.6949E-04)
29	RAW COOLING WATER BOOSTER	B	3	A	M	C	WO3	0.3271E-04	(0.1539E-04,0.6949E-04)
30	REACTOR BUILDING CLOSED COOLING	B	3	A	M	C	WO3	0.3271E-04	(0.1539E-04,0.6949E-04)
31	REACTOR FW	B	3	R	T	C	PO5	0.7084E-04	(0.3934E-04,0.1276E-03)
32	REACTOR RECIRCULATING	B	3	R	M	C	NO4	0.3937E-04	(0.1436E-04,0.1079E-03)
33	RESIDUAL HEAT REMOVAL	B	3	A	M	C	NO8	0.1939E-03	(0.1112E-03,0.3382E-03)
34	RHR SERVICE WATER	B	3	A	M	C	WO4	0.3271E-04	(0.1539E-04,0.6949E-04)
35	SEAL WATER INJECTION TO FW	B	3	A	M	C	PO5	0.3489E-03	(0.1018E-03,0.1195E-02)
36	CIRCULATION	B	4	R	M	C	PO6	0.7084E-04	(0.3934E-04,0.1276E-03)
37	CONDENSATE	B	4	R	M	C	PO4	0.7084E-04	(0.3934E-04,0.1276E-03)
38	CONTROL ROD DRIVE	B	4	A	M	C	NO2	0.1939E-03	(0.1112E-03,0.3382E-03)
39	REACTOR BUILDING CLOSED COOLING	B	4	A	M	C	WO3	0.3271E-04	(0.1539E-04,0.6949E-04)
40	REACTOR FW	B	4	R	M	C	PO5	0.7084E-04	(0.3934E-04,0.1276E-03)
41	REACTOR RECIRCULATING	B	4	R	M	C	NO4	0.3937E-04	(0.1436E-04,0.1079E-03)
42	RESIDUAL HEAT REMOVAL	B	4	A	M	C	NO8	0.1939E-03	(0.1112E-03,0.3382E-03)
43	SERVICE WATER	B	4	A	M	C	WO4	0.3271E-04	(0.1539E-04,0.6949E-04)

TABLE XVIII

INCIPIENT TIME-DEPENDENT FRAC PUMP FAILURE RATE ESTIMATES PER OPERATING HOUR

1	BORIC ACID TRANSFER	P	1	A	M	C	NO9	0.4525E-03	(0.3413E-03,0.5999E-03)
2	BORON INJECTION RECIRCULATION	P	1	A	M	C	NO9	0.4525E-03	(0.3413E-03,0.5999E-03)
3	CIRCULATING WATER	P	1	R	M	C	PO6	0.4525E-03	(0.3413E-03,0.5999E-03)
4	COMPONENT-COOLING WATER	P	1	A	M	C	WO3	0.4525E-03	(0.3413E-03,0.5999E-03)
5	CONDENSATE	P	1	R	M	C	PO4	0.4525E-03	(0.3413E-03,0.5999E-03)
6	FW TURBINE MAIN LUBE OIL	P	1	R	M	PD	PO5	0.4525E-03	(0.3413E-03,0.5999E-03)
7	CHARGING	P	1	R	M	PD	NO9	0.4525E-03	(0.3413E-03,0.5999E-03)
8	REACTOR COOLANT	P	1	R	M	C	NO4	0.4525E-03	(0.3413E-03,0.5999E-03)
9	RESIDUAL HEAT REMOVAL	P	1	A	M	C	NO8	0.4525E-03	(0.3413E-03,0.5999E-03)
10	SERVICE WATER	P	1	A	M	C	WO4	0.4525E-03	(0.3413E-03,0.5999E-03)
11	SERVICE WATER BOOSTER	P	1	A	M	C	WO4	0.4525E-03	(0.3413E-03,0.5999E-03)
12	STEAM GENERATOR FEED	P	1	R	T	C	PO5	0.9769E-03	(0.5874E-03,0.1625E-02)
13	BORIC ACID TRANSFER	P	2	A	M	C	NO9	0.4525E-03	(0.3413E-03,0.5999E-03)
14	BORON INJECTION RECIRCULATION	P	2	A	M	C	SO3	0.4525E-03	(0.3413E-03,0.5999E-03)
15	CHARGING/HIGH-HEAD SAFETY INJECTION	P	2	A	M	C	NO9	0.4525E-03	(0.3413E-03,0.5999E-03)
16	CIRCULATING WATER	P	2	R	M	C	PO6	0.4525E-03	(0.3413E-03,0.5999E-03)
17	COMPONENT-COOLING WATER	P	2	A	M	C	WO3	0.4525E-03	(0.3413E-03,0.5999E-03)
18	CONDENSATE	P	2	R	M	C	PO4	0.4525E-03	(0.3413E-03,0.5999E-03)
19	FILTERED SEAL WATER	P	2	A	M	C	WO4	0.4525E-03	(0.3413E-03,0.5999E-03)
20	REACTOR COOLANT	P	2	R	M	C	NO4	0.4525E-03	(0.3413E-03,0.5999E-03)
21	RESIDUAL HEAT REMOVAL	P	2	A	M	C	NO8	0.4525E-03	(0.3413E-03,0.5999E-03)
22	SERVICE WATER	P	2	A	M	C	WO4	0.4525E-03	(0.3413E-03,0.5999E-03)
23	STEAM GENERATOR FEED	P	2	R	M	C	PO5	0.4525E-03	(0.3413E-03,0.5999E-03)
24	CONDENSATE	B	3	R	M	C	PO4	0.1364E-03	(0.1020E-03,0.1825E-03)
25	CONDENSATE BOOSTER	B	3	R	M	C	PO4	0.1364E-03	(0.1020E-03,0.1825E-03)
26	CONDENSER CIRCULATING	B	3	R	M	C	PO6	0.1364E-03	(0.1020E-03,0.1825E-03)
27	CONTROL ROD DRIVE	B	3	A	M	C	NO2	0.1364E-03	(0.1020E-03,0.1825E-03)
28	RAW COOLING WATER	B	3	A	M	C	WO3	0.1364E-03	(0.1020E-03,0.1825E-03)
29	RAW COOLING WATER BOOSTER	B	3	A	M	C	WO3	0.1364E-03	(0.1020E-03,0.1825E-03)
30	REACTOR BUILDING CLOSED COOLING	B	3	A	M	C	WO3	0.1364E-03	(0.1020E-03,0.1825E-03)
31	REACTOR FW	B	3	R	T	C	PO5	0.2946E-03	(0.1691E-03,0.5132E-03)
32	REACTOR RECIRCULATING	B	3	R	M	C	NO4	0.1364E-03	(0.1020E-03,0.1825E-03)
33	RESIDUAL HEAT REMOVAL	B	3	A	M	C	NO8	0.1364E-03	(0.1020E-03,0.1825E-03)
34	RHR SERVICE WATER	B	3	A	M	C	WO4	0.1364E-03	(0.1020E-03,0.1825E-03)
35	SEAL WATER INJECTION TO FW	B	3	A	M	C	PO5	0.1334E-03	(0.1020E-03,0.1825E-03)
36	CIRCULATION	B	4	R	M	C	PO6	0.1364E-03	(0.1020E-03,0.1825E-03)
37	CONDENSATE	B	4	R	M	C	PO4	0.1364E-03	(0.1020E-03,0.1825E-03)
38	CONTROL ROD DRIVE	B	4	A	M	C	NO2	0.1364E-03	(0.1020E-03,0.1825E-03)
39	REACTOR BUILDING CLOSED COOLING	B	4	A	M	C	WO3	0.1364E-03	(0.1020E-03,0.1825E-03)
40	REACTOR FW	B	4	R	M	C	PO5	0.1364E-03	(0.1020E-03,0.1825E-03)
41	REACTOR RECIRCULATING	B	4	R	M	C	NO4	0.1364E-03	(0.1020E-03,0.1825E-03)
42	RESIDUAL HEAT REMOVAL	B	4	A	M	C	NO8	0.1364E-03	(0.1020E-03,0.1825E-03)
43	SERVICE WATER	B	4	A	M	C	WO4	0.1364E-03	(0.1020E-03,0.1825E-03)

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APPENDIX A

CODED IPRDS PUMP FAILURE DATA BASES

TABLE A-I

DESCRIPTION OF THE DEMAND-RELATED FAILURE DATA BASE

Factors	Columns
RTYPE (Reactor Type)	(2)
PWR	1
BWR	2
SYSTEM	(4)
Nuclear	1
Engineered Safety	2
Containment	3
Electrical	4
Power Conversion	5
Process Auxiliary	6
Plant Auxiliary	7
PLANT	(43)
Plant 1 (PWR)	1
Plant 2 (PWR)	2
Plant 3 (BWR)	3
Plant 4 (BWR)	4
OPMODE (Operating Mode)	(45)
Standby	1
Alternating	2
PTYPE (Pump Type)	(47)
Positive Displacement	1
Centrifugal	2
DRIVER	(49)
Motor	1
Diesel	2
Turbine	3
Number of Catastrophic Demand-Related Failures	(50-54)
Number of Degraded Demand-Related Failures	(55-59)
Number of Incipient Demand-Related Failures	(60-65)
Population Demands[a]	(66-74)

[a]Total number of component demands in the operating period.

TABLE A-II

THE CODED PUMP DEMAND-RELATED FAILURE DATA BASE

1	2	AUX FW	1	1	2	2	1	14	12	60
1	2	AUX FW	1	1	2	3	1	2	7	60
1	1	BORIC ACID TRANSFER	1	2	2	1	2	1	11	120
1	1	BORON INJECTION RECIRCULATION	1	2	2	1	0	3	34	120
1	1	CENTRIFUGAL CHARGING	1	1	2	1	4	1	19	120
1	6	COMPONENT-COOLING WATER	1	2	2	1	0	0	15	180
1	3	CONTAINMENT SPRAY	1	1	2	1	1	0	7	120
1	4	DIESEL FUEL OIL TRANSFER	1	1	2	1	2	0	0	120
1	7	FIRE	1	1	2	1	2	4	7	60
1	7	FIRE	1	1	2	2	1	1	4	60
1	7	FIRE JOCKEY	1	1	2	1	0	1	29	60
1	5	FW TURBINE EMER LUBE OIL	1	1	1	1	0	0	1	120
1	5	FW TURBINE LUBE OIL TRANSFER	1	1	1	1	0	0	0	60
1	1	RESIDUAL HEAT REMOVAL	1	2	2	1	3	0	13	120
1	2	SAFETY INJECTION	1	1	2	1	1	0	14	120
1	6	SERVICE WATER	1	2	2	1	0	6	16	180
1	6	SERVICE WATER BOOSTER	1	2	2	1	1	6	20	240
1	2	AUX FW	2	1	2	1	0	1	3	38
1	2	AUX FW	2	1	2	3	0	0	4	19
1	1	BORIC ACID TRANSFER	2	2	2	1	0	0	0	38
1	2	BORON INJECTION RECIRCULATION	2	2	2	1	0	0	4	38
1	1	CHARGING/HIGH-HEAD SAFETY INJECTION	2	2	2	1	2	4	7	58
1	3	CHEMICAL ADDITION (CONTAINMENT SPRAY)	2	1	2	1	1	0	1	19
1	6	COMPONENT-COOLING WATER	2	2	2	1	0	0	0	58
1	4	DIESEL-GENERATOR FUEL OIL TRANSFER	2	1	1	1	0	2	0	77
1	4	DIESEL-GENERATOR OIL CIRCULATION	2	1	1	1	0	0	1	38
1	6	FILTERED SEAL WATER	2	2	2	1	0	0	0	38
1	7	FIRE	2	1	1	1	1	1	2	19
1	7	FIRE	2	1	2	2	5	0	1	19
1	7	FUEL OIL TRANSFER	2	1	1	1	0	0	0	19
1	2	LOW-HEAD SAFETY INJECTION	2	1	2	1	0	0	0	38
1	3	INSIDE RECIRCULATION SPRAY	2	1	2	1	0	0	0	38
1	3	OUTSIDE RECIRCULATION SPRAY	2	1	2	1	0	0	0	38
1	3	QUENCH SPRAY	2	1	2	1	0	0	1	38
1	1	RESIDUAL HEAT REMOVAL	2	2	2	1	0	0	1	38
1	6	SERVICE WATER	2	2	2	1	0	2	4	58
2	1	CONTROL ROD DRIVE	3	2	2	1	1	34	9	210
2	2	CORE SPRAY	3	1	2	1	0	0	4	520
2	4	ENGINE-DRIVEN FUEL	3	1	2	2	0	0	0	520
2	7	FIRE	3	1	2	1	6	1	2	170
2	2	HIGH-PRESSURE COOLANT INJECTION	3	1	2	3	4	1	3	130
2	2	HPCI BOOSTER	3	1	2	3	0	0	5	130
2	4	LUBE OIL TRANSFER	3	1	2	1	1	0	1	56
2	6	RAW COOLING WATER	3	2	2	1	3	1	16	520
2	6	RAW COOLING WATER BOOSTER	3	2	2	1	0	1	14	184
2	6	REACTOR BUILDING CLOSED COOLING	3	2	2	1	0	1	6	390
2	2	REACTOR CORE ISOLATION COOLING	3	1	2	3	0	1	0	130
2	1	RESIDUAL HEAT REMOVAL	3	2	2	1	2	2	7	520
2	6	RHR SERVICE WATER	3	2	2	1	2	9	43	430
2	5	SEAL WATER INJECTION TO FW	3	2	2	1	0	0	3	260
2	1	LIQUID CONTROL	3	1	1	1	3	4	11	260
2	4	TRANSFER	3	1	2	1	0	0	1	960
2	3	CONTAINMENT SPRAY	4	1	2	1	2	0	2	288
2	1	CONTROL ROD DRIVE	4	2	2	1	1	0	8	144
2	2	CORE SPRAY	4	1	2	1	1	0	10	288
2	2	CORE SPRAY BOOSTER	4	1	2	1	0	0	4	288
2	4	DIESEL-GENERATOR TRANSFER	4	1	2	2	0	0	0	287
2	4	EMER DIESEL-GENERATOR FUEL	4	1	1	2	0	2	3	144
2	6	EMER SERVICE WATER	4	1	2	1	6	20	11	288
2	7	FIRE	4	1	2	2	2	1	14	144
2	7	FIRE JOCKEY	4	1	2	1	0	0	0	72
2	6	REACTOR BUILDING CLOSED COOLING	4	2	2	1	0	0	6	144
2	1	RESIDUAL HEAT REMOVAL	4	2	2	1	0	0	2	216
2	6	SERVICE WATER	4	2	2	1	1	2	7	144
2	1	LIQUID CONTROL (POISON)	4	1	1	1	0	0	9	144

TABLE A-III

DESCRIPTION OF THE TIME-DEPENDENT FAILURE DATA BASE

Factors	Columns
RTYPE (Reactor Type)	(2)
PWR	1
BWR	2
SYSTEM	(4)
Nuclear	1
Engineered Safety	2
Power Conversion	3
Process Auxiliary	4
PLANT	(43)
Plant 1 (PWR)	1
Plant 2 (PWR)	2
Plant 3 (BWR)	3
Plant 4 (BWR)	4
OPMODE (Operating Mode)	(45)
Running	1
Alternating	2
PTYPE (Pump Type)	(47)
Positive Displacement	1
Centrifugal	2
DRIVER	(49)
Motor	1
Turbine	2
Number of Catastrophic Time-Dependent Failures	(50-54)
Number of Degraded Time-Dependent Failures	(55-59)
Number of Incipient Time-Dependent Failures	(60-65)
Population Hours[a]	(66-74)

[a]Total number of component hours (in the operating mode) in the operating period.

TABLE A-IV

THE CODED PUMP TIME-RELATED FAILURE DATA BASE

1	1	BORIC ACID TRANSFER	1	2	2	1	0	1	11	44000
1	1	BORON INJECTION RECIRCULATION	1	2	2	1	0	3	34	44000
1	3	CIRCULATING WATER	1	1	2	1	5	4	23	48400
1	4	COMPONENT-COOLING WATER	1	2	2	1	1	0	15	44000
1	3	CONDENSATE	1	1	2	1	3	5	18	48000
1	3	FW TURBINE MAIN LUBE OIL	1	1	1	1	0	1	1	48000
1	1	CHARGING	1	1	1	1	1	4	25	24000
1	1	REACTOR COOLANT	1	1	2	1	1	0	28	96800
1	1	RESIDUAL HEAT REMOVAL	1	2	2	1	1	0	13	20000
1	4	SERVICE WATER	1	2	2	1	3	6	16	79000
1	4	SERVICE WATER BOOSTER	1	2	2	1	5	6	20	110000
1	3	STEAM GENERATOR FEED	1	1	2	2	8	11	59	48000
1	1	BORIC ACID TRANSFER	2	2	2	1	0	0	0	14000
1	2	BORON INJECTION RECIRCULATION	2	2	2	1	4	0	4	14000
1	1	CHARGING/HIGH-HEAD SAFETY INJECTION	2	2	2	1	2	4	7	6500
1	3	CIRCULATING WATER	2	1	2	1	3	3	18	25800
1	4	COMPONENT-COOLING WATER	2	2	2	1	0	0	0	14000
1	3	CONDENSATE	2	1	2	1	3	10	4	13000
1	4	FILTERED SEAL WATER	2	2	2	1	0	0	0	14000
1	1	REACTOR COOLANT	2	1	2	1	0	0	1	19320
1	1	RESIDUAL HEAT REMOVAL	2	2	2	1	0	0	1	7600
1	4	SERVICE WATER	2	2	2	1	3	2	4	25000
1	3	STEAM GENERATOR FEED	2	1	2	1	6	2	8	13000
2	3	CONDENSATE	3	1	2	1	0	1	9	160000
2	3	CONDENSATE BOOSTER	3	1	2	1	0	6	33	160000
2	3	CONDENSER CIRCULATING	3	1	2	1	2	5	6	160000
2	1	CONTROL ROD DRIVE	3	2	2	1	3	34	9	110000
2	4	RAW COOLING WATER	3	2	2	1	4	1	16	230000
2	4	RAW COOLING WATER BOOSTER	3	2	2	1	0	1	14	82000
2	4	REACTOR BUILDING CLOSED COOLING	3	2	2	1	0	1	6	95000
2	3	REACTOR FW	3	1	2	2	13	14	30	160000
2	1	REACTOR RECIRCULATING	3	1	2	1	0	4	13	110000
2	1	RESIDUAL HEAT REMOVAL	3	2	2	1	1	2	7	42000
2	4	RHR SERVICE WATER	3	2	2	1	3	9	43	110000
2	3	SEAL WATER INJECTION TO FW	3	2	2	1	1	0	3	54000
2	3	CIRCULATION	4	1	2	1	1	0	6	150000
2	3	CONDENSATE	4	1	2	1	1	0	4	110000
2	1	CONTROL ROD DRIVE	4	2	2	1	2	0	8	37000
2	4	REACTOR BUILDING CLOSED COOLING	4	2	2	1	0	0	6	53000
2	3	REACTOR FW	4	1	2	1	1	0	19	110000
2	1	REACTOR RECIRCULATING	4	1	2	1	2	5	25	187000
2	1	RESIDUAL HEAT REMOVAL	4	2	2	1	1	0	2	15000
2	4	SERVICE WATER	4	2	2	1	4	2	7	84000

APPENDIX B

DEGRADED AND INCIPIENT DEMAND-RELATED PUMP FAILURE RATE ANALYSES

TABLE B-I

DEGRADED DEMAND-RELATED FRAC FAILURE RATE MODEL ANALYSIS

One-Factor Models	P-Values
RTYPE	---
SYSTEM	0.1085×10^{-1}
OPMODE	0.6203
PTYPE	0.8493×10^{-1}
DRIVER	0.8888×10^{-1}

Two-Factor Models	P-Values
RTYPE, PLANT	0.9137
RTYPE, SYSTEM	0.2035×10^{-1}
RTYPE, OPMODE	0.9021
RTYPE, PTYPE	0.2310
RTYPE, DRIVER	0.1549
SYSTEM, OPMODE	0.1473×10^{-1}
SYSTEM, PTYPE	0.1687×10^{-1}
SYSTEM, DRIVER	0.1670×10^{-2}
OPMODE, DRIVER	0.9448×10^{-1}
OPMODE, PTYPE	0.2313
DRIVER, PTYPE	0.3525×10^{-1}

Three-Factor Models	P-Values
RTYPE, SYSTEM, PLANT	---
RYPTE, OPMODE, PLANT	---
RTYPE, PTYPE, PLANT	---
RTYPE, DRIVER, PLANT	---
RTYPE, SYSTEM, OPMODE	0.2364×10^{-1}
RTYPE, SYSTEM, PTYPE	0.2973×10^{-1}
RTYPE, SYSTEM, DRIVER	0.3389×10^{-2}
RTYPE, SYSTEM, PTYPE	0.6060×10^{-1}
SYSTEM, PTYPE, OPMODE	0.1532×10^{-1}
SYSTEM, DRIVER, OPMODE	0.2285×10^{-2}
PTYPE, DRIVER, OPMODE	0.6255×10^{-1}
PTYPE, RTYPE, OPMODE	0.4114×10^{0}
DRIVER, RTYPE, OPMODE	0.1496×10^{0}
DRIVER, SYSTEM, PTYPE	0.2727×10^{-2}

TABLE B-I (cont)

Four-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE	---
RTYPE, PLANT, SYSTEM, PTYPE	---
RTYPE, PLANT, SYSTEM, DRIVER	---
RTYPE, PLANT, OPMODE, PTYPE	0.3912
RTYPE, PLANT, OPMODE, DRIVER	---
RTYPE, PLANT, PTYPE, DRIVER	---
SYSTEM, RTYPE, DRIVER, OPMODE	0.4265×10^{-2}
SYSTEM, RTYPE, DRIVER, PTYPE	0.5271×10^{-2}
SYSTEM, RTYPE, OPMODE, PTYPE	0.2191×10^{-1}
DRIVER, RTYPE, OPMODE, PTYPE	0.9620×10^{-1}
DRIVER, SYSTEM, OPMODE, PTYPE	0.2473×10^{-2}

Five-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE, PTYPE	---
RTYPE, PLANT, SYSTEM, OPMODE, DRIVER	---
RTYPE, PLANT, SYSTEM, DRIVER, PTYPE	---
RTYPE, PLANT, OPMODE, PTYPE, DRIVER	---
RTYPE, SYSTEM, PTYPE, DRIVER, OPMODE	0.4270×10^{-2}

Six-Factor Model	P-Value
RTYPE, PLANT, OPMODE DRIVER, PTYPE, SYSTEM	---

TABLE B-II

DEGRADED DEMAND-RELATED MSS FRAC MODEL

Average Failure Rate Estimate--1.51×10^{-2}(8.091×10^{-3})

Fixed Factors

Level of Influence	Factor	Level	Description	R_j	Failure Rate Adjustment
1	SYSTEM	1	Nuclear	27.78	5.00 (2.188)
		2	Engineered Safety		3.00 (2.037)
		3	Containment		0.39 (0.441)
		4	Electrical		0.34 (0.250)
		5	Power Conversion		0.18 (0.282)
		6	Process Auxiliary		2.10 (0.923)
		7	Plant Auxiliary		1.31 (0.774)
2	DRIVER	1	Motor	10.52	0.99 (0.542)
		2	Diesel		3.26 (1.389)
		3	Turbine		0.31 (0.200)

Random Factor

Factor	Variance Component
ERROR	3.186

TABLE B-III

BEST AND WORST CASE DEGRADED DEMAND-RELATED FRAC
PUMP FAILURE RATE ESTIMATES

Case	SYSTEM	DRIVER	Estimate
Best	Power Conversion	Turbine	8.64×10^{-5}/d
Worst	Nuclear	Diesel	2.49×10^{-1}/d

Note: $2.49 \times 10^{-1}/8.64 \times 10^{-5} = 2882 \approx 3.5$ orders of magnitude between the best and worst case estimates.

TABLE B-IV

DEGRADED DEMAND-RELATED FRAC FAILURE RATE MODEL ANALYSIS

One-Factor Models	P-Value
RTYPE	0.1344×10^{-6}
SYSTEM	0.1393×10^{-2}
OPMODE	0.9042
PTYPE	0.1504
DRIVER	0.9503

Two-Factor Models	P-Value
RTYPE, PLANT	---
RTYPE, SYSTEM	0.5548×10^{-8}
RTYPE, OPMODE	0.9165×10^{-6}
RTYPE, PTYPE	0.7489×10^{-6}
RTYPE, DRIVER	0.3316×10^{-5}
SYSTEM, OPMODE	0.2208×10^{-2}
SYSTEM, PTYPE	0.1642×10^{-2}
SYSTEM, DRIVER	0.6158×10^{-2}
OPMODE, DRIVER	0.9959
OPMODE, PTYPE	0.2933
DRIVER, PTYPE	0.5301

Three-Factor Models	P-Value
RTYPE, SYSTEM, PLANT	---
RTYPE, OPMODE, PLANT	---
RTYPE, PTYPE, PLANT	---
RTYPE, DRIVER, PLANT	---
RTYPE, SYSTEM, OPMODE	0.1704×10^{-7}
RTYPE, SYSTEM, PTYPE	0.1707×10^{-7}
RTYPE, SYSTEM, DRIVER	0.4090×10^{-7}
RTYPE, SYSTEM, PTYPE	0.9400×10^{-5}
SYSTEM, PTYPE, OPMODE	0.3291×10^{-2}
SYSTEM, DRIVER, OPMODE	0.8709×10^{-2}
PTYPE, DRIVER, OPMODE	0.6328
PTYPE, RTYPE, OPMODE	0.3374×10^{-5}
DRIVER, RTYPE, OPMODE	0.1104×10^{-4}
DRIVER, SYSTEM, PTYPE	0.6690×10^{-2}

TABLE B-IV (cont)

Four-Factor Models	P-Value
RTYPE, PLANT, SYSTEM, OPMODE	---
RTYPE, PLANT, SYSTEM, PTYPE	---
RTYPE, PLANT, SYSTEM, DRIVER	---
RTYPE, PLANT, OPMODE, PTYFE	---
RTYPE, PLANT, OPMODE, DRIVER	---
RTYPE, PLANT, PTYPE, DRIVER	---
SYSTEM, RTYPE, DRIVER, OPMODE	0.1116×10^{-6}
SYSTEM, RTYPE, DRIVER, PTYPE	0.1121×10^{-6}
SYSTEM, RTYPE, OPMODE, PTYPE	0.4927×10^{-7}
DRIVER, RTYPE, OPMODE, PTYPE	0.2860×10^{-4}
DRIVER, SYSTEM, OPMODE, PTYPE	0.1186×10^{-1}

Five-Factor Models	P-Value
RTYPE, PLANT, SYSTEM, OPMODE, PTYPE	---
RTYPE, PLANT, SYSTEM, OPMODE, DRIVER	---
RTYPE, PLANT, SYSTEM, DRIVER, PTYPE	---
RTYPE, PLANT, OPMODE, PTYPE, DRIVER	---
RTYPE, SYSTEM, PTYPE, DRIVER, OPMODE	0.2919×10^{-6}

Six-Factor Model	P-Value
RTYPE, PLANT, SYSTEM OPMODE, PTYPE, DRIVER	---

TABLE B-V

INCIPIENT DEMAND-RELATED MSS FRAC MODEL

Average Failure Rate Estimate--4.13×10^{-2}(7.541×10^{-3})

Fixed Factors

Level of Influence	Factor	Level	Description	R_j	Failure Rate Adjustment
1	SYSTEM	1	Nuclear	12.45	2.04 (0.463)
		2	Engineered Safety		1.46 (0.378)
		3	Containment		0.57 (0.279)
		4	Electrical		0.29 (0.172)
		5	Power Conversion		0.30 (0.228)
		6	Process Auxiliary		1.87 (0.413)
		7	Plant Auxiliary		3.61 (0.980)
2	RTYPE	1	PWR	2.90	1.71 (0.156)
		2	BRW		0.59 (0.054)

Random Factor

Factor	Variance Component
ERROR	3.273

TABLE B-VI

BEST AND WORST CASE DEGRADED DEMAND-RELATED FRAC PUMP FAILURE RATE ESTIMATES

Case	SYSTEM	RTYPE	Estimate
Best	Electrical	BWR	7.00×10^{-3}/d
Worst	Plant Auxiliary	PWR	2.55×10^{-1}/d

Note: $2.55 \times 10^{-1}/7.00 \times 10^{-3} = 36.43 \approx 1.6$ orders of magnitude between the best and worst case estimates.

APPENDIX C

DEGRADED AND INCIPIENT TIME-DEPENDENT PUMP FAILURE RATE ANALYSES

TABLE C-I

DEGRADED TIME-DEPENDENT FRAC FAILURE RATE MODEL ANALYSIS

One-Factor Models	P-Values
RTYPE	0.1805
SYSTEM	0.0993
OPMODE	0.5078
PTYPE	---
DRIVER	0.6614

Two-Factor Models	P-Values
RTYPE, PLANT	0.1696
RTYPE, SYSTEM	0.0298
RTYPE, OPMODE	0.2501
RTYPE, PTYPE	0.4016
RTYPE, DRIVER	0.3764
SYSTEM, OPMODE	0.0153
SYSTEM, PTYPE	0.1792
SYSTEM, DRIVER	0.1691
OPMODE, DRIVER	0.5640
OPMODE, PTYPE	0.8220
DRIVER, PTYPE	0.9365

Three-Factor Models	P-Values
RTYPE, PLANT, SYSTEM	0.0165
RTYPE, PLANT, OPMODE	0.2115
RTYPE, PLANT, PTYPE	0.3145
RTYPE, PLANT, DRIVER	0.2545
RTYPE, SYSTEM, OPMODE	0.0021
RTYPE, SYSTEM, PTYPE	0.0397
RTYPE, SYSTEM, DRIVER	0.0447
RTYPE, PTYPE, SYSTEM	0.5858
PTYPE, SYSTEM, OPMODE	0.0253
DRIVER, OPMODE, SYSTEM	0.0285
OPMODE, PTYPE, DRIVER	0.7671
RTYPE, PTYPE, OPMODE	0.4387
RTYPE, DRIVER, OPMODE	0.2847
SYSTEM, DRIVER, PTYPE	0.2693

TABLE C-I (cont)

Four-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE	0.0035
RTYPE, PLANT, SYSTEM, PTYPE	0.0249
RTYPE, PLANT, SYSTEM, DRIVER	0.0121
RTYPE, PLANT, OPMODE, PTYPE	0.3386
RTYPE, PLANT, OPMODE, DRIVER	0.1724
RTYPE, PLANT, PTYPE, DRIVER	0.3957
SYSTEM, RTYPE, DRIVER, OPMODE	0.0031
RTYPE, PTYPE, DRIVER, SYSTEM	0.0561
PTYPE, SYSTEM, OPMODE, RTYPE	0.0049
DRIVER, OPMODE, RTYPE, PTYPE	0.4516
OPMODE, PTYPE, DRIVER, SYSTEM	0.0424

Five-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE, PTYPE	0.6799×10^{-2}
RTYPE, PLANT, SYSTEM, OPMODE, DRIVER	0.2790×10^{-2}
RTYPE, PLANT, SYSTEM, DRIVER, PTYPE	0.1892×10^{-1}
RTYPE, PLANT, OPMODE, PTYPE, DRIVER	0.2483×10^{0}
RTYPE, SYSTEM, PTYPE, DRIVER, OPMODE	0.6725×10^{-2}

Six-Factor Model	P-Value
RTYPE, PLANT, OPMODE DRIVER, PTYPE, SYSTEM	0.5099×10^{-2}

TABLE C-II

DEGRADED TIME-DEPENDENT MSS FRAC MODEL

Average Failure Rate Estimate--4.70 x 10^{-5}(3.90 x 10^{-5})

Fixed Factors

Level of Influence	Factor	Level	Description	R_j	Failure Rate Adjustment
1	SYSTEM	1	Nuclear	33.40	2.79 (2.361)
		2	Engineered Safety		0.15 (0.373)
		3	Power Conversion		5.01 (4.644)
		4	Process Conversion		0.47 (0.411)
2	OPMODE	1	Running	4.93	0.45 (0.129)
		2	Alternating		2.22 (0.634)
3	RTYPE	1	PWR	2.24	1.50 (0.244)
		2	BWR		0.67 (0.109)

Random Factor

Factor	Variance Component
ERROR	3.521

TABLE C-III

BEST AND WORST CASE DEGRADED TIME-DEPENDENT FRAC PUMP FAILURE RATE ESTIMATES

Case	SYSTEM	OPMODE	RTYPE	Estimate
Best	Engineered Safety	Running	BWR	2.13 x 10^{-6}/h
Worst	Power Conversion	Alternating	PWR	7.84 x 10^{-6}/h

Note: 7.84 x 10^{-4}/2.13 x 10^{-6} = 368.08 ≈ 2.6 orders of magnitude between the best and worst case estimates.

TABLE C-IV

INCIPIENT TIME-DEPENDENT FRAC FAILURE RATE MODEL ANALYSIS

One-Factor Models	P-Values
RTYPE	0.2848×10^{-6}
SYSTEM	0.4408×10^{0}
OPMODE	0.3981×10^{0}
PTYPE	0.8205×10^{-1}
DRIVER	0.1245×10^{-1}

Two-Factor Models	P-Values
RTYPE, PLANT	---
RTYPE, SYSTEM	0.1302×10^{-4}
RTYPE, OPMODE	0.1335×10^{-5}
RTYPE, PTYPE	0.1004×10^{-5}
RTYPE, DRIVER	0.4100×10^{-7}
SYSTEM, OPMODE	0.5951×10^{0}
SYSTEM, PTYPE	0.2613×10^{0}
SYSTEM, DRIVER	0.6435×10^{-1}
OPMODE, DRIVER	0.4538×10^{-1}
OPMODE, PTYPE	0.1933×10^{0}
DRIVER, PTYPE	0.4442×10^{-2}

Three-Factor Models	P-Values
RTYPE, PLANT, SYSTEM	---
RYPTE, PLANT, OPMODE	---
RTYPE, PLANT, PTYPE	---
RTYPE, PLANT, DRIVER	---
RTYPE, SYSTEM, OPMODE	0.3907×10^{-4}
RTYPE, SYSTEM, PTYPE	0.2057×10^{-4}
RTYPE, SYSTEM, DRIVER	0.1623×10^{-5}
RTYPE, PTYPE, DRIVER	0.5614×10^{-7}
OPMODE, PTYPE, SYSTEM	0.2587×10^{0}
OPMODE, DRIVER, SYSTEM	0.1084×10^{0}
OPMODE, DRIVER, PTYPE	0.1125×10^{-1}
OPMODE, RTYPE, PTYPE	0.3623×10^{-5}
OPMODE, RTYPE, DRIVER	0.2034×10^{-6}
SYSTEM, PTYPE, DRIVER	0.3545×10^{-1}

TABLE C-IV (cont)

Four-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE	---
RTYPE, PLANT, SYSTEM, PTYPE	---
RTYPE, PLANT, SYSTEM, DRIVER	---
RTYPE, PLANT, OPMODE, PTYPE	---
RTYPE, PLANT, OPMODE, DRIVER	---
RTYPE, PLANT, PTYPE, DRIVER	---
RTYPE, OPMODE, SYSTEM, DRIVER	0.4697×10^{-5}
RTYPE, PTYPE, DRIVER, SYSTEM	0.2031×10^{-5}
RTYPE, PTYPE, OPMODE, SYSTEM	0.4293×10^{-4}
RTYPE, PTYPE, OPMODE, DRIVER	0.2005×10^{-6}
SYSTEM, PTYPE, OPMODE, DRIVER	0.3409×10^{-1}

Five-Factor Models	P-Values
RTYPE, PLANT, SYSTEM, OPMODE, PTYPE	---
RTYPE, PLANT, SYSTEM, OPMODE, DRIVER	---
RTYPE, PLANT, SYSTEM, PTYPE, DRIVER	---
RTYPE, PLANT, OPMODE, PTYPE, DRIVER	---
RTYPE, SYSTEM, OPMODE, PTYPE, DRIVER	0.3649×10^{-5}

Six-Factor Model	P-Values
RTYPE, PLANT, SYSTEM, OPMODE PTYPE, DRIVER	---

TABLE C-V

INCIPIENT TIME-DEPENDENT MSS FRAC MODEL

Average Failure Rate Estimate--$3.65 \times 10^{-4} (5.02 \times 10^{-5})$

Fixed Factors

Level of Influence	Factor	Level	Description	R_j	Failure Rate Adjustment
1	RTYPE	1	PWR	3.31	1.82 (0.181)
		2	BWR		0.55 (0.055)
2	DRIVER	1	Motor	2.16	0.68 (0.093)
		2	Turbine		1.47 (0.201)

Random Factor

Factor	Variance Component
ERROR	5.596

TABLE C-VI

BEST AND WORST CASE INCIPIENT TIME-DEPENDENT
FRAC PUMP FAILURE RATE ESTIMATES

Case	RTYPE	DRIVER	Estimate
Best	BWR	Motor	1.37×10^{-4}/h
Worst	PWR	Turbine	9.77×10^{-4}/h

Note: $9.77 \times 10^{-4}/1.37 \times 10^{-4} = 7.13 \approx 0.9$ orders of magnitude between the best and worst case estimates.

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14 ABSTRACT (200 words or less)

In-Plant Reliability Data System (IPRDS) pump failure data on over 60 selected pumps in four nuclear power plants are statistically analyzed using the Failure Rate Analysis Code (FRAC). A major purpose of the analysis is to determine which environmental, system, and operating factors adequately explain the variability in the failure data. Catastrophic, degraded, and incipient failure severity categories are considered for both demand-related and time-dependent failures.

For catastrophic demand-related pump failures, the variability is explained by the following factors listed in their order of importance: system application, pump driver, operating mode, reactor type, pump type, and unidentified plant-specific influences. Quantitative failure rate adjustments are provided for the effects of these factors.

In the case of catastrophic time-dependent pump failures, the failure rate variability is explained by three factors: reactor type, pump driver, and unidentified plant-specific influences.

Finally, point and confidence interval failure rate estimates are provided for each selected pump by considering the influential factors. Both types of estimates represent an improvement over the estimates computed exclusively from the data on each pump.

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