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SAVANNAH RIVER SITE

GENERIC DATA BASE DEVELOPMENT (U)

June 1993

DOES NOT CONTAIN
UNCLASSIFIED CONTROLLED
NUCLEAR INFORMATION

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Date: 7/22/93

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

SAFETY • RESPONSIBILITY • SECURITY
SRS
SAVANNAH RIVER SITE

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT NO. DE-AC09-89SR18035

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SAVANNAH RIVER SITE

GENERIC DATA BASE DEVELOPMENT (U)

by

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT NO. DE-AC09-89SR18035

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ABSTRACT

This report describes the results of a project to improve the generic component failure data base for the Savannah River Site (SRS). A representative list of components and failure modes for SRS risk models was generated by reviewing existing safety analyses and component failure data bases and from suggestions from SRS safety analysts. Then sources of data or failure rate estimates were identified and reviewed for applicability. A major source of information was the Nuclear Computerized Library for Assessing Reactor Reliability, or NUCLARR.[1] This source includes an extensive collection of failure data and failure rate estimates for commercial nuclear power plants. A recent Idaho National Engineering Laboratory report on failure data from the Idaho Chemical Processing Plant was also reviewed.[2] From these and other recent sources, failure data and failure rate estimates were collected for the components and failure modes of interest. This information was aggregated to obtain a recommended generic failure rate distribution (mean and error factor) for each component failure mode. Results are presented in Table 1 in this report.

A major difference between this generic data base and previous efforts is that this effort attempted to base failure rate estimates on actual data (failure events) rather than on existing failure rate estimates. This effort was successful in that over 75% of the results are now based on actual data.

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1. INTRODUCTION

As part of an overall effort to upgrade the methodologies for safety analyses of nonreactor nuclear facilities at the Savannah River Site (SRS), a new generic component failure data base was developed. The project to update the SRS generic component failure data base had several goals:

- Provide information for various failure modes for each component, where possible. An example is to provide failure rates for valve failure to open/close upon demand and valve spurious operation, rather than just valve failure. Such failure mode information is often necessary for detailed fault tree models.
- Base component failure rates on actual data (failure events) wherever possible.
- Use the most up-to-date and applicable data sources available.
- Provide a clear documentation trail for each component failure rate estimate, such that others can review the basis for each estimate.

The entire project was structured such that these goals could be accomplished. All of the goals were met.

Based on a review of existing safety analyses and component failure data bases, and based on additional input from SRS safety analysts, a comprehensive list of components and failure modes was generated. The list is shown in Table 1. Approximately 500 component and failure mode combinations were identified. Given this list of components and failure modes, sources were identified that contained applicable failure data or failure rate estimates.

2. DATA SOURCES

Sources used to develop the SRS component generic data base may contain actual failure data or failure rate estimates. Also, sources containing failure data may vary in the quality or detail of the information. Therefore, three categories of sources were established:

1. Category 1 - Sources with actual failure data obtained from a detailed review of failure events (to ensure applicability to the failure mode being considered) and a detailed review of component populations and exposure durations (or demands). Such data include the plant-specific component failure data collected for probabilistic risk assessments (PRAs) or reliability studies. The NUCLARR[1] data base has 19 Category 1 sources, all from nuclear power plants. For this project, the Savannah River Site (SRS) reactor data were added. The data sources include the following:

   - WSRC-RP-89-776, Rev. 0[3]
   - WSRC-RP-90-1258, Rev. 0[4]
   - DPST-87-642.[5]

   Including these Category 1 sources increased the Category 1 data by nearly 20%.

2. Category 2 - Sources with actual failure data, but which have an added uncertainty in the data compared with Category 1 sources. This added uncertainty can result from a less comprehensive search for actual failures, a more approximate method for determining component populations or exposure durations (or demands), or a less clear breakdown of failures into the failure modes of concern. NUCLARR has 10 Category 2 sources in its data base. For this project, an additional five Category 2 sources were identified and used:

   - NPRD-3[6] - By carefully reviewing failure mode information presented in tables in this document, the failure data presented in NPRD-3 could be divided into the failure modes of interest for this project.
   - OREDA[7] - Failure data from components in offshore oil drilling facilities are presented in this report. In some cases judgment was needed to break down the data by failure mode.
   - WIN-330 - This document lists failure data obtained from the Department of Energy (DOE) Idaho Chemical Processing Plant. However, this document does not distinguish failure modes, so some judgement was needed to break down the data by failure mode.
   - Tritium[8, 9, and 10] - These documents include failure data from a tritium handling facility at the Los Alamos National Laboratory. Again, judgement was needed to break down the data by failure mode.
   - LNG1[11] - Failure data from liquid natural gas facility components are presented in this document. Judgement was needed to break down the data by failure mode.

   Addition of these five sources more than doubled the amount of data from Category 2 sources in NUCLARR.

3. Category 3 - Sources that list only failure rate estimates. Six representative sources were used in this project. May more such sources exist. The six were chosen to represent a variety of industries.

All of the sources used in this project are listed in Table 2.

3. AGGREGATION ROUTINES

As discussed in Section 2 of this report, sources of data were grouped into three categories, depending upon the type and quality of information presented. For a given component and failure mode, several sources within a category might have failure information. Also, a single source may contain several sets of failure data. Therefore, aggregation routines are needed to combine the information from the different sources to obtain a representative result. Two different aggregation routines were used:

1. Combining actual failure data (failures and component exposure hours or demands) from different sources (used for Categories 1 and 2)
2. Combining failure rate estimates that also include error factor estimates (used for Category 3).

For Categories 1 and 2, the aggregation procedure is as follows[1]:

1. Compute R and R_2 from source data:

$$R = (\Sigma f_i)/(\Sigma T_i)$$

$$R_2 = [\Sigma f_i(f_i - 1)/T_i]/(\Sigma T_i)$$

where f_i = number of failures from source i

T_i = component exposure time (h) from source i.

2. Match moments to obtain underlying normal distribution:

$$M = 2 \ln(R) - 0.5 \ln(R_2)$$

$$S^2 = \ln(R_2) - 2 \ln(R).$$

3. Determine mean and error factor of lognormal distribution:

$$Mn = \exp(M + S^2/2)$$

$$EF = \exp(1.645\ S)$$

where Mn = mean

EF = error factor (95th percentile/50th percentile).

For data involving demands rather than exposure hours, the same equations apply, but with T_i replaced by D_i (number of demands from source i). If the procedure described above resulted in an error factor greater than 30, the error factor was chosen to be 30.

Three special cases may arise when aggregating actual failure data, such that the above routine does not work. The first is the case where only one data set is available (number of failures and number of hours or demands). In this case a Bayesian update of a non-informative prior was used to determine the mean estimate[36]:

$$Mn = (2n + 1)/(2T) \qquad \text{(for time-related data)}$$

$$Mn = (2n + 1)/(2D + 2) \qquad \text{(for demand-related data).}$$

In both cases, an error factor of 10 was used. The error factor of 10 was chosen by examining the aggregated results in Tables 3 and 4 and calculating an average error factor.

The second special case occurs when all of the data sources involve zero or one failure. In this case, the data were combined (failures added and exposure hours or demands added) to obtain one data set which was then treated similarly to the case just described.

Finally, the third case arises when S^2 is less than zero. This case was treated the same as the second special case.

For Category 3, the aggregation routine is the following[37]:

1. Determine variance for each source:

   $$S_i^2 = [(\ln EF)/1.645]^2.$$

2. Determine natural logarithm of median for each source:

   $$\omega_i = \ln(Mn_i) - S_i^2/2$$

   where ω_i = natural logarithm of median.

3. Determine average of source variances:

   $$S_{ave}^2 = (\Sigma\, S_i^2)/n_s$$

   where n_s = number of sources.

4. Determine average of natural logarithms of medians:

   $$\omega_{ave} = (\Sigma\, \omega_i)/n_s.$$

5. Determine variance of natural logarithms of medians:

   $$S_\omega^2 = \Sigma(\omega_i - \omega_{ave})^2/n_s.$$

6. Determine mean and error factor of lognormal distribution:

$$\omega = [\Sigma(\omega_i/S_i)]/[\Sigma(1/S_i)]$$

$$Mn = \exp(\omega + S^2/2)$$

$$EF = \exp(1.645\ S)$$

where S = larger of S_{ave} or S_ω.

Some of the Category 3 sources do not list error factors. In such cases, an error factor (3, 5, 10, or 30) was assumed based on an average of error factors from the other sources. If no sources listed an error factor, then 10 was used. Also, if the aggregation resulted in an error factor greater than 30, then the error factor was assumed to be 30. Finally, if a single source listed several failure rate estimates, then the estimates for that source were aggregated using the procedure described above. Then the result for that source was combined with the other sources.

Because a goal of this project was to base component failure rate estimates on actual failure data (contained in Categories 1 and 2) wherever possible, and because the quality of data in Category 1 sources is expected to be better than that for Category 2, aggregations were performed only within categories. Results from each category aggregation were not combined to obtain an overall result.

4. DATA SEARCH

Results of the search for component failure information are summarized in Tables 3 through 5. Tables 3a through 3f present the Category 1 data by component, failure mode, and type of system. The NUCLARR1 column in Tables 3a through 3f actually represents the aggregation of all of the Category 1 sources in NUCLARR. Tables 4a through 4f present the Category 2 results, and Tables 5a through 5f, the Category 3 results. Also presented in each table are the aggregated results (mean failure rate and error factor).

5. RECOMMENDED RESULTS

Recommended component generic failure rates are presented in Tables 1a through 1f. The recommended results were obtained from the Category 1 aggregation, if such data existed. If not, then the Category 2 results were used. Finally, if neither Category 1 nor Category 2 information were available, then the Category 3 results were used. Also, because the product of this effort is a generic data base, the mean frequencies were rounded off to 1, 3, or 5 times the appropriate power of 10. Error factors obtained from the aggregation process were rounded off to 3, 5, 10, or 30. Tables 6a through 6f contain more detailed notes concerning the selections of recommended failure rates.

A review of Tables 6a through 6f indicates that approximately 75% of the recommended failure rate estimates are based on actual failures from nuclear power plants or other types of facilities. The remaining 25% of the estimates had to be generated from sources listing only failure rates.

Also listed in Tables 1a through 1f are identifiers such as PIP-LE-W for each of the system/component/failure mode failure rate distributions. In the identifier, the first three letters, PIP, indicate the type of component, which is a pipe. The second set of letters, LE, indicates the failure mode, which is external leakage. The final letter, W, indicates the type of system, which is water system. Tables 7, 8, and 9 list the codes used for components, failure modes, and processing fluids. Parts of this naming scheme were obtained from the report Review and Development of Common Nomenclature for Naming and Labeling Schemes for Probabilistic Risk Assessment.[38] However, in some cases the naming schemes for components and failure modes in Reference 38 were changed to allow for a more consistent approach. Also, many additional components had to be added.

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Table 1a. Water system recommended generic failure rates.			
System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Water Valve (Standby or Safety) Manual Fails to open/close	XVM-CC-W or XVM-OO-W	3.0E-4/d	10
Plugs	XVM-PG-W	5.0E-8/h	10
Leakage (internal)	XVM-LI-W	1.0E-6/h	10
Rupture (internal)	XVM-RI-W	5.0E-8/h	30
Leakage (external)	XVM-LE-W	1.0E-8/h	10
Rupture (external)	XVM-RE-W	5.0E-10/h	30
Check Fails to open	CKV-CC-W	5.0E-5/d	10
Fails to close	CKV-OO-W	1.0E-3/d	5
Plugs	CKV-PG-W	5.0E-8/h	10
Leakage (internal)	CKV-LI-W	1.0E-6/h	10
Rupture (internal)	CKV-RI-W	5.0E-8/h	30
Leakage (external)	CKV-LE-W	1.0E-8/h	10
Rupture (external)	CKV-RE-W	5.0E-10/h	30
Motor-Operated Fails to open/close	MOV-CC-W or MOV-OO-W	3.0E-3/d	5
Spurious operation	MOV-CO-W or MOV-OC-W	3.0E-7/h	5
Plugs	MOV-PG-W	5.0E-8/h	10
Leakage (internal)	MOV-LI-W	1.0E-6/h	10
Rupture (internal)	MOV-RI-W	5.0E-8/h	30
Leakage (external)	MOV-LE-W	1.0E-8/h	10
Rupture (external)	MOV-RE-W	5.0E-10/h	30
Air-Operated Fails to open/close	AOV-CC-W or AOV-OO-W	1.0E-3/d	30
Spurious operation	AOV-CO-W or AOV-OC-W	1.0E-6/h	5
Plugs	AOV-PG-W	5.0E-8/h	10
Leakage (internal)	AOV-LI-W	1.0E-6/h	10
Rupture (internal)	AOV-RI-W	5.0E-8/h	30

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1a. Water system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor*
Leakage (external)	AOV-LE-W	1.0E-8/h	10
Rupture (external)	AOV-RE-W	5.0E-10/h	30
Solenoid-Operated Fails to open/close	SOV-CC-W or SOV-OO-W	1.0E-3/d	10
Spurious operation	SOV-CO-W or SOV-OC-W	5.0E-7/h	10
Plugs	SOV-PG-W	5.0E-8/h	10
Leakage (internal)	SOV-LI-W	1.0E-6/h	10
Rupture (internal)	SOV-RI-W	5.0E-8/h	30
Leakage (external)	SOV-LE-W	1.0E-8/h	10
Rupture (external)	SOV-RE-W	5.0E-10/h	30
Safety/Relief Fails to open	SRV-CC-W	3.0E-3/d	3
Fails to reclose	SRV-OO-W	3.0E-3/d	3
Leakage (internal)	SRV-LI-W	1.0E-6/h	10
Rupture (internal)	SRV-RI-W	5.0E-8/h	30
Leakage (external)	SRV-LE-W	1.0E-8/h	10
Rupture (external)	SRV-RE-W	5.0E-10/h	30
Vacuum-Breaker Fails to open	VBV-CC-W	1.0E-2/d	10
Fails to reclose	VBV-OO-W	1.0E-2/d	10
Leakage (internal)	VBV-LI-W	1.0E-6/h	10
Rupture (internal)	VBV-RI-W	5.0E-8/h	30
Leakage (external)	VBV-LE-W	1.0E-8/h	10
Rupture (external)	VBV-RE-W	5.0E-10/h	30
Explosive Fails to open	EXV-CC-W	1.0E-4/d	10
Leakage (internal)	EXV-LI-W	1.0E-6/h	10
Rupture (internal)	EXV-RI-W	5.0E-8/h	30
Leakage (external)	EXV-LE-W	1.0E-8/h	10
Rupture (external)	EXV-RE-W	5.0E-10/h	30
Valve (Control) Motor-Operated Fails open	CMV-FO-W	3.0E-6/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1a. Water system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Fails closed	CMV-FC-W	3.0E-6/h	10
Fails to respond	CMV-NR-W	3.0E-6/h	10
Plugs	CMV-PG-W	5.0E-8/h	10
Leakage (external)	CMV-LE-W	1.0E-8/h	10
Rupture (external)	CMV-RE-W	5.0E-10/h	30
Air-Operated Fails open	CAV-FO-W	3.0E-6/h	10
Fails closed	CAV-FC-W	3.0E-6/h	10
Fails to respond	CAV-NR-W	3.0E-6/h	10
Plugs	CAV-PG-W	5.0E-8/h	10
Leakage (external)	CAV-LE-W	1.0E-8/h	10
Rupture (external)	CAV-RE-W	5.0E-10/h	30
Solenoid-Operated Fails open	CSV-FO-W	3.0E-6/h	10
Fails closed	CSV-FC-W	3.0E-6/h	10
Fails to respond	CSV-FO-W	3.0E-6/h	10
Plugs	CSV-PG-W	5.0E-8/h	10
Leakage (external)	CSV-LE-W	1.0E-8/h	10
Rupture (external)	CSV-RE-W	5.0E-10/h	30
Pump Motor-Driven Fails to start	MDP-FS-W	3.0E-3/d	5
Fails to run	MDP-FR-W	3.0E-5/h	10
Overspeed	MDP-OS-W	5.0E-6/h	10
Fails to stop	MDP-NS-W	3.0E-3/d	5
Leakage (external)	MDP-LE-W	3.0E-8/h	10
Rupture (external)	MDP-RE-W	1.0E-9/h	30
Turbine-Driven Fails to start	TDP-FS-W	3.0E-2/d	3
Fails to run	TDP-FR-W	1.0E-4/h	30
Overspeed	TDP-OS-W	3.0E-5/h	10
Fails to stop	TDP-NS-W	3.0E-2/d	3
Leakage (external)	TDP-LE-W	3.0E-8/h	10
Rupture (external)	TDP-RE-W	1.0E-9/h	30

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1a. Water system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Diesel-Driven Fails to start	DDP-FS-W	1.0E-2/d	5
Fails to run	DDP-FR-W	5.0E-3/h	5
Overspeed	DDP-OS-W	1.0E-3/h	5
Fails to stop	DDP-NS-W	1.0E-2/d	5
Leakage (external)	DDP-LE-W	3.0E-8/h	10
Rupture (external)	DDP-RE-W	1.0E-9/h	30
Piping/Hose/Jumper Piping Leakage (external)	PIP-LE-W	3.0E-9/h-ft	10
Rupture (external)	PIP-RE-W	1.0E-10/h-ft	30
Plugs	PIP-PF-W	1.0E-10/h-ft	30
Hose Leakage (external)	HOS-LE-W	1.0E-9/h-ft	10
Rupture (external)	HOS-RE-W	1.0E-8/h-ft	10
Plugs	HOS-PG-W	1.0E-8/h-ft	10
Jumper Leakage (external)	JPR-LE-W	1.0E-6/h	10
Rupture (external)	JPR-RE-W	1.0E-8/h	30
Plugs	JPR-PG-W	5.0E-8/h	10
Vessel Tank (Unpressurized) Leakage (external)	TKU-LE-W	1.0E-8/h	10
Rupture (external)	TKU-RE-W	5.0E-10/h	30
Tank (Pressurized) Leakage (external)	TKP-LE-W	1.0E-8/h	10
Rupture (external)	TKP-RE-W	5.0E-10/h	30
Flange/Gasket Leakage (external)	FLG-LE-W	1.0E-8/h	10
Rupture (external)	FLG-RE-W	1.0E-10/h	30
Heat Exchanger Shell/Tube Fouling (tubes)	HTX-FL-W	1.0E-7/h	10
Plugs (tubes)	HTX-PG-W	3.0E-8/h	10
Leakage (tubes)	HTX-LI-W	1.0E-7/h	10
Rupture (tubes)	HTX-RI-W	5.0E-9/h	30
Leakage (shell)	HTX-LE-W	1.0E-8/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1a. Water system recommended generic failure rates.			
System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Rupture (shell)	HTX-RE-W	5.0E-10/h	30
Heater (Electrical) Fails to heat	HTE-FH-W	1.0E-6/h	10
Overheats	HTE-OH-W	3.0E-7/h	10
Leakage (external)	HTE-LE-W	1.0E-7/h	10
Rupture (external)	HTE-RE-W	5.0E-9/h	30
Strainer/Filter Plugs	FLT-PG-W	3.0E-6/h	10
Leakage (internal)	FLT-LI-W	3.0E-6/h	10
Rupture (internal)	FLT-RI-W	5.0E-7/h	10
Orifice Plugs	ORF-PG-W	1.0E-6/h	3
Miscellaneous Travelling Screen Plugs	TRS-PG-W	5.0E-7/h	10

a. *Error factor is the 95th percentile/50th percentile.*

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1b. Chemical process system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Chemical Process Valve (Standby or Safety) Manual Fails to open/close	XVM-CC-C or XVM-OO-C	3.0E-4/d	10
Plugs	XVM-PG-C	5.0E-8/h	10
Leakage (internal)	XVM-LI-C	1.0E-6/h	10
Rupture (internal)	XVM-RI-C	5.0E-8/h	30
Leakage (external)	XVM-LE-C	5.0E-7/h	10
Rupture (external)	XVM-RE-C	3.0E-8/h	30
Check Fails to open	CKV-CC-C	5.0E-5/d	10
Fails to close	CKV-OO-C	1.0E-3/d	10
Plugs	CKV-PG-C	5.0E-8/h	10
Leakage (internal)	CKV-LI-C	1.0E-6/h	10
Rupture (internal)	CKV-RI-C	5.0E-8/h	30
Leakage (external)	CKV-LE-C	5.0E-7/h	10
Rupture (external)	CKV-RE-C	3.0E-8/h	30
Motor-Operated Fails to open/close	MOV-CC-C or MOV-OO-C	3.0E-3/d	10
Spurious operation	MOV-CO-C or MOV-OC-C	3.0E-7/h	10
Plugs	MOV-PG-C	5.0E-8/h	10
Leakage (internal)	MOV-LI-C	1.0E-6/h	10
Rupture (internal)	MOV-RI-C	5.0E-8/h	10
Leakage (external)	MOV-LE-C	5.0E-7/h	10
Rupture (external)	MOV-RE-C	3.0E-8/h	30
Air-Operated Fails to open/close	AOV-CC-C or AOV-OO-C	1.0E-3/d	30
Spurious operation	AOV-CO-C or AOV-OC-C	1.0E-6/h	10
Plugs	AVO-CO-C or AOV-OC-C	5.0E-8/h	10
Leakage (internal)	AOV-LI-C	1.0E-6/h	10
Rupture (internal)	AOV-RI-C	5.0E-8/h	30
Leakage (external)	AOV-LE-C	5.0E-7/h	10
Rupture (external)	AOV-RE-C	3.0E-8/h	30

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1b. Chemical process system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Solenoid-Operated Fails to open/close	SOV-CC-C or SOV-OO-C	1.0E-3/d	10
Spurious operation	SOV-CO-C or SOV-OC-C	5.0E-7/h	10
Plugs	SOV-PG-C	5.0E-8/h	10
Leakage (internal)	SOV-LI-C	1.0E-6/h	10
Rupture (internal)	SOV-RI-C	5.0E-8/h	30
Leakage (external)	SOV-LE-C	5.0E-7/h	10
Rupture (external)	SOV-RE-C	3.0E-8/h	30
Safety/Relief Fails to open	SRV-CC-C	3.0E-3/d	10
Fails to reclose	SRV-OO-C	3.0E-3/d	10
Leakage (internal)	SRV-LI-C	1.0E-6/h	10
Rupture (internal)	SRV-RI-C	5.0E-8/h	30
Leakage (external)	SRV-LE-C	5.0E-7/h	10
Rupture (external)	SRV-RE-C	3.0E-8/h	30
Vacuum-Breaker Fails to open	VBV-CC-C	1.0E-2/d	10
Fails to reclose	VBV-OO-C	1.0E-2/d	10
Leakage (internal)	VBV-LI-C	1.0E-6/h	10
Rupture (internal)	VBV-RI-C	5.0E-8/h	30
Leakage (external)	VBV-LE-C	5.0E-7/h	10
Rupture (external)	VBV-RE-C	3.0E-8/h	30
Explosive Fails to open	EXV-CC-C	1.0E-4/d	10
Leakage (internal)	EXV-LI-C	1.0E-6/h	10
Rupture (internal)	EXV-RI-C	5.0E-8/h	10
Leakage (external)	EXV-LE-C	5.0E-7/h	10
Rupture (external)	EXV-RE-C	3.0E-8/h	30
Valve (Control) Motor-Operated Fails open	CMV-FO-C	3.0E-6/h	10
Fails closed	CMV-FC-C	3.0E-6/h	10
Fails to respond	CMV-NR-C	3.0E-6/h	10
Plugs	CMV-PG-C	5.0E-8/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1b. Chemical process system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor*
Leakage (external)	CMV-LE-C	5.0E-7/h	10
Rupture (external)	CMV-RE-C	3.0E-8/h	30
Air-Operated Fails open	CAV-FO-C	3.0E-6/h	10
Fails closed	CAV-FC-C	3.0E-6/h	10
Fails to respond	CAV-NR-C	3.0E-6/h	10
Plugs	CAV-PG-C	5.0E-8/h	10
Leakage (external)	CAV-LE-C	5.0E-7/h	10
Rupture (external)	CAV-RE-C	3.0E-8/h	30
Solenoid-Operated Fails open	CSV-FO-C	3.0E-6/h	10
Fails closed	CSV-FC-C	3.0E-6/h	10
Fails to respond	CSV-NR-C	3.0E-6/h	10
Plugs	CSV-PG-C	5.0E-8/h	10
Leakage (external)	CSV-LE-C	5.0E-7/h	10
Rupture (external)	CSV-RE-C	3.0E-8/h	30
Pump Motor-Driven Fails to start	MDP-FS-C	1.0E-2/d	10
Fails to run	MDP-FR-C	1.0E-4/h	10
Overspeed	MDP-OS-C	3.0E-5/h	10
Fails to stop	MDP-NS-C	1.0E-2/d	10
Leakage (external)	MDP-LE-C	1.0E-6/h	10
Rupture (external)	MDP-RE-C	5.0E-8/h	30
Turbine-Driven Fails to start	TDP-FS-C	3.0E-2/d	10
Fails to run	TDP-FR-C	1.0E-4/h	30
Overspeed	TDP-OS-C	3.0E-5/h	10
Fails to stop	TDP-NS-C	3.0E-2/d	10
Leakage (external)	TDP-LE-C	1.0E-6/h	10
Rupture (external)	TDP-RE-C	5.0E-8/h	30
Diesel-Driven Fails to start	DDP-FS-C	1.0E-2/d	10
Fails to run	DDP-FR-C	5.0E-3/h	10
Overspeed	DDP-OS-C	1.0E-3/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1b. Chemical process system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor*
Fails to stop	DDP-NS-C	1.0E-2/d	10
Leakage (external)	DDP-LE-C	1.0E-6/h	10
Rupture (external)	DDP-RE-C	5.0E-8/h	30
Piping/Hose/Jumper Piping Leakage (external)	PIP-LE-C	3.0E-9/h-ft	10
Rupture (external)	PIP-RE-C	1.0E-10/h-ft	30
Plugs	PIP-PG-C	1.0E-10/h-ft	30
Hose Leakage (external)	HOS-LE-C	1.0E-9/h-ft	10
Rupture (external)	HOS-RE-C	1.0E-8/h-ft	10
Plugs	HOS-PG-C	1.0E-8/h-ft	10
Jumper Leakage (external)	JPR-LE-C	1.0E-6/h	10
Rupture (external)	JPR-RE-C	1.0E-8/h	30
Plugs	JPR-PG-C	5.0E-8/h	10
Vessel Tank (Unpressurized) Leakage (external)	TKU-LE-C	1.0E-7/h	10
Rupture (external)	TKU-RE-C	5.0E-9/h	30
Tank (Pressurized) Leakage (external)	TKP-LE-C	1.0E-7/h	10
Rupture (external)	TKP-RE-C	5.0E-9/h	30
Flange/Gasket Leakage (external)	FLG-LE-C	1.0E-7/h	10
Rupture (external)	FLG-RE-C	1.0E-9/h	10
Heat Exchanger Shell/Tube Fouling (tubes)	HTX-FL-C	1.0E-6/h	10
Plugs (tubes)	HTX-PG-C	3.0E-7/h	10
Leakage (tubes)	HTX-LI-C	1.0E-6/h	10
Rupture (tubes)	HTX-RI-C	5.0E-8/h	30
Leakage (shell)	HTX-LE-C	1.0E-7/h	10
Rupture (shell)	HTX-RE-C	5.0E-9/h	30
Heater (Electrical) Fails to heat	HTE-FH-C	1.0E-5/h	10
Overheats	HTE-OH-C	3.0E-6/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1b. Chemical process system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Leakage (external)	HTE-LE-C	1.0E-6/h	10
Rupture (external)	HTE-RE-C	5.0E-8/h	30
Strainer/Filter Plugs	FLT-PG-C	3.0E-6/h	10
Leakage (internal)	FLT-LI-C	3.0E-6/h	10
Rupture (internal)	FLT-RI-C	5.0E-7/h	10
Orifice Plugs	ORF-PG-C	1.0E-6/h	10
Miscellaneous Mixer/Blender Failure	MIX-FA-C	5.0E-6/h	10
Agitator Failure	AGI-FA-C	5.0E-6/h	10
Centrifuge Failure	CTF-FA-C	5.0E-6/h	10

a. Error factor is the 95th percentile/50th percentile.

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1c. *Compressed gas system recommended generic failure rates.*

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor*
Compressed Gas Valve (Standby or Safety) Manual Fails to open/close	XVM-CC-G or XVM-OO-G	1.0E-3/d	10
Plugs	XVM-PG-G	5.0E-7/h	10
Leakage (internal)	XVM-LI-G	1.0E-5/h	10
Rupture (internal)	XVM-RI-G	5.0E-7/h	30
Leakage (external)	XVM-LE-G	1.0E-7/h	10
Rupture (external)	XVM-RE-G	5.0E-9/h	30
Check Fails to open	CKV-CC-G	1.0E-4/d	10
Fails to close	CKV-OO-G	3.0E-3/d	10
Plugs	CKV-PG-G	5.0E-7/h	10
Leakage (internal)	CKV-LI-G	1.0E-5/h	10
Rupture (internal)	CKV-RI-G	5.0E-7/h	30
Leakage (external)	CKV-LE-G	1.0E-7/h	10
Rupture (external)	CKV-RE-G	5.0E-9/h	30
Motor-Operated Fails to open/close	MOV-CC-G or MOV-OO-G	1.0E-2/d	10
Spurious operation	MOV-CO-G or MOV-OC-G	3.0E-7/h	10
Plugs	MOV-PG-G	5.0E-7/h	10
Leakage (internal)	MOV-LI-G	1.0E-5/h	10
Rupture (internal)	MOV-RI-G	5.0E-7/h	30
Leakage (external)	MOV-LE-G	1.0E-7/h	10
Rupture (external)	MOV-RE-G	5.0E-9/h	30
Air-Operated Fails to open/close	AOV-CC-G or AOV-OO-G	3.0E-3/d	30
Spurious operation	AOV-CO-G or AOV-OC-G	1.0E-6/h	10
Plugs	AOV-PG-G	5.0E-7/h	10
Leakage (internal)	AOV-LI-G	1.0E-5/h	10
Rupture (internal)	AOV-RI-G	5.0E-7/h	30
Leakage (external)	AOV-LE-G	1.0E-7/h	10
Rupture (external)	AOV-RE-G	5.0E-9/h	30

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1c. Compressed gas system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Solenoid-Operated Fails to open/close	SOV-CC-G or SOV-OO-G	3.0E-3/d	10
Spurious operation	SOV-CO-G or SOV-OC-G	5.0E-7/h	10
Plugs	SOV-PG-G	5.0E-7/h	10
Leakage (internal)	SOV-LI-G	1.0E-5/h	10
Rupture (internal)	SOV-RI-G	5.0E-7/h	30
Leakage (external)	SOV-LE-G	1.0E-7/h	10
Rupture (external)	SOV-RE-G	5.0E-9/h	30
Safety/Relief Fails to open	SRV-CC-G	1.0E-2/d	10
Fails to reclose	SRV-OO-G	1.0E-2/d	10
Leakage (internal)	SRV-LI-G	1.0E-5/h	10
Rupture (internal)	SRV-RI-G	5.0E-7/h	30
Leakage (external)	SRV-LE-G	1.0E-7/h	10
Rupture (external)	SRV-RE-G	5.0E-9/h	30
Vacuum-Breaker Fails to open	VBV-CC-G	3.0E-2/d	10
Fails to reclose	VBV-OO-G	3.0E-2/d	10
Leakage (internal)	VBV-LI-G	1.0E-5/h	10
Rupture (internal)	VBV-RI-G	5.0E-7/h	30
Leakage (external)	VBV-LE-G	1.0E-7/h	10
Rupture (external)	VBV-RE-G	5.0E-9/h	30
Valve (Control) Motor-Operated Fails open	CMV-FO-G	3.0E-6/h	10
Fails closed	CMV-FC-G	3.0E-6/h	10
Fails to respond	CMV-NR-G	3.0E-6/h	10
Plugs	CMV-PG-G	5.0E-7/h	10
Leakage (external)	CMV-LE-G	1.0E-7/h	10
Rupture (external)	CMV-RE-G	5.0E-9/h	30
Air-Operated Fails open	CAV-FO-G	3.0E-6/h	10
Fails closed	CAV-FC-G	3.0E-6/h	10
Fails to respond	CAV-NR-G	3.0E-6/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1c. Compressed gas system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Plugs	CAV-PG-G	5.0E-7/h	10
Leakage (external)	CAV-LE-G	1.0E-7/h	10
Rupture (external)	CAV-RE-G	5.0E-9/h	30
Solenoid-Operated Fails open	CSV-FO-G	3.0E-6/h	10
Fails closed	CSV-FC-G	3.0E-6/h	10
Fails to respond	CSV-NR-G	3.0E-6/h	10
Plugs	CSV-PG-G	5.0E-7/h	10
Leakage (external)	CSV-LE-G	1.0E-7/h	10
Rupture (external)	CSV-RE-G	5.0E-9/h	30
Compressor Motor-Driven Fails to start	MDC-FS-G	5.0E-3/d	5
Fails to run	MDC-FR-G	5.0E-5/h	3
Overspeed	MDC-OS-G	1.0E-5/h	5
Fails to stop	MDC-NS-G	5.0E-3/d	5
Leakage (external)	MDC-LE-G	3.0E-7/h	10
Rupture (external)	MDC-RE-G	1.0E-8/h	30
Piping/Hose/Jumper/Tube Piping Leakage (external)	PIP-LE-G	3.0E-8/h-ft	10
Rupture (external)	PIP-RE-G	1.0E-9/h-ft	30
Plugs	PIP-PG-G	1.0E-9/h-ft	30
Hose Leakage (external)	HOS-LE-G	1.0E-8/h-ft	10
Rupture (external)	HOS-RE-G	1.0E-7/h-ft	10
Plugs	HOS-PG-G	1.0E-7/h-ft	10
Jumper Leakage (external)	JPR-LE-G	1.0E-5/h	10
Rupture (external)	JPR-RE-G	1.0E-7/h	30
Plugs	JPR-PG-G	1.0E-7/h	30
Tube Leakage (external)	TUB-LE-G	3.0E-7/h-ft	10
Rupture (external)	TUB-RE-G	1.0E-8/h-ft	30
Plugs	TUB-PG-G	1.0E-8/h-ft	30

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1c. Compressed gas system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Vessel Tank (Pressurized) Leakage (external)	TKP-LE-G	1.0E-7/h	10
Rupture (external)	TKP-RE-G	5.0E-9/h	30
Cylinder (Pressurized) Leakage (external)	CYL-LE-G	1.0E-7/h	10
Rupture (external)	CYL-RE-G	5.0E-9/h	30
Flange/Gasket Leakage (external)	FLG-LE-G	1.0E-7/h	10
Rupture (external)	FLG-RE-G	1.0E-9/h	10
Heat Exchanger Shell/Tube Fouling (tubes)	HTX-FL-G	1.0E-5/h	10
Plugs (tubes)	HTX-PG-G	3.0E-6/h	10
Leakage (tubes)	HTX-LI-G	1.0E-5/h	10
Rupture (tubes)	HTX-RI-G	5.0E-7/h	30
Leakage (shell)	HTX-LE-G	1.0E-6/h	10
Rupture (shell)	HTX-RE-G	5.0E-8/h	30
Heater (Electrical) Fails to heat	HTE-FH-G	1.0E-6/h	10
Overheats	HTE-OH-G	3.0E-7/h	10
Leakage (external)	HTE-LE-G	1.0E-6/h	10
Rupture (external)	HTE-RE-G	5.0E-8/h	30
Vaporizer Failure	VAP-FA-G	1.0E-4/h	10
Air Dryer Failure	ADR-FA-G	5.0E-6/h	10
Filter Plugs	FLT-PG-G	3.0E-6/h	10
Leakage (internal)	FLT-LI-G	3.0E-6/h	10
Rupture (internal)	FLT-RI-G	5.0E-7/h	10
Orifice Plugs	ORF-PG-G	1.0E-6/h	10

a. Error factor is the 95th percentile/50th percentile.

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1d. HVAC/exhaust system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
HVAC/Exhaust Damper (Standby or Safety) Manual Fails to open/close	XDM-CC-H or XDM-OO-H	3.0E-3/d	10
Plugs	XDM-PG-H	5.0E-7/h	10
Leakage (internal)	XDM-LI-H	1.0E-5/h	10
Rupture (internal)	XDM-RI-H	5.0E-7/h	30
Leakage (external)	XDM-LE-H	1.0E-7/h	10
Rupture (external)	XDM-RE-H	5.0E-9/h	30
Motor-Operated Fails to open/close	MOD-CC-H or MOD-OO-H	3.0E-2/d	10
Spurious operation	MOD-CO-H or MOD-OC-H	3.0E-6/h	10
Plugs	MOD-PG-H	5.0E-7/h	10
Leakage (internal)	MOD-LI-H	1.0E-5/h	10
Rupture (internal)	MOD-RI-H	5.0E-7/h	10
Leakage (external)	MOD-LE-H	1.0E-7/h	10
Rupture (external)	MOD-RE-H	5.0E-9/h	30
Air-Operated Fails to open/close	AOD-CC-H or AOD-OO-H	1.0E-2/d	30
Spurious operation	AOD-CO-H or AOD-OC-H	1.0E-5/h	10
Plugs	AOD-PG-H	5.0E-7/h	10
Leakage (internal)	AOD-LI-H	1.0E-5/h	10
Rupture (internal)	AOD-RI-H	5.0E-7/h	10
Leakage (external)	AOD-LE-H	1.0E-7/h	10
Rupture (external)	AOD-RE-H	5.0E-9/h	30
Damper (Control) Motor-Operated Fails open	CMD-FO-H	3.0E-6/h	10
Fails closed	CMD-FC-H	3.0E-6/h	10
Fails to respond	CMD-NR-H	3.0E-6/h	10
Plugs	CMD-PG-H	5.0E-7/h	10
Leakage (external)	CMD-LE-H	1.0E-7/h	10
Rupture (external)	CMD-RE-H	5.0E-9/h	30
Air-Operated Fails open	CAD-FO-H	3.0E-6/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1d. HVAC/exhaust system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor*
Fails closed	CAD-FC-H	3.0E-6/h	10
Fails to respond	CAD-NR-H	3.0E-6/h	10
Plugs	CAD-PG-H	5.0E-7/h	10
Leakage (external)	CAD-LE-H	1.0E-7/h	10
Rupture (external)	CAD-RE-H	5.0E-9/h	30
Fan/Blower Motor-Driven Fails to start	MDF-FS-H	5.0E-3/d	5
Fails to run	MDF-FR-H	3.0E-5/h	3
Overspeed	MDF-OS-H	5.0E-6/h	10
Fails to stop	MDF-NS-H	5.0E-3/d	10
Leakage (external)	MDF-LE-H	3.0E-7/h	10
Rupture (external)	MDF-RE-H	1.0E-8/h	30
Diesel-Driven Fails to start	DDF-FS-H	1.0E-2/d	10
Fails to run	DDF-FR-H	5.0E-3/h	10
Overspeed	DDF-OS-H	1.0E-3/h	10
Fails to stop	DDF-NS-H	1.0E-2/d	10
Leakage (external)	DDF-LE-H	3.0E-7/h	10
Rupture (external)	DDF-RE-H	1.0E-8/h	10
Ducting Leakage (external)	DCT-LE-H	3.0E-7/h-ft	10
Rupture (external)	DCT-RE-H	1.0E-8/h-ft	30
Plugs	DCT-PG-H	1.0E-8/h-ft	30
Heat Exchanger Air Conditioning Unit/ Chiller Fails to start	ACU-FS-H	1.0E-2/d	10
Fails to run	ACU-FR-H	3.0E-5/h	10
Fan Cooler Unit Fails to start	FCU-FS-H	1.0E-2/d	5
Fails to run	FCU-FR-H	1.0E-5/h	3
Heater (Electrical) Fails to heat	HTE-FH-H	1.0E-6/h	3
Overheats	HTE-OH-H	3.0E-7/h	10
Heater (Gas) Fails to heat	HTG-FH-H	1.0E-3/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1d. HVAC/exhaust system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Overheats	HTG-OH-H	3.0E-4/h	10
Filter Normal Plugs	FLT-PG-H	3.0E-6/h	10
Leakage (internal)	FLT-LI-H	3.0E-6/h	10
Rupture (internal)	FLT-RI-H	5.0E-7/h	10
Low-Efficiency Plugs	FLL-PG-H	3.0E-6/h	10
Leakage (internal)	FLL-LI-H	3.0E-6/h	10
Rupture (internal)	FLL-RI-H	5.0E-7/h	10
HEPA Plugs	HPA-PG-H	3.0E-6/h	10
Leakage (internal)	HPA-LI-H	3.0E-6/h	10
Rupture (internal)	HPA-RI-H	5.0E-7/h	10
Sand Plugs	FLS-PG-H	3.0E-6/h	10
Leakage (internal)	FLS-LI-H	3.0E-6/h	10
Rupture (internal)	FLS-RI-H	5.0E-7/h	10
Baghouse Plugs	BAG-PG-H	3.0E-5/h	10
Leakage (internal)	BAG-LI-H	3.0E-5/h	10
Rupture (internal)	BAG-RI-H	5.0E-6/h	10
Miscellaneous Mist Eliminator Failure	MTE-FA-H	1.0E-4/h	10
Scrubber Failure	SBR-FA-H	1.0E-6/h	10
Precipitator Failure	PCP-FA-H	5.0E-5/h	10

a. Error factor is the 95th percentile/50th percentile.

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1e. Electrical distribution system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Electric Power Generator Diesel-Driven Fails to start	DDG-FS-E	1.0E-2/d	3
Fails to run	DDG-FR-E	5.0E-3/h	3
Motor-Driven (ac to dc) Fails to start	MDG-FS-E	1.0E-5/h	10
Fails to run	MDG-FR-E	3.0E-5/h	10
Gas-Turbine-Driven Fails to start	GTG-FS-E	3.0E-2/d	10
Fails to run	GTG-FR-E	3.0E-4/h	10
Hydro-Turbine-Driven Fails to start	HDG-FS-E	3.0E-3/d	10
Fails to run	HDG-FR-E	3.0E-4/h	10
Battery Failure	BAT-FA-E	1.0E-5/h	3
Charger Rectifier Failure	RCT-FA-E	1.0E-5/h	3
Bus Metal-Enclosed Failure	BUM-FA-E	1.0E-7/h	5
Bare Failure	BUB-FA-E	1.0E-6/h	10
Cable/Joint/ *Termination/Jumper* Cable (Copper, 1000ft) Failure	CBL-FA-E	3.0E-6/h	3
Joint (Copper) Failure	JNT-FA-E	3.0E-6/h	30
Termination (Copper) Failure	TMN-FA-E	3.0E-7/h	10
Jumper (Power) Failure	JPR-FA-E	5.0E-6/h	10
Circuit Breaker General Fails to open/close	CBR-CC-E or CBR-OO-E or CBR-NR-E	5.0E-4/d	5
Spurious operation	CBR-CO-E or CBR-OC-E or CBR-SO-E	3.0E-7/h	10
Reactor Trip Fails to open	RTB-CC-E	5.0E-3/d	5

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1e. Electrical distribution system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Spurious operation	RTB-CO-E	3.0E-6/h	10
Relay Protective Fails to open/close	RLP-CC-E or RLP-OO-E or RLP-NR-E	1.0E-3/d	10
Spurious operation	RLP-CO-E or RLP-OC-E or RLP-SO-E	1.0E-7/h	10
Control Fails to open/close	RLC-CC-E or RLC-OO-E or RLC-NR-E	1.0E-4/d	10
Spurious operation	RLC-CO-E or RLC-OC-E or RLC-SO-E	3.0E-7/h	30
Bistable Fails to open/close	BIS-CC-E or BIS-OO-E or BIS-NR-E	1.0E-5/d	10
Spurious operation	BIS-CO-E or BIS-OC-E or BIS-SO-E	3.0E-7/h	10
Switch Push-Button (Manual) Fails to open/close	XSP-CC-E or XSP-OO-E or XSP-NR-E	1.0E-6/h	10
Spurious operation	XSP-CO-E or XSP-OC-E or XSP-SO-E	1.0E-6/h	10
Rotary (Manual) Fails to open/close	XSR-CC-E or XSR-OO-E or XSR-NR-E	5.0E-8/h	10
Spurious operation	XSR-CO-E or XSR-OC-E or XSR-SO-E	5.0E-7/h	10
Key-Operated (Manual) Fails to open/close	XSK-CC-E or XSK-OO-E or XSK-NR-E	3.0E-7/h	10
Spurious operation	XSK-CO-E or XSK-OC-E or XSK-SO-E	1.0E-6/h	10
Automatic-Transfer Fails to open/close	ATS-CC-E or ATS-OO-E or ATS-NR-E	1.0E-6/h	10
Spurious operation	ATS-CO-E or ATS-OC-E or ATS-SO-E	1.0E-6/h	10
Limit Fails to open/close	LMS-CC-E or LMS-OO-E or LMS-NR-E	1.0E-6/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1e. Electrical distribution system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Spurious operation	LMS-CO-E or LMS-OC-E or LMS-SO-E	1.0E-6/h	5
Fuse Fail to open	FUS-CC-E	1.0E-7/h	10
Premature opening	FUS-SO-E	1.0E-8/h	10
Inverter Failure	INV-FA-E	1.0E-5/h	3
Motor AC Fails to start	MRA-FS-E	3.0E-4/d	3
Fails to run	MRA-FR-E	5.0E-6/h	3
DC Fails to start	MRD-FS-E	3.0E-4/d	3
Fails to run	MRD-FR-E	1.0E-5/h	3
Synchro Failure	SYN-FA-E	1.0E-5/h	10
Transformer Power Failure	TFP-FA-E	1.0E-6/h	10
Instrumentation/Control Failure	TFI-FA-E	1.0E-6/h	10

a. Error factor is the 95th percentile/50th percentile.

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 1f. Instrumentation and control system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Instrumentation and Control Alarm/Annunciator Fails to alarm	ALR-NR-I	3.0E-5/h	10
Spurious operation	ALR-SO-I	5.0E-6/h	10
Sensor/Transmitter/ Transducer/Process Switch Temperature Failure	TST-FA-I	1.0E-6/h	3
Pressure Failure	PST-FA-I	1.0E-6/h	3
Differential Pressure Failure	DPS-FA-I	3.0E-6/h	10
Flow Failure	FST-FA-I	3.0E-6/h	3
Level Failure	LST-FA-I	5.0E-7/h	3
Humidity Failure	UST-FA-I	1.0E-5/h	10
pH Failure	HST-FA-I	5.0E-7/h	5
Oxygen Concentration Failure	OXC-FA-I	1.0E-5/h	10
CO_2 Concentration Failure	COC-FA-I	1.0E-4/h	10
Hydrogen Concentration Failure	HYC-FA-I	1.0E-5/h	3
Nitrogen Concentration Failure	NIC-FA-I	1.0E-5/h	3
Hydrocarbon Concentration Failure	HCC-FA-I	1.0E-5/h	3
Helium Concentration Failure	HEC-FA-I	1.0E-5/h	3
Speed Failure	SST-FA-I	1.0E-6/h	10
Seismic Failure	SET-FA-I	1.0E-6/h	5
Radiation Failure	RST-FA-I	5.0E-6/h	5
Indicator Failure	IND-FA-I	1.0E-5/h	10
Amplifier Failure	AMP-FA-I	5.0E-6/h	10

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 11. Instrumentation and control system recommended generic failure rates.

System/Component/Failure Mode	Identifier	Recommended Failure Rate Distribution (lognormal)	
		Mean	Error Factor[a]
Modifier/Signal Conditioner Failure	SCR-FA-I	3.0E-7/h	3
Logic Module Failure	LOG-FA-I	3.0E-6/h	5
Recorder Failure	REC-FA-I	3.0E-5/h	30
Sampler Failure	SAM-FA-I	1.0E-5/h	10
Analyzer Failure	ANA-FA-I	5.0E-6/h	10
Timer Failure	TMR-FA-I	5.0E-6/h	10
Gas Chromatograph Failure	GCR-FA-I	5.0E-5/h	10
Voltage Regulator Failure	VRG-FA-I	3.0E-6/h	10
Transmitter Failure	TRM-FA-I	3.0E-6/h	10
Transducer Failure	TRD-FA-I	1.0E-6/h	10
Programmable Logic Controller Failure	PLC-FA-I	3.0E-5/h	10

a. Error factor is the 95th percentile/50th percentile.

Note: Modification of the recommended mean may be appropriate for components subjected to harsh environments.

Table 2. Data sources used in generic data base development.

Category 1
Big Rock Point PRA[12]
Oconee-3 PRA[13]
Zion PRA[14]
Indian Point PRA[15]
Reliability data from Swedish nuclear power plants[16]
Millstone 1 PRA[17]
Connecticut Yankee PRA[18]
B&W nuclear power plant (name withheld)[a]
European nuclear power plant (name withheld) PRA[a]
GE nuclear power plant (name withheld)[a]
Westinghouse nuclear power plant (name withheld)[a]
7 other nuclear power plant (names withheld) PRAs[a]
Savannah River Site reactors[3, 4, and 5]
Category 2
Licensee event report (LER) survey of pumps at nuclear power plants[19]
LER survey of valves[20]
LER survey of inverters[21]
LER survey of selected instrumentation and control components[22]
In-plant Reliability Data Base (IPRD) survey of pumps[23]
IPRD survey of valves[24]
IPRD survey of diesel generators, batteries, chargers, and inverters[25]
Nuclear Safety Analysis Center (NSAC) survey of diesel generators[26]
Pipe break survey[27]
LER survey of pipes, valves, pumps, etc.[28]
Nonelectronic Parts Reliability Data (military)[6]
OREDA data for offshore oil drilling components[7]
Chemical processing plant[2]
Tritium handling facility[8, 9, and 10]
Liquid natural gas plant components[11]
Category 3
WASH-1400[29]
Center for Chemical Process Safety[30]
IEEE Std 500-1984[31]
Natural gas facility components[32]
Gasification-combined-cycle power generation components[33]
Coal-fired power generation components[34]
Generic data base for nuclear reactor components[35]

a. See Reference 1 for more details on these studies.

Table 3a. Category 1 data for water system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Water Valve (Standby or Safety) Manual Fails to open/close	38/8.8E+4d, 7/2.1E+8h [1]	0/7.1E+3d, 0/1.3E+4d, 0/8.4E+2d, 0/5.8E+2d [1]	3.5E-4/d(18), 3.3E-8/h(88)
Plugs		0/4.6E+5h, 0/7.6E+3h, 0/1.5E+3h [2]	1.1E-6/h(10) [1]
Leakage (internal)		0/8.8E+1h [3]	5.7E-3/h(10) [1]
Rupture (internal)		[3]	
Leakage (external)			
Rupture (external)			
Check Fails to open	1/2.5E+4d [2]	1/3.3E+3d, 0/3.6E+2d, 0/4.7E+2d, 0/2.2E+2d, 0/2.7E+3d, [4]	6.0E-5/d(10) [2]
Fails to close	18/1.2E+4d [3]	[4]	9.8E-4/d(4.6) [2]
Plugs			
Leakage (internal)	36/1.2E+7h [4]	0/4.1E+7h [5]	6.8E-7/h(63)
Rupture (internal)	[4]	[5]	
Leakage (external)			
Rupture (external)			

Table 3a. Category 1 data for water system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Motor-Operated Fails to open/close	390/1.2E+5d, 15/3.1E+6h [5]	29/9.2E+3d, 10/7.5E+2d, 29/5.3E+3d, 4/1.8E+3d [6]	3.3E-3/d(6.3), 4.8E-6/h(9.6)
Spurious operation	1/2.1E+7h [6]	2/1.3E+7h, 0/2.5E+6h, 7/4.4E+6h, 0/1.9E+6h [7]	2.3E-7/h(7.2)
Plugs		1/1.8E+7h, 0/2.5E+6h, 0/4.4E+6h, 0/1.9E+6h [8]	5.6E-8/h(10)
Leakage (internal)		1/1.8E+6h [9]	8.3E-7/h(10)
Rupture (internal)		[9]	
Leakage (external)			
Rupture (external)			
Air-Operated Fails to open/close	110/9.4E+4d, 2/4.8E+6h [7]	4/2.9E+3d, 0/8.8E+2d, 1/6.0E+2d [10]	1.2E-3/d(21), 5.2E-7/h(10)
Spurious operation	13/6.2E+6h [8]	0/4.0E+6h, 0/5.0E+5h, 0/1.5E+3h [11]	1.2E-6/h(5.4)
Plugs		0/4.0E+6h, 0/5.0E+5h, 0/2.6E+1h [12]	1.1E-7/h(10) [1]

Table 3a. Category 1 data for water system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Leakage (internal)	8/5.3E+6h [9]		1.6E-6/h(10)
Rupture (internal)	[9]		
Leakage (external)			
Rupture (external)			
Solenoid-Operated Fails to open/close	2/3.5E+3d, 16/2.3E+7h [10]	2/2.3E+3d [13]	7.8E-4/d(10), 7.1E-7/h(10)
Spurious operation	0/8.1E+5h [11]	0/1.5E+3h [14]	6.1E-7/h(10) [1]
Plugs		0/1.5E+3h [15]	3.3E-4/h(10) [1]
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Safety/Relief Fails to open	15/5.4E+3d, 0/5.9E+6h [12]		2.7E-3/d(3.3), 8.5E-8/h(10) [1]
Fails to reclose	47/2.0E+4d [13]		2.3E-3/d(1.7)
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			

Table 3a. Category 1 data for water system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Vacuum-Breaker Fails to open	0/4.5E+1d, 0/1.1E+3h [14]		1.1E-2/d(10), 4.4E-4/h(10) [1]
Fails to reclose			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Explosive Fails to open		0/2.7E+1d [16]	1.8E-2/d(10) [1]
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Valve (Control) Motor-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Air-Operated Fails open			
Fails closed			

Table 3a. Category 1 data for water system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Solenoid-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Pump Motor-Driven Fails to start	137/4.9E+4d [15]	25/2.1E+3d, 3/2.6E+2d, 42/3.7E+3d, 6/2.4E+3d [17]	3.7E-3/d(4.7)
Fails to run	216/7.5E+6h [16]	23/1.7E+6h, 0/4.1E+2h, 0/3.1E+4h, 19/2.6E+6h [18]	2.2E-5/h(17)
Overspeed			
Fails to stop		5/2.6E+2d, 5/2.4E+3d [19]	3.8E-3/d(4.4)
Leakage (external)			
Rupture (external)			

Table 3a. Category 1 data for water system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Turbine-Driven Fails to start	45/2.0E+3d, 3/6.4E+4h [17]		2.2E-2/d(3.8), 5.5E-5/h(10)
Fails to run	19/1.4E+5h [18]		1.4E-4/h(22)
Overspeed			
Fails to stop			
Leakage (external)			
Rupture (external)			
Diesel-Driven Fails to start	15/1.9E+3d [19]		7.9E-3/d(5.8)
Fails to run	3/6.5E+2h [20]		4.6E-3/h(7.4)
Overspeed			
Fails to stop			
Leakage (external)			
Rupture (external)			
Piping/Hose/Jumper Piping Leakage (external)			
Rupture (external)			
Plugs			
Hose Leakage (external)			
Rupture (external)			
Plugs			

Table 3a. Category 1 data for water system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Jumper Leakage (external)			
Rupture (external)			
Plugs			
Vessel Tank (Unpressurized) Leakage (external)	0/6.9E+5h [21]		7.3E-7/h(10) [1]
Rupture (external)	[21]		
Tank (Pressurized) Leakage (external)			
Rupture (external)			
Flange/Gasket Leakage (external)			
Rupture (external)			
Heat Exchanger Shell/Tube Fouling (tubes)			
Plugs (tubes)	0/1.9E+6h [22]		2.6E-7/h(10) [1]
Leakage (tubes)	0/3.8E+5h [23]		1.3E-6/h(10) [1]
Rupture (tubes)	[23]		
Leakage (shell)	0/1.6E+6h [24]		3.1E-7/h(10) [1]
Rupture (shell)	[24]		
Heater (Electrical) Fails to heat			
Overheats			

Table 3a. Category 1 data for water system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Leakage (external)			
Rupture (external)			
Strainer/Filter Plugs	2/6.0E+5h [25]	0/2.5E+4h [20]	4.0E-6/h(10)
Leakage (internal)			
Rupture (internal)			
Orifice Plugs			
Miscellaneous Travelling Screen Plugs		0/9.6E+5h [21]	5.2E-7/h(10) [1]

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR1 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990.

All failure data were obtained from Tables 6 and 7 in the reference. These tables list the aggregations of Category 1 source data from NUCLARR as it existed in August 1989.

1. Manual valve fail to operate data used.

2. Check valve fail to open data used.

3. Check valve fail to close data used.

Table 3a. Category 1 data for water system.

4. Check valve leakage data used. Size of leakage not indicated.

5. Motor-operated valve fail to operate data used.

6. Motor-operated valve spurious operation data used.

7. Pneumatic valve fail to operate and fail to open data used.

8. Pneumatic valve spurious operation data used.

9. Pneumatic valve internal leakage data used. Size of leakage not indicated.

10. Solenoid-operated valve fail to operate data used.

11. Solenoid-operated valve spurious operation data used.

12. Relief valve fail to operate and fail to open data used.

13. Relief valve fail to close data used.

14. Vacuum-breaker valve fail to operate data used.

15. Motor-driven pump fail to start data used.

16. Motor-driven pump fail to run data used.

17. Turbine-driven pump fail to start data used.

18. Turbine-driven pump fail to run data used.

19. Diesel-driven pump fail to start data used.

20. Diesel-driven pump fail to run data used.

21. Tank (unpressurized) external leakage data used. Size of leakage not indicated.

22. Heat exchanger tube plugged data used.

23. Heat exchanger internal leakage data used. Size of leakage not indicated.

Table 3a. Category 1 data for water system.

24. Heat exchanger external leakage data used. Size of leakage not indicated.

25. Strainer plugged data used.

SRS-REACTORS - D. S. Cramer, Valve Reliability for the Level 1 PRA (U), Savannah River Site, WSRC-RP-89-776, Rev. 0, 1991; D. S. Cramer, Check Valve Reliability for the Level 1 PRA (U), Savannah River Site, WSRC-RP-90-1258, Rev. 0, 1991; and D. S. Cramer, Data Base Development and Equipment Reliability for Phase 1 of the Probabilistic Risk Analysis, Savannah River Site, DPST-87-642, October 1987.

1. Data are from Table 27 (first reference, above) for gate and plug valves. Fail to open (CC) and fail to close (OO) data used.

2. Data are from Table 27 (first reference) for gate and plug valves. Fails to remain open (OC) data used.

3. Data are from Table 27 (first reference) for gate and plug valves. Fails to remain closed (CO) data used. Size of internal leakage not indicated.

4. Data are from Table 1 (second reference). Failures are not broken down into fails to open and fails to close in this reference.

5. Data are from Table 1 (second reference). Fails to remain closed (CO) data used. Size of internal leakage not indicated.

6. Data are from Table 27 (first reference) for gate and plug motor-operated valves. Data used only in cases where mechanical and electrical driver entries indicated the same number of demands. Data include mechanical and electrical driver failures. Fail to open (CC) and fail to close (OO) data used.

7. See Note 6 above. Data include only electrical driver failures. Fails to remain closed (CO) and fails to remain open (OC) data used.

8. See Note 6 above. Data include only mechanical failures. Fails to remain open (OC) data used.

9. See Note 6 above. Data include only mechanical failures. Fails to remain closed (CO) data used. Size of internal leakage not indicated.

10. Data are from Table 27 (first reference) for butterfly and diaphragm air-operated valves. Data used only in cases where mechanical and air-driven entries indicated the same number of demands. Data include mechanical and air driver failures. Fail to open (CC) and fail to close (OO) data used.

11. See Note 10 above. Data include only air driver failures. Fails to remain closed (CO) and fails to remain open (OC) data used.

12. See Note 10 above. Data include only mechanical failures. Fails to remain open (OC) data used.

13. Data are from Table 27 (first reference) for solenoid-operated valves. Fail to open (CC) and fail to close (OO) data used.

14. See Note 13 above. Data include only solenoid driver failures. Fails to remain closed (CO) and fails to remain open (OC) data used.

Table 3a. Category 1 data for water system.

15. See Note 13 above. Data include only mechanical failures. Fails to remain open (OC) data used.

16. Data are from Table V.3 (third reference) for explosive valves. Fail to open (CC) data used.

17. Data are from Tables P.1, P.4, P.5, P.7, and P.8 (third reference). Data include mechanical and motor driver failures. Fail to start data used.

18. See Note 17 above. Fail to run data used.

19. See Note 17 above. Fail to stop data used.

20. Data are from Table P.6 (third reference) for screens. Plugged failure data used.

21. Data are from Table W.1 (third reference) for travelling screen. Plugged failure data used.

Aggregated Results

1. Failure rate based on zero failures, and may be conservatively high.

2. SRS-REACTOR data are not broken down into failure modes. NUCLARR1 data indicate that most failures are fail to close. Therefore, the SRS-REACTOR failure was assumed to be fails to close.

Table 3b. Category 1 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Chemical Process			
Valve (Standby or Safety)			
Manual			
Fails to open/close			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Check			
Fails to open			
Fails to close			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Motor-Operated			
Fails to open/close			
Spurious operation			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			

Table 3b. Category 1 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Air-Operated Fails to open/close			
Spurious operation			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Solenoid-Operated Fails to open/close			
Spurious operation			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Safety/Relief Fails to open			
Fails to reclose			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Vacuum-Breaker Fails to open			

Table 3b. Category 1 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Fails to reclose			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Explosive Fails to open			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Valve (Control) Motor-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Air-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			

Table 3b. Category 1 data for chemical process system.			
System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Rupture (external)			
Solenoid-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Pump Motor-Driven Fails to start			
Fails to run			
Overspeed			
Fails to stop			
Leakage (external)			
Rupture (external)			
Turbine-Driven Fails to start			
Fails to run			
Overspeed			
Fails to stop			
Leakage (external)			
Rupture (external)			
Diesel-Driven Fails to start			

Table 3b. Category 1 data for chemical process system.			
System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Fails to run			
Overspeed			
Fails to stop			
Leakage (external)			
Rupture (external)			
Piping/Hose/Jumper Piping Leakage (external)			
Rupture (external)			
Plugs			
Hose Leakage (external)			
Rupture (external)			
Plugs			
Jumper Leakage (external)			
Rupture (external)			
Plugs			
Vessel Tank (Unpressurized) Leakage (external)			
Rupture (external)			
Tank (Pressurized) Leakage (external)			
Rupture (external)			

Table 3b. Category 1 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Flange/Gasket			
Leakage (external)			
Rupture (external)			
Heat Exchanger			
Shell/Tube			
Fouling (tubes)			
Plugs (tubes)			
Leakage (tubes)			
Rupture (tubes)			
Leakage (shell)			
Rupture (shell)			
Heater (Electrical)			
Fails to heat			
Overheats			
Leakage (external)			
Rupture (external)			
Strainer/Filter			
Plugs			
Leakage (internal)			
Rupture (internal)			
Orifice			
Plugs			
Miscellaneous			
Mixer/Blender			
Failure			
Agitator			
Failure			

Table 3b. Category 1 data for chemical process system.			
System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Centrifuge Failure			

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Table 3c. Category 1 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Compressed Gas			
Valve (Standby or Safety)			
Manual			
Fails to open/close			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Check			
Fails to open			
Fails to close			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Motor-Operated			
Fails to open/close			
Spurious operation			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			

Table 3c. Category 1 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Air-Operated Fails to open/close			
Spurious operation			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Solenoid-Operated Fails to open/close			
Spurious operation			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Safety/Relief Fails to open			
Fails to reclose			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Vacuum-Breaker Fails to open			

Table 3c. Category 1 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Fails to reclose			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Valve (Control) Motor-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Air-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Solenoid-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			

Table 3c. Category 1 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Leakage (external)			
Rupture (external)			
Compressor Motor-Driven Fails to start	10/1.4E+3d [1]	2/3.3E+2d, 4/4.4E+2d [1]	7.5E-3/d(7.1)
Fails to run	23/3.0E+5h [2]	6/1.7E+5h, 2/8.9E+4h [2]	5.6E-5/h(1.2)
Overspeed			
Fails to stop			
Leakage (external)			
Rupture (external)			
Piping/Hose/Jumper/Tube Piping Leakage (external)			
Rupture (external)			
Plugs			
Hose Leakage (external)			
Rupture (external)			
Plugs			
Jumper Leakage (external)			
Rupture (external)			
Plugs			
Tube Leakage (external)			

Table 3c. Category 1 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Rupture (external)			
Plugs			
Vessel Tank (Pressurized) Leakage (external)			
Rupture (external)			
Cylinder (Pressurized) Leakage (external)			
Rupture (external)			
Flange/Gasket Leakage (external)			
Rupture (external)			
Heat Exchanger Shell/Tube Fouling (tubes)			
Plugs (tubes)			
Leakage (tubes)			
Rupture (tubes)			
Leakage (shell)			
Rupture (shell)			
Heater (Electrical) Fails to heat			
Overheats			
Leakage (external)			
Rupture (external)			

Table 3c. Category 1 data for compressed gas system.			
System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Vaporizer Failure			
Air Dryer Failure	0/8.6E + 4h [3]		5.8E-6/h(10) [1]
Filter Plugs			
Leakage (internal)			
Rupture (internal)			
Orifice Plugs			

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR1 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990.

All failure data were obtained from Tables 6 and 7 in the reference. These tables list the aggregations of Category 1 source data from NUCLARR as it existed in August 1989.

1. Blower/compressor fail to start data used.

Table 3c. Category 1 data for compressed gas system.

2. Blower/compressor fail to run data used.

3. Air dryer fail to operate data used.

SRS-REACTORS - D. S. Cramer, Data Base Development and Equipment Reliability for Phase 1 of the Probabilistic Risk Analysis, Savannah River Site, DPST-87-642, October 1987.

1. Data are from Tables G.2 and G.3. Air dryer failures are included in the data. Fail to start data used.

2. Data are from Tables G.2 and G.3. Air dryer failures are included in the data. Fail to run data used.

Aggregated Results

1. Failure rate based on zero failures and may be conservatively high.

Table 3d. Category 1 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
HVAC/Exhaust			
Damper (Standby or Safety)			
Manual			
Fails to open/close			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Motor-Operated			
Fails to open/close			
Spurious operation			
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Air-Operated	3/1.2E+3d [1]	10/3.5E+2d, 17/2.1E+2d, 12/2.5E+3d, 8/5.3E+2d, 2/5.3E+2d [1]	9.9E-3/d(6.1)
Fails to open/close			
Spurious operation		5/2.9E+5h, 5/9.2E+5h, 0/8.7E+5h, 10/2.9E+5h, 3/2.9E+5h, 1/2.9E+5h [2]	8.2E-6/h(4.2)

Table 3d. Category 1 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Plugs			
Leakage (internal)			
Rupture (internal)			
Leakage (external)			
Rupture (external)			
Damper (Control) Motor-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Air-Operated Fails open			
Fails closed			
Fails to respond			
Plugs			
Leakage (external)			
Rupture (external)			
Fan/Blower Motor-Driven Fails to start	11/1.5E+3d [2]	1/1.2E+3d [3]	4.4E-3/d(5.4)
Fails to run	13/5.2E+5h [3]	14/4.2E+5h [4]	2.9E-5/h(2.4)

Table 3d. Category 1 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Overspeed			
Fails to stop			
Leakage (external)			
Rupture (external)			
Diesel-Driven Fails to start			
Fails to run			
Overspeed			
Fails to stop			
Leakage (external)			
Rupture (external)			
Ducting Leakage (external)			
Rupture (external)			
Plugs			
Heat Exchanger Air Conditioning Unit/ Chiller Fails to start	8/6.1E+2d [4]		1.4E-2/d(10)
Fails to run	4/1.9E+5h [5]		2.4E-5/h(10)
Fan Cooler Unit Fails to start	21/2.5E+3d [6]		8.4E-3/d(7.2)
Fails to run	2/2.3E+5h [7]		8.8E-6/h(2.9)
Heater (Electrical) Fails to heat			

Table 3d. Category 1 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Overheats			
Heater (Gas) Fails to heat			
Overheats			
Filter Normal Plugs			
Leakage (internal)			
Rupture (internal)			
Low-Efficiency Plugs			
Leakage (internal)			
Rupture (internal)			
HEPA Plugs			
Leakage (internal)			
Rupture (internal)			
Sand Plugs			
Leakage (internal)			
Rupture (internal)			
Baghouse Plugs			
Leakage (internal)			
Rupture (internal)			

Table 3d. Category 1 data for HVAC/exhaust system.			
System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Miscellaneous Mist Eliminator Failure			
Scrubber Failure			
Precipitator Failure			

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR1 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990.

All failure data were obtained from Tables 6 and 7 in the reference. These tables list the aggregations of Category 1 source data from NUCLARR as it existed in August 1989.

1. Damper fail to operate data used. Type of damper not indicated (air-operated assumed).

2. Ventilator fan fail to start data used.

3. Ventilator fan fail to run data used.

Table 3d. Category 1 data for HVAC/exhaust system.

4. Air conditioning unit fail to start data used.

5. Air conditioning unit fail to run data used.

6. Fan/cooler unit fail to start data used.

7. Fan/cooler unit fail to run data used.

SRS-REACTORS - D. S. Cramer, Data Base Development and Equipment Reliability for Phase 1 of the Probabilistic Risk Analysis, Savannah River Site, DPST-87-642, October 1987 and D. S. Cramer, Reliability of Dampers in the Reactor Confinement System, Savannah River Site, SRL-PRA-900011, Revision 3, January 25, 1990.

1. Data are from Table 1 (second reference). Fail to open (CC) and fail to close (OO) data used.

2. Data are from Table 1 (second reference). Fails to remain open (OC) and fails to remain closed (CO) data used.

3. Data are from Tables VENT.7, VENT.8, and VENT.9 (first reference). Fails to start data used.

4. Data are from Tables VENT.7, VENT.8, and VENT.9 (first reference). Fails to run data used.

Table 3e. Category 1 data for electrical distribution system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Electric Power Generator Diesel-Driven Fails to start	92/8.7E+3d [1]	26/9.1E+2d, 16/9.5E+2d [1]	1.3E-2/d(2.2)
Fails to run	29/6.6E+3h [2]	1/5.8E+2h [2]	4.1E-3/h(3.3)
Motor-Driven (ac to dc) Fails to start			
Fails to run	31/1.5E+6h [3]		2.1E-5/h(10)
Gas-Turbine-Driven Fails to start	35/9.4E+2d [4]		3.8E-2/d(10)
Fails to run	1/5.7E+3h [5]		2.6E-4/h(10)
Hydro-Turbine-Driven Fails to start	12/4.1E+3d [6]		3.1E-3/d(10)
Fails to run			
Battery Failure	7/5.9E+2d, 8/9.4E+5h [7]	12/1.8E+3d [3]	8.0E-3/d(1.2), 8.4E-6/h(3.7)
Charger Rectifier Failure	29/1.6E+6h [8]		1.8E-5/h(1.7)
Bus Metal-Enclosed Failure	1/1.4E+7h [9]		1.1E-7/h(10)
Bare Failure	[9]		

Table 3e. Category 1 data for electrical distribution system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Cable/Joint/Termination/Jumper			
Cable (Copper, 1000ft)			
Failure			
Joint (Copper)			
Failure			
Termination (Copper)			
Failure			
Jumper (Power)			
Failure			
Circuit Breaker	101/1.8E+5d [10]	4/1.3E+3d [4]	5.6E-4/d(4.5)
General			
Fails to open/close			
Spurious operation	15/4.1E+7h [11]		3.8E-7/h(10)
Reactor Trip			
Fails to open			
Spurious operation			
Relay		5/4.5E+3d [5]	1.2E-3/d(10)
Protective			
Fails to open/close			
Spurious operation			
Control			
Fails to open/close			
Spurious operation			
Bistable			
Fails to open/close			
Spurious operation			

Table 3e. Category 1 data for electrical distribution system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Switch			
Push-Button (Manual)			
Fails to open/close			
Spurious operation			
Rotary (Manual)			
Fails to open/close			
Spurious operation			
Key-Operated (Manual)			
Fails to open/close			
Spurious operation			
Automatic-Transfer			
Fails to open/close	1/7.5E+1d [12]		2.0E-2/d(10)
Spurious operation			
Limit			
Fails to open/close	0/1.3E+4d, 7/8.2E+6h [13]		4.0E-5/d(10), 9.2E-7/h(10) [1]
Spurious operation			
Fuse			
Fail to open			
Premature opening			
Inverter			
Failure	0/6.3E+1d, 23/1.9E+6h [14]		7.9E-3/d(10), 1.2E-5/h(1.9) [1]
Motor			
AC			
Fails to start			
Fails to run			

Table 3e. Category 1 data for electrical distribution system.			
System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
DC Fails to start			
Fails to run			
Synchro Failure			
Transformer Power Failure	1/1.8E+6h [15]		8.2E-7/h(10)
Instrumentation/Control Failure	5/6.2E+6 [16]		8.9E-7/h(10)

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR1 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990.

All failure data were obtained from Tables 6 and 7 in the reference. These tables list the aggregations of Category 1 source data from NUCLARR as it existed in August 1989.

1. Diesel generator fail to start data used.

2. Diesel generator fail to run data used.

3. Motor-driven generator fail to run data used.

4. Gas-turbine-driven generator fail to start data used.

5. Gas-turbine-driven generator fail to run data used.

Table 3e. Category 1 data for electrical distribution system.

6. Hydro-turbine-driven generator fail to start data used.

7. Battery fail to operate data used.

8. Battery charger fail to operate data used.

9. Electrical conductor (bus) fail to operate data used. Type of bus not indicated.

10. Circuit breaker data (except for spurious failure mode) used.

11. Circuit breaker spurious data used.

12. Automatic transfer switch fail to operate data used.

13. Instrumentation (limit) switch fail to operate data used.

14. Power electronics (inverter) fail to operate data used.

15. Power transformer fail to operate data used.

16. Control and instrumentation transformer fail to operate data used.

SRS-REACTORS - D. S. Cramer, Data Base Development and Equipment Reliability for Phase 1 of the Probabilistic Risk Analysis, Savannah River Site, DPST-87-642, October 1987.

1. Data are from Tables E.10 and VENT.5. Fail to start data used.

2. Data are from Tables E.10 and VENT.5. Fail to run data used.

3. Data are from Table E.1.

4. Data are from Table E.11.

5. Data are from Table E.13.

Aggregated Results

1. Failure rate based on zero failures and may be conservatively high.

Table 3f. Category 1 data for instrumentation and control system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Instrumentation and Control			
Alarm/Annunciator			
Fails to alarm			
Spurious operation			
Sensor/Transmitter/Transducer/Process Switch			
Temperature	12/5.7E+4d, 78/7.6E+7h [1]	2/8.7E+5h, 6/1.2E+6h [1]	2.8E-4/d(3.5), 1.1E-6/h(3.3)
Failure			
Pressure	[1]		2.8E-4/d(3.5), 1.1E-6/h(3.3)
Failure			
Differential Pressure			
Failure			
Flow			
Failure			
Level			
Failure			
Humidity			
Failure			
pH			
Failure			
Oxygen Concentration			
Failure			
CO_2 Concentration			
Failure			
Hydrogen Concentration			
Failure			
Nitrogen Concentration			
Failure			
Hydrocarbon Concentration			
Failure			

Table 3f. Category 1 data for instrumentation and control system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Helium Concentration Failure			
Speed Failure			
Seismic Failure			
Radiation Failure			
Indicator Failure			
Amplifier Failure			
Modifier/Signal Conditioner Failure			
Logic Module Failure			
Recorder Failure			
Sampler Failure			
Analyzer Failure			
Timer Failure			
Gas Chromatograph Failure			
Voltage Regulator Failure			
Transmitter Failure	57/2.6E+7h [2]		2.2E-6/h(1.4)

Table 31. Category 1 data for instrumentation and control system.			
System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]		
	NUCLARR1	SRS-REACTORS	Aggregated Results[b]
Transducer Failure			
Programmable Logic Controller Failure			

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR1 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990.

All failure data were obtained from Tables 6 and 7 in the reference. These tables list the aggregations of Category 1 source data from NUCLARR as it existed in August 1989.

1. Transducer (sensor) data used. First data entry is for failure to operate. Second data entry is for spurious operation. Type of sensor not indicated.

2. Transmitter failure to operate data used.

SRS-REACTORS - D. S. Cramer, Data Base Development and Equipment Reliability for Phase 1 of the Probabilistic Risk Analysis, Savannah River Site, DPST-87-642, October 1987.

1. Thermocouple data from Table E.16 used.

Table 4a. Category 2 data for water system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Water Valve (Standby or Safety) Manual Fails to open/close	9/6.5E+4d [1]	2.5/3.8E+6h, 1.5/2.5E+6h [1]					1.4E-4/d(19), 7.1E-7/h(10)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)	124/1.3E+10h [2]	5/3.8E+6h, 3/2.5E+6h [1]					1.0E-8/h(9.6)
Rupture (external)	7/1.3E+10h [3]	0/3.8E+6h, 0/2.5E+6h [1]					5.8E-10/h(10)
Check Fails to open	3/4.7E+4d [4]	3.3/2.2E+7h, 1.4/1.8E+7h [2]					1.8E-5/d(10), 1.3E-7/h(10)
Fails to close	[4]	10.7/2.2E+7h, 4.4/1.8E+7h [2]					5.7E-5/d(10), 3.9E-7/h(10)
Plugs							
Leakage (internal)	55/1.0E+8h [5]	52.9/2.2E+7h, 21.8/1.8E+7h [3]					9.1E-7/h(2.9)
Rupture (internal)	[5]	[3]					
Leakage (external)	124/1.3E+10h [2]	52.9/2.2E+7h, 21.8/1.8E+7h [3]					1.5E-8/h(26)
Rupture (external)	7/1.3E+10h [3]	0/2.2E+7h, 0/1.8E+7h [4]					5.8E-10/h(10)

Table 4a. Category 2 data for water system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Motor-Operated Fails to open/close	287/7.5E + 4d [6]						3.8E-3/d(1.8)
Spurious operation	24/1.4E + 8h [7]						1.8E-7/h(11)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)	124/1.3E + 10h [2]						9.6E-9/h(10)
Rupture (external)	7/1.3E + 10h [3]						5.8E-10/h(10)
Air-Operated Fails to open/close	85/2.9E + 4d [8]		16/8.9E + 2d [1]				3.4E-3/d(3.8)
Spurious operation	10/1.1E + 7h [9]		9/4.3E + 6h [1]				1.2E-6/h(2.0)
Plugs							
Leakage (internal)	8/1.4E + 7h [10]		7/4.3E + 6h [1]				6.9E-7/h(2.6)
Rupture (internal)	[10]		3/4.3E + 6h [1]				3.0E-7/h(2.6)
Leakage (external)	124/1.3E + 10h [2]		5/4.3E + 6h [1]				9.9E-9/h(7.6)
Rupture (external)	7/1.3E + 10h [3]		0/4.3E + 6h [1]				5.8E-10/h(10)
Solenoid-Operated Fails to open/close	96/9.0E + 3d [11]	0.3/4.6E + 4h, 2.8/4.8E + 7h [5]					1.1E-2/d(10), 7.5E-8/h(10)

Table 4a. Category 2 data for water system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Spurious operation	1/8.8E+4h [12]	0.1/4.6E+4h, 1.2/4.8E+7h [5]					5.6E-8/h(10)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)	124/1.3E+10h [2]	3.9/4.6E+4h, 41.4/4.8E+7h [5]					1.3E-8/h(37)
Rupture (external)	7/1.3E+10h [3]	0/4.6E+4h, 0/4.8E+7h [5]					5.8E-10/h(10)
Safety/Relief Fails to open	130/4.9E+4d [13]						1.2E-2/d(3.3)
Fails to reclose							
Leakage (internal)		4/9.7E+5h, 7.5/9.2E+6h [6]					1.1E-6/h(2.5)
Rupture (internal)							
Leakage (external)		4/9.7E+5h, 7.5/9.2E+6h [6]					1.1E-6/h(2.5)
Rupture (external)		0/9.7E+5h, 0/9.2E+6h [6]					4.9E-8/h(10)
Vacuum-Breaker Fails to open							
Fails to reclose							
Leakage (internal)							

Table 4a. Category 2 data for water system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Valve (Control) Motor-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Air-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Solenoid-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							

Table 4a. Category 2 data for water system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Pump Motor-Driven Fails to start	84/1.0E+5d [14]	1.4/8.4E+5h, 2.9/2.6E+6h, 6.0/2.6E+6h [7]	2/3.0E+2d, 3/6.3E+4h, 10/2.7E+5h [2]				8.3E-4/d(9.1), 3.7E-6/h(8.3)
Fails to run	242/2.4E+7h [15]	0.8/8.4E+5h, 1.8/2.6E+6h, 3.7/2.6E+6h [7]	2/2.0E+2h, 8/6.3E+4h, 17/6.3E+4h [2]				9.4E-6/h(11)
Overspeed		0.2/8.4E+5h, 0.4/2.6E+6h, 0.7/2.6E+6h [7]					1.9E-6/h(11)
Fails to stop							
Leakage (external)	43/1.6E+9h [16]	3.6/8.4E+5h, 7.7/2.6E+6h, 15.9/2.6E+6h [7]	1/6.3E+4h, 24/2.7E+5h [2]				5.9E-8/h(55)
Rupture (external)	2/1.6E+9h [17]	0.02/8.4E+5h, 0.05/2.6E+6h, 0.11/2.6E+6h [7]	0/6.3E+4h, 0/2.7E+5h [2]				1.7E-9/h(10)
Turbine-Driven Fails to start	72/7.1E+3d [18]						1.0E-2/d(10)
Fails to run	22/2.2E+5h [19]						1.0E-4/h(1.7)
Overspeed							
Fails to stop							
Leakage (external)	43/1.6E+9h [16]						2.7E-8/h(10)
Rupture (external)	2/1.6E+9h [17]						1.6E-9/h(10)

Table 4a. Category 2 data for water system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Diesel-Driven Fails to start	10/1.1E+3d [20]		75/1.1E+3d, 2/3.0E+2d [3]				3.4E-2/d(4.0)
Fails to run			4/2.0E+2h [3]				2.3E-2/h(10)
Overspeed							
Fails to stop							
Leakage (external)	43/1.6E+9h [16]		1/3.8E+5h [3]				2.7E-8/h(10)
Rupture (external)	2/1.6E+9h [17]		0/3.8E+5h [3]				1.6E-9/h(10)
Piping/Hose/Jumper Piping Leakage (external)	456/ 2.0E+11h-ft [21]						2.3E-9/h-ft(10)
Rupture (external)	11/ 2.0E+11h-ft [22]						5.8E-11/h-ft(10)
Plugs							
Hose Leakage (external)		0/ 1.7E+7h-ft, 1.9/ 1.4E+9h-ft [8]					1.7E-9/h-ft(10)
Rupture (external)		0/ 1.7E+7h-ft, 14/ 1.4E+9h-ft [8]					1.0E-8/h-ft(10)
Plugs							
Jumper Leakage (external)							

Table 4a. Category 2 data for water system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Rupture (external)							
Plugs							
Vessel Tank (Unpressurized) Leakage (external)	8/6.3E+8h [23]	7/4.3E+6h [9]					2.2E-8/h(19)
Rupture (external)	1/6.3E+8h [24]	[9]					3.0E-9/h(19)
Tank (Pressurized) Leakage (external)	[23]	93/8.2E+6h, 565/1.2E+7h [10]					1.0E-6/h(24)
Rupture (external)	[24]	3.9/8.2E+6h, 24/1.2E+7h [10]					4.5E-8/h(23)
Flange/Gasket Leakage (external)	116/6.3E+9h [25]	16/1.2E+7h [11]					2.1E-8/h(11)
Rupture (external)	1/6.3E+9h [26]	[11]					1.8E-10/h(11)
Heat Exchenger Shell/Tube Fouling (tubes)							
Plugs (tubes)							
Leakage (tubes)	53/3.2E+8h [27]		4/6.6E+4h [4]				1.8E-7/h(17)
Rupture (tubes)	2/3.2E+8h [28]						7.8E-9/h(10)
Leakage (shell)	2/3.2E+8h [29]						7.8E-9/h(10)
Rupture (shell)	0/3.2E+8h [30]						1.6E-9/h(10)

Table 4a. Category 2 data for water system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Heater (Electrical)							
Fails to heat		1.2/8.2E+5h [12]					1.8E-6/h(10)
Overheats		0.2/8.2E+5h [12]					3.0E-7/h(10)
Leakage (external)							
Rupture (external)							
Strainer/Filter							
Plugs							
Leakage (internal)		26/1.2E+7h [13]					2.2E-6/h(10)
Rupture (internal)		7.7/1.2E+7h [13]					6.8E-7/h(10)
Orifice							
Plugs							
Miscellaneous							
Travelling Screen							
Plugs							

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR2 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990. Also, S. A. Eide et al., Component External Leakage and Rupture Frequency Estimates, Idaho National Engineering Laboratory, EGG-SSRE-9639, N[illegible] 1991.

All failure data except for the leakage failure mode were obtained from Tables 6 and 7 in the first reference. These tables list the aggregations of Category 2 sou[illegible] data from NUCLARR as it existed in August 1989. The external leakage data were obtained from the second reference. These data were not in NUCLARR at the time the reference was published, but since then the data have been entered into NUCLARR.

Table 4a. Category 2 data for water system.

1. Manual valve fail to operate data used.
2. Valve external leakage data used (second reference).
3. Valve external rupture data used (second reference).
4. Check valve fail to operate data used. Data include both fails to open and fails to close.
5. Check valve internal leakage data used. Size of internal leakage not indicated.
6. Motor-operated valve fail to operate, fail to open, and fail to close data used.
7. Motor-operated valve spurious operation data used.
8. Pneumatic valve fail to operate and fail to open data used.
9. Pneumatic valve spurious operation data used.
10. Pneumatic valve internal leakage data used. Size of internal leakage not indicated.
11. Solenoid valve fail to operate data used.
12. Solenoid valve spurious operation data used.
13. Relief valve fail to open data used.
14. Motor-driven pump fail to start data used.
15. Motor-driven pump fail to run data used.
16. Pump external leakage data used (second reference).
17. Pump external rupture data used (second reference).
18. Steam-turbine-driven pump fail to start data used.
19. Steam-turbine-driven pump fail to run data used.
20. Diesel-driven pump fail to start data used.

Table 4a. Category 2 data for water system.

21. Piping external leakage data used (second reference).

22. Piping external rupture data used (second reference).

23. Tank external leakage data used (second reference).

24. Tank external rupture data used (second reference).

25. Flange external leakage data used (second reference).

26. Flange external rupture data used (second reference).

27. Heat exchanger tube leakage data used (second reference).

28. Heat exchanger tube rupture data used (second reference).

29. Heat exchanger shell leakage data used (second reference).

30. Heat exchanger shell rupture data used (second reference).

NPRD-3 - M. J. Rossi, Nonelectronic Parts Reliability Data, Reliability Analysis Center, Rome Air Development Center, NPRD-3, 1985.

All failure data apply to a ground fixed (GF) environment, unless otherwise indicated. Commercial (C), military (M), and unknown source (?) data were used if available. Failure mode information was used to determine what % of failures were fail to open/close, spurious operation, etc. Unknown failure mode events were not considered. The NPRD-3 failures include degraded and incipient failures as well as catastrophic failures. Only catastrophic failures were used for this study. For valves, circuit breakers, relays, and switches, the following mapping of NPRD-3 failure modes into the failure modes of interest was used:

Fail to open/close/operate - binding, breach (not for valves), contaminated, cracked/fractured, no movement, no operation, seized, stuck open, and stuck closed

Spurious operation - arcing, burned, collapsed, displaced, false response, improper flow, intermittent, opened, overheated, and shorted

Plugs - none identified

Leakage (internal) - none identified except for leaking (one-half of events applied to internal leakage for check and relief valves)

Table 4a. Category 2 data for water system.

Leakage (external) - leaking

Rupture (external) - breach (valves only).

For pumps, fans, and diesel generators, the following mapping was used:

Fail to start - contaminated, cracked/fractured, no movement, no operation

Fail to run - binding, broken, displaced, false response, improper flow, intermittent, overheated, seized, shorted, stuck closed, stuck open

Overspeed (subset of fail to run) - improper flow (one-half of events used), stuck open

Fail to stop - none identified

Leakage (external) - leaking

Rupture (external) - breach (not for generator)

For vessels, piping, hoses, and jumpers, the following mapping was used:

Leakage (external) - cracked/fractured, leaking

Rupture (external) - broken, breach.

For filters, the following mapping was used:

Plug - improper flow (one-half of events used)

Leakage (internal) - improper flow (one-half of events used)

Rupture (internal) - broken, cracked/fractured, ruptured.

For heaters, the following mapping was used:

Fail to heat - cracked/fractured, no operation, opened

Table 4a. Category 2 data for water system.

Overheat - shorted.

1. Manually-activated valve data used (p. 153). Failure mode information (p. 297) indicates 25% of failures are fail to open/close, 50% are external leakage, and 0% are external rupture.

2. Check valve data used (p. 150). Failure mode information (p. 296) indicates 8.2% of failures are fail to close and 2.5% are fail to open.

3. Check valve data used (p. 150). Failure mode information (p. 296) indicates 80.8% of failures are leaking. One-half of these were assigned to internal leakage/rupture and the other half to external leakage. Size of internal leakage not indicated.

4. Check valve data used (p. 150). Failure mode information (p. 296) indicates 0% of failures are external rupture.

5. Solenoid valve data used (p. 156). Failure mode information (p. 306) indicates 4.4% of failures are fail to open/close, 1.8% are spurious operation, 65.8% are external leakage, and 0% are external rupture.

6. Relief valve data used (p. 155). Failure mode information (p. 299) indicates 100% of failures are leaking. One-half of these were assigned to internal leakage/rupture and the other half to external leakage. Size of internal leakage not indicated.

7. Centrifugal pump data used (p. 104). Failure mode information (p. 291) indicates 19.4% of failures are fail to start, 11.9% are fail to run, 2.4% are overspeed, 51.4% are external leakage, and 0.34% are external rupture.

8. Hose data used (p. 82). Second entry is for ground mobile (GM) environment. Failure mode information (p. 290) indicates 12% of failures are external leakage and 88% are external rupture. Each hose was assumed to be 20 ft.

9. Storage tank data used (p. 143). No failure mode information, so 100% assumed to be external leakage/rupture. Size of leakage not indicated.

10. Accumulator data used (p. 26). Both entries are for ground mobile (GM) environment. Failure mode information (p. 289) indicates 83% of failure are external leakage and 3.4% are external rupture.

11. General gasket data used (p. 71). No failure mode information, to 100% assumed to be external leakage/rupture. Size of leakage not indicated.

12. Electrical heater data used (p. 81). Failure mode information (p. 287) indicates 62% of failures are fail to heat and 7.7% are overheat.

13. Fluid filter data used (p. 67). Failure mode information (p. 285) indicates 75% of failures are internal leakage and 22% are internal rupture.

Table 4a. Category 2 data for water system.

OREDA - Offshore Reliability Data Handbook, Offshore Reliability Data (OREDA), Norway, 1984.

All failure information was taken from the critical failure mode category, unless otherwise indicated.

1. Pneumatically-operated deluge valve in fire fighting system data used (p. 97). Improper operation (degraded failure mode) used for spurious operation, internal leakage (degraded failure mode) used for internal leakage, significant internal leakage used for internal rupture, and external leakage (incipient failure mode) used for external leakage.

2. Electric motor, gear/shaft driven fire water pump (p. 95), single stage electric motor driven (p. 173), and multistage electric motor driven (p. 181) data used. Fails to run data based on operational time. Leakage (incipient failure mode) used for external leakage.

3. Diesel motor, gear/shaft driven (p. 91) and hydraulically driven (p. 93) pump data used. Fails to run data based on operation time. Leakage (incipient failure mode) used for external leakage.

4. Water/water tube/shell type heat exchanger data used (p. 207). Leakage (degraded failure mode) used for tube leakage.

WIN-330 - J. N. Wilkinson et al., Idaho Chemical Processing Plant Failure Rate Database, Idaho National Engineering Laboratory, WIN-330, October 1991.

All failure information was taken from Appendix C, p. 32.

Table 4b. Category 2 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Chemical Process							
Valve (Standby or Safety)							
Manual							
Fails to open/close							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Check							
Fails to open							
Fails to close							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Motor-Operated							
Fails to open/close							
Spurious operation							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							

Table 4b. Category 2 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Air-Operated Fails to open/close			2/1.5E+2d, 2/5.0E+5h [1]	364/4.8E+8 h, 131/2.8E+7 h [1]			1.7E-2/d(10), 2.0E-7/h(5) [1]
Spurious operation			1/3.9E+6h [1]	[1]			2.2E-8/h(10) [1]
Plugs				[1]			2.2E-8/h(10) [1]
Leakage (internal)			15/6.6E+5h, 1/5.0E+5h [1]	[1]			7.3E-7/h(5) [1]
Rupture (internal)			0/6.6E+5h, 0/5.0E+5h [1]	[1]			2.2E-8/h(10) [1,2]
Leakage (external)			9/1.5E+6h, 1/5.0E+5h, 1/3.9E+6h [1]	170/4.8E+8 h, 46/2.8E+7h [2]			4.2E-7/h(3.6) [3]
Rupture (external)			0/1.5E+6h, 0/5.0E+5h, 0/3.9E+6h [1]	[2]			1.8E-8/h(10) [2,3]
Solenoid-Operated Fails to open/close							
Spurious operation							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							

Table 4b. Category 2 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Rupture (external)							
Safety/Relief Fails to open							
Fails to reclose							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Vacuum-Breaker Fails to open							
Fails to reclose							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Valve (Control) Motor-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Air-Operated Fails open			3/5.8E+5h [2]				6.0E-6/h(10)

Table 4b. Category 2 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Fails closed			1/5.8E+5h [2]				2.6E-6/h(10)
Fails to respond							
Plugs							
Leakage (external)			6/5.8E+5h [2]				1.1E-5/h(10)
Rupture (external)							
Solenoid-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Pump Motor-Driven Fails to start			3/6.3E+4h, 10/1.3E+3d, 12/8.2E+6h, 4/4.0E+4h [3]	168/4.5E+6 h, 48/1.4E+6h [3]			8.1E-3/d(10), 8.9E-6/h(4.1) [4]
Fails to run			3/6.3E+4h, 9/2.6E+3h, 5/6.5E+4h, 4/8.7E+3h [3]	[3]			5.8E-4/h(12) [4]
Overspeed				[3]			
Fails to stop				[3]			
Leakage (external)			22/1.9E+5h, 65/8.2E+6h [3]	21/4.5E+6h, 23/1.4E+6h [4]			9.2E-6/h(5.4) [5]

Table 4b. Category 2 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Rupture (external)			0/1.9E+5h, 0/8.2E+6h [3]	[4]			5.2E-8/h(10) [5]
Turbine-Driven Fails to start							
Fails to run							
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Diesel-Driven Fails to start							
Fails to run							
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Piping/Hose/Jumper Piping Leakage (external)							
Rupture (external)							
Plugs							
Hose Leakage (external)							
Rupture (external)							
Plugs							

Table 4b. Category 2 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Jumper Leakage (external)							
Rupture (external)							
Plugs							
Vessel Tank (Unpressurized) Leakage (external)				13/4.6E+6h, 19/8.0E+6h [5]			2.6E-6/h(10)
Rupture (external)				[5]			
Tank (Pressurized) Leakage (external)			24/1.7E+6h [4]	13/4.6E+6h, 19/8.0E+6h [5]			3.7E-6/h(3.8) [5]
Rupture (external)			2/1.7E+6h [4]	[5]			3.8E-7/h(10) [5]
Flange/Gasket Leakage (external)							
Rupture (external)							
Heat Exchanger Shell/Tube Fouling (tubes)			13/2.3E+6h [5]	31/1.6E+6h, 15/8.4E+5h [6]			7.8E-6/h(1.3) [6]
Plugs (tubes)				[6]			
Leakage (tubes)			12/2.3E+6h, 1/2.2E+4h [5]	[6]			7.2E-6/h(1.3) [6]
Rupture (tubes)				[6]			
Leakage (shell)				[6]			
Rupture (shell)				[6]			
Heater (Electrical) Fails to heat			4/2.2E+4h, 1/1.2E+5h [6]				3.5E-5/h(5.8)

Table 4b. Category 2 data for chemical process system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Overheats			1/2.2E+4h [6]				7.0E-6/h(10) [7]
Leakage (external)							
Rupture (external)							
Strainer/Filter Plugs		1.2/5.8E+6h [1]	19/6.4E+5h [7]				3.1E-6/h(11)
Leakage (internal)		2.7/5.8E+6h [1]					7.0E-6/h(11) [8]
Rupture (internal)		0/5.8E+6h [1]					7.0E-7/h(11) [2,8]
Orifice Plugs							
Miscellaneous Mixer/Blender Failure							
Agitator Failure				4/6.3E+5h, 4/6.8E+5h [7]			6.5E-6/h(10)
Centrifuge Failure							

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Table 4b. Category 2 data for chemical process system.

Notes

NUCLARR2 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990. Also, S. A. Eide et al., Component External Leakage and Rupture Frequency Estimates, Idaho National Engineering Laboratory, EGG-SSRE-9639, November 1991.

All failure data except for the leakage failure mode were obtained from Tables 6 and 7 in the first reference. These tables list the aggregations of Category 2 source data from NUCLARR as it existed in August 1989. The leakage data were obtained from the second reference. These data were not in NUCLARR at the time the reference was published, but since then the data have been entered into NUCLARR.

NPRD-3 - M. J. Rossi, Nonelectronic Parts Reliability Data, Reliability Analysis Center, Rome Air Development Center, NPRD-3, 1985.

All failure data apply to a ground fixed (GF) environment, unless otherwise indicated. Commercial (C), military (M), and unknown source (?) data were used if available. Failure mode information was used to determine what % of failures were fail to open/close, spurious operation, etc. Unknown failure mode events were not considered. The NPRD-3 failures include degraded and incipient failures as well as catastrophic failures. Only catastrophic failures were used for this study. For valves, circuit breakers, relays, and switches, the following mapping of NPRD-3 failure modes into the failure modes of interest was used:

Fail to open/close/operate - binding, breach (not for valves), contaminated, cracked/fractured, no movement, no operation, seized, stuck open, and stuck closed

Spurious operation - arcing, burned, collapsed, displaced, false response, improper flow, intermittent, opened, overheated, and shorted

Plugs - none identified

Leakage (internal) - none identified except for leaking (one-half of events applied to internal leakage for check and relief valves)

Leakage (external) - leaking

Rupture (external) - breach (valves only).

For pumps, fans, and diesel generators, the following mapping was used:

Fail to start - contaminated, cracked/fractured, no movement, no operation

Fail to run - binding, broken, displaced, false response, improper flow, intermittent, overheated, seized, shorted, stuck closed, stuck open

Table 4b. Category 2 data for chemical process system.

Overspeed (subset of fail to run) - improper flow (one-half of events used), stuck open

Fail to stop - none identified

Leakage (external) - leaking

Rupture (external) - breach (not for generator)

For vessels, piping, hoses, and jumpers, the following mapping was used:

Leakage (external) - cracked/fractured, leaking

Rupture (external) - broken, breach.

For filters, the following mapping was used:

Plug - improper flow (one-half of events used)

Leakage (internal) - improper flow (one-half of events used)

Rupture (internal) - broken, cracked/fractured, ruptured.

For heaters, the following mapping was used:

Fail to heat - cracked/fractured, no operation, opened

Overheat - shorted.

1. Gas filter data used (p. 68). Failure mode information (p. 286) indicates 16.7% of failures are plugs, 38.9% are internal leakage, and 0% are internal rupture.

Table 4b. Category 2 data for chemical process system.

OREDA - Offshore Reliability Data Handbook, Offshore Reliability Data (OREDA), Norway, 1984.

All failure information was taken from the critical failure mode category, unless otherwise indicated.

1. Hydraulically and pneumatically operated valve (oil fluid) data used (pp. 111, 117, and 159). Improper operation (degraded failure mode) data used for spurious operation. Internal leakage (degraded failure mode) data used for internal leakage, and external leakage (degraded failure mode) used for external leakage.

2. Pneumatically operated control valve data used (p. 167). Significant internal leakage data used for fails open and plugged data used for fails closed. External leakage (degraded failure mode) data used for external leakage.

3. Single stage centrifugal, single stage reciprocating, and multistage centrifugal pump data used (pp. 175, 177, 179, 183, and 185). Fails to run data based on operational time. External leakage (incipient failure mode) data used for external leakage.

4. Separator data used (p. 143). Minor leakage (incipient failure mode) data used for external leakage, and major leakage and break data used for external rupture.

5. Oil/water (p. 193) and glycol/water (p. 203) tube/shell heat exchanger data used. Leakage (degraded failure mode) data used for tube leakage.

6. Oil (p. 215) and glycol (p. 219) heater data used.

7. Hydraulic (oil) system filter data used (p. 285). Clogged filter/line (degraded failure model) data used for plugs.

WIN-330 - J. N. Wilkinson et al., Idaho Chemical Processing Plant Failure Rate Database, Idaho National Engineering Laboratory, WIN-330, October 1991.

All failure information was taken from Appendix C, p. 32.

1. Valve (non-acid and acid fluid) data used (other failure mode). All valves assumed to be air-operated. Failure modes (other than leak) not indicated.

2. See Note 1. Leak failure mode data used for external leakage/rupture.

3. Pump (non-acid and acid fluid) data used (other failure mode). All pumps assumed to be motor-operated. Failure modes (other than leak) not indicated.

4. See Note 3. Leak failure mode data used for external leakage/rupture.

5. Vessel (non-acid and acid fluid) data used for unpressurized and pressurized tanks. All failure mode data used for external leakage/rupture.

Table 4b. Category 2 data for chemical process system.

6. Heat exchanger/condenser (non-acid and acid fluid) data used. Failure modes not indicated.

7. Agitator (non-acid and acid fluid) data used. Failure modes not indicated.

TRITIUM - L. C. Cadwallader and M. A. Stolpe Gavett, Tritium Waste Treatment System Component Failure Data Analysis from June 18, 1984 to December 31, 1989, Idaho National Engineering Laboratory, EGG-FSP-8973, Rev. 1, November 1990; L. C. Cadwallader, M. A. Stolpe Gavett, and L. Quintana, Tritium Room Air Monitor Component Failure Data Analysis from January 1, 1984 to December 31, 1990, Idaho National Engineering Laboratory, EGG-FSP-9450, May 1991; and L. C. Cadwallader and D. P. Sanchez, Secondary Containment System Component Failure Data Analysis from 1984 to 1991, Idaho National Engineering Laboratory, EGG-FSP-10323, August 1992.

Aggregated Results

1. All failure data were combined to obtain an overall failure rate. The OREDA data were used to estimate the fraction for each failure mode. Data indicate 4 fails to open/close, 16 internal leakages, and zero spurious operations, plugs, and internal ruptures. Zero failure cases were handled using a Bayesian update of a noninformative prior with zero events in 20 "demands".

2. Failure rate based on zero failures and may be conservatively high.

3. Similar to Note 1. Ruptures are zero events in 11 "demands".

4. One-half of WIN-330 failures were assigned to fails to start. Fails to run result was increased by the same amount that the fails to start estimate was increased.

5. Leakage/rupture combined result was calculated. Then OREDA data were used to partition into external leakage and external rupture.

6. Combined fouling and tube leakage result was calculated. Then OREDA data were used to partition into fouling and tube leakage.

7. One-fifth of fails to heat result used, based on OREDA data.

8. Plugs result multiplied by 2.7/1.2 to obtain internal leakage result, and by 1/12(1.2) + 2| to obtain rupture result, based on NPRD-3 data.

Table 4c. Category 2 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Compressed Gas Valve (Standby or Safety) Manual Fails to open/close		0/8.3E+5h [1]			3/1.6E+3d [1]		2.2E-3/d(10), 6.0E-7/h(10)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)		0/8.3E+5h [1]			0/3.9E+6h [1]		1.1E-7/h(10)
Rupture (external)		[1]			[1]		
Check Fails to open		4.1/1.6E+6h [2]	1/3.1E+6h [1]				1.1E-6/h(2.7)
Fails to close		8.9/1.6E+6h [2]					2.4E-6/h(2.7) [1]
Plugs							
Leakage (internal)		13/1.6E+6h [3]					8.4E-6/h(10)
Rupture (internal)		[3]	1/3.1E+6h [1]				4.8E-7/h(10)
Leakage (external)		13/1.6E+6h [3]					8.4E-6/h(10)
Rupture (external)		0/1.6E+6h [4]					3.1E-7/h(10) [2]
Motor-Operated Fails to open/close					10/2.0E+4d [2]		5.3E-4/d(10)
Spurious operation							
Plugs							
Leakage (internal)							

Table 4c. Category 2 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Rupture (internal)							
Leakage (external)					0/3.3E+6h [2]		1.5E-7/h(10)
Rupture (external)							
Air-Operated Fails to open/close		0.6/1.8E+7h [5]	13/6.0E+6h, 13/4.2E+6h, 9/6.7E+5h, 2/5.1E+5h, 12/2.7E+3d, 15/6.2E+3d [2]				3.0E-3/d(1.2), 1.3E-6/h(6.5)
Spurious operation		0.3/1.8E+7h [5]	27/2.3E+6h, 15/2.2E+6h [2]				1.9E-6/h(8.1)
Plugs			1/2.3E+6h [2]				6.5E-7/h(10)
Leakage (internal)			9/6.0E+6h, 8/4.2E+6h, 14/2.3E+6h [2]				2.5E-6/h(2.5)
Rupture (internal)			0/6.0E+6h, 0/4.2E+6h, 4/2.3E+6h, 2/2.2E+6h [2]				4.1E-7/h(4.8)
Leakage (external)		9.2/1.8E+7h [5]	10/4.2E+6h, 19/2.3E+6h [2]				1.6E-6/h(5.5)
Rupture (external)		0/1.8E+7h [5]	0/4.2E+6h, 0/2.3E+6h [2]				2.0E-8/h(10) [2]
Solenoid-Operated Fails to open/close		0.8/1.9E+6h [6]					6.8E-7/h(10)

Table 4c. Category 2 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Spurious operation		0.3/1.9E+6h [6]					4.2E-7/h(10)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)		12.5/1.9E+6h [6]					6.8E-6/h(10)
Rupture (external)		0/1.9E+6h [6]					2.6E-7/h(10) [2]
Safety/Relief Fails to open							
Fails to reclose							
Leakage (internal)		3.5/4.3E+6h [7]					9.3E-7/h(10)
Rupture (internal)		[7]					
Leakage (external)		3.5/4.3E+6h [7]					9.3E-7/h(10)
Rupture (external)		0/4.3E+6h [8]					1.2E-7/h(10) [2]
Vacuum-Breaker Fails to open							
Fails to reclose							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							

Table 4c. Category 2 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Valve (Control)							
Motor-Operated							
Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Air-Operated							
Fails open			1/2.3E + 6h, 5/1.2E + 6h [3]		0/4.3E + 5h, 29/6.9E + 5h [3]		3.0E-6/h(6.1) [3]
Fails closed					[3]		3.0E-6/h(6.1) [3]
Fails to respond			3/2.3E + 6h, 3/1.2E + 6h [3]		[3]		3.0E-6/h(6.1) [3]
Plugs							
Leakage (external)			3/2.3E + 6h, 14/1.2E + 6h [3]				4.9E-6/h(3.7)
Rupture (external)			0/2.3E + 6h, 0/1.2E + 6h [3]				1.4E-7/h(10) [2]
Solenoid-Operated							
Fails open					2/1.6E + 6d [4]		1.6E-6/d(10) [4]
Fails closed					[4]		[4]
Fails to respond					[4]		[4]
Plugs							

Table 4c. Category 2 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Leakage (external)							
Rupture (external)							
Compressor Motor-Driven Fails to start		5.2/3.2E+6h [9]			2/6.4E+4d [5]	116/2.3E+6 h [1]	3.9E-5/d(10), 8.2E-6/h(3.6)
Fails to run		8.6/3.2E+6h [9]	80/3.1E+4h, 129/2.0E+4 h [4]		1/4.5E+4h [5]	[1]	1.3E-5/h(3.6), 4.1E-3/h(2.0) [5]
Overspeed		1.7/3.2E+6h [9]				[1]	2.6E-6/h(5) [5]
Fails to stop						[1]	
Leakage (external)		0/3.2E+6h [9]					7.2E-7/h(10) [5]
Rupture (external)		[9]					
Piping/Hose/Jumper/Tube Piping Leakage (external)							
Rupture (external)							
Plugs							
Hose Leakage (external)							
Rupture (external)							
Plugs							
Jumper Leakage (external)							
Rupture (external)							
Plugs							

Table 4c. Category 2 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Tube Leakage (external)							
Rupture (external)							
Plugs							
Vessel Tank (Pressurized) Leakage (external)		0.3/2.8E + 6h [10]			0/4.8E + 4h, 0/9.5E + 4h, 0/4.8E + 4h [6]		2.3E-7/h(10) [6]
Rupture (external)		0.1/2.8E + 6h [10]			[6]		7.5E-8/h(10) [6]
Cylinder (Pressurized) Leakage (external)							
Rupture (external)							
Flange/Gasket Leakage (external)							
Rupture (external)							
Heat Exchanger Shell/Tube Fouling (tubes)							
Plugs (tubes)							
Leakage (tubes)			25/4.6E + 5h, 1/1.3E + 5h [5]				4.4E-5/h(1.8)
Rupture (tubes)			0/4.6E + 5h, 0/1.3E + 5h [5]				8.5E-7/h(10) [2]
Leakage (shell)							
Rupture (shell)							

Table 4c. Category 2 data for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Heater (Electrical)							
Fails to heat					0/4.8E+4h [7]		1.0E-5/h(10) [2]
Overheats							
Leakage (external)							
Rupture (external)							
Vaporizer							
Failure						28/1.9E+5h [2]	1.4E-4/h(10)
Air Dryer							
Failure			1/1.2E+5h [6]		0/4.8E+4h [8]		8.9E-6/h(10)
Filter							
Plugs				61/4.2E+6h [1]	0/1.9E+5h [9]		1.4E-5/h(1.3) [4]
Leakage (internal)				[1]	[9]		[4]
Rupture (internal)				[1]	[9]		[4]
Orifice							
Plugs					0/2.4E+5h [10]		2.1E-6/h(10) [2]

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR2 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990. Also, S. A. Eide et al., Component External Leakage and Rupture Frequency Estimates, Idaho National Engineering Laboratory, EGG-SSRE-9639, November 1991.

All failure data except for the leakage failure mode were obtained from Tables 6 and 7 in the first reference. These tables list the aggregations of Category 2 source data from NUCLARR as it existed in August 1989. The leakage data were obtained from the second reference. These data were not in NUCLARR at the time the reference was published, but since then the data have been entered into NUCLARR.

Table 4c. Category 2 data for compressed gas system.

NPRD-3 - M. J. Rossi, Nonelectronic Parts Reliability Data, Reliability Analysis Center, Rome Air Development Center, NPRD-3, 1985.

All failure data apply to a ground fixed (GF) environment, unless otherwise indicated. Commercial (C), military (M), and unknown source (?) data were used if available. Failure mode information was used to determine what % of failures were fail to open/close, spurious operation, etc. Unknown failure mode events were not considered. The NPRD-3 failures include degraded and incipient failures as well as catastrophic failures. Only catastrophic failures were used for this study. For valves, circuit breakers, relays, and switches, the following mapping of NPRD-3 failure modes into the failure modes of interest was used:

Fail to open/close/operate - binding, breach (not for valves), contaminated, cracked/fractured, no movement, no operation, seized, stuck open, and stuck closed

Spurious operation - arcing, burned, collapsed, displaced, false response, improper flow, intermittent, opened, overheated, and shorted

Plugs - none identified

Leakage (internal) - none identified except for leaking (one-half of events applied to internal leakage for check and relief valves)

Leakage (external) - leaking

Rupture (external) - breach (valves only).

For pumps, fans, and diesel generators, the following mapping was used:

Fail to start - contaminated, cracked/fractured, no movement, no operation

Fail to run - binding, broken, displaced, false response, improper flow, intermittent, overheated, seized, shorted, stuck closed, stuck open

Overspeed (subset of fail to run) - improper flow (one-half of events used), stuck open

Fail to stop - none identified

Leakage (external) - leaking

Rupture (external) - breach (not for generator)

Table 4a. Category 2 data for compressed gas system.

For vessels, piping, hoses, and jumpers, the following mapping was used:

Leakage (external) - cracked/fractured, leaking

Rupture (external) - broken, breach.

For filters, the following mapping was used:

Plug - improper flow (one-half of events used)

Leakage (internal) - improper flow (one-half of events used)

Rupture (internal) - broken, cracked/fractured, ruptured.

For heaters, the following mapping was used:

Fail to heat - cracked/fractured, no operation, opened

Overheat - shorted.

1. Manual valve data used (p. 159). Failure mode information (p. 302 for bellows valve) indicates 18.5% of failures are fails to open/close, 68% are external leakage, and 1.4% are external rupture. The actual data indicated no failures.

2. Check valve data used (p. 158). Failure mode information (p. 303) indicates 9.2% of failures are fails to open and 20% are fails to close.

3. Check valve data used (p. 158). Failure mode information (p. 303) indicates 57.8% of failures are leaking. One-half of these were assigned to internal leakage/rupture and the other half to external leakage. Internal leakage size not indicated.

4. Check valve data used (p. 158). Failure mode information (p. 303) indicates 0% of failures are external rupture.

5. Pneumatic valve data used (p. 160). Failure mode information (p. 306) indicates 4.4% of failures are fails to open/close, 1.8% are spurious operation, 66% are external leakage, and 0% are external rupture.

6. Solenoid valve data used (p. 161). See Note 5 for failure mode information.

Table 4c. Category 2 data for compressed gas system.

7. Relief valve data used (p. 161). Failure mode information (p. 299 for hydraulic relief valve) indicates 100% of failures are leakage. One-half of these were assigned to internal leakage/rupture and the other half to external leakage.

8. Relief valve data used (p. 161). Failure mode information (p. 299 for hydraulic relief valve) indicates 0% of failures are external rupture.

9. Compressor data used (p. 45). Data are for ground mobile (GM) environment. Failure mode information (p. 324 for centrifugal fan/blower) indicates 27.3% of failures are fails to start, 45.5% are fails to run, 9.1% are overspeed, and 0% are external leakage or rupture.

10. Accumulator data used (p. 26). Failure mode information (p. 288 for pneumatic and hydraulic accumulator) indicates 32.2% of failures are external leakage and 10.5% are external rupture.

OREDA - Offshore Reliability Data Handbook, Offshore Reliability Data (OREDA), Norway, 1984.

All failure information was taken from the critical failure mode category, unless otherwise indicated.

1. Check valve (hydrocarbon gas) data used (p. 163). Plugged data used for fails to open. Significant internal leakage data used for internal rupture.

2. Hydraulically operated (hydrocarbon gas) data used (pp. 113, 115, 119, 121, 155, and 157). Internal leakage (degraded failure mode) data used for internal leakage. External leakage (degraded failure mode) data used for external leakage. Improper operation (degraded failure mode) data used for spurious operation.

3. Hydraulically operated and pneumatically operated (hydrocarbon gas) control valve data used (pp. 165 and 169). Internal leakage (degraded failure mode) data used for fails open. Failed to operate data used for fails to respond. External leakage (degraded failure mode) data used for external leakage.

4. Centrifugal and reciprocating (>1500 psig) compressor data used (pp. 229 and 231). No gas flow data used for fails to run.

5. Gas/water (p. 197), gas/freon (p. 201), and air/water (p. 209) tube/shell heat exchanger data used. Leakage (degraded failure mode) data used for tube failure.

6. Electric heater (non hydrocarbon service) data used (p. 219).

Table 4c. Category 2 data for compressed gas system.

WIN-330 - J. N. Wilkinson et al., Idaho Chemical Processing Plant Failure Rate Database, Idaho National Engineering Laboratory, WIN-330, October 1991.

All failure information was taken from Appendix C, p. 32.

1. Filter (offgas) data used. Failure modes not indicated.

TRITIUM - L. C. Cadwallader and M. A. Stolpe Gavett, Tritium Waste Treatment System Component Failure Data Analysis from June 18, 1984 to December 31, 1989, Idaho National Engineering Laboratory, EGG-FSP-8973, Rev. 1, November 1990; L. C. Cadwallader, M. A. Stolpe Gavett, and L. Quintana, Tritium Room Air Monitor Component Failure Data Analysis from January 1, 1984 to December 31, 1990, Idaho National Engineering Laboratory, EGG-FSP-9450, May 1991; and L. C. Cadwallader and D. P. Sanchez, Secondary Containment System Component Failure Data Analysis from 1984 to 1991, Idaho National Engineering Laboratory, EGG-FSP-10323, August 1992.

1. Manual valve data used (Table A-1, first reference). Failure modes not indicated.
2. Motor-operated valve data used (Table A-1, first reference). Failure modes (except for leak) not indicated.
3. Pressure control valve data used (Table A-1, first reference and p. 23, third reference). Failure modes (other than leak) not indicated.
4. Solenoid control valve data used (p. 27, third reference). Failure modes (other than leak) not indicated.
5. Compressor data used (Table A-1, third reference).
6. Tritium waste gas tank data used (Table A-1, first reference).
7. Electrical heater data used (Table A-1, first reference). Failure modes (except for leak) not indicated.
8. Moisture collector data used (Table A-1, first reference). Failure modes not indicated.
9. Filter data used (Table A-1, first reference). Failure modes not indicated.
10. Orifice data used (Table A-1, first reference).

Table 4c. Category 2 data for compressed gas system.

LNG1 - D. W. Johnson and J. R. Welker, Development of an Improved LNG Plant Failure Rate Data Base, Gas Research Institute, PB82-153503, September 1981.

1. Compressor system data used (p. 9). Failure modes not indicated.

2. Vaporizer data used (p. 9).

Aggregated Results

1. The NPRD-3 data indicate a ratio of 8.9 to 4.1 for fails to close versus fails to open. Therefore, the aggregated result for fails to open was multiplied by 8.9/4.1 to obtain the fails to close estimate.

2. Failure rate based on zero failures and may be conservatively high.

3. Fails open, fails closed, and fails to respond data combined. Assumed that fails closed is as likely as fails open. Therefore, each failure mode assigned one-third of the total failure rate.

4. Failure modes not indicated.

5. All failure modes combined. OREDA data treated separately. NPRD-3 data used to partition among failure modes.

6. Both failure modes combined. NPRD-3 data used to partition between failure modes.

Table 4d. Category 2 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
HVAC/Exhaust							
Damper (Standby or Safety)							
Manual							
Fails to open/close							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Motor-Operated							
Fails to open/close							
Spurious operation							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Air-Operated							
Fails to open/close							
Spurious operation							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							

Table 4d. Category 2 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Damper (Control)							
Motor-Operated							
Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Air-Operated							
Fails open			48/6.1E+6h [1]				8.0E-6/h(10) [1]
Fails closed			[1]				[1]
Fails to respond			5/6.1E+6h [1]				9.0E-7/h(10)
Plugs							
Leakage (external)			2/6.1E+6h [1]				4.1E-7/h(10)
Rupture (external)			1/6.1E+6h [1]				2.5E-7/h(10)
Fan/Blower							
Motor-Driven							
Fails to start		2.2/6.7E+5h, 4.6/6.1E+6h, 11.2/2.3E+6h [1]	24/3.5E+6h [2]				3.3E-6/h(2.9)
Fails to run		3.6/6.7E+5h, 7.7/6.1E+6h, 18.6/2.3E+6h [1]	33/3.5E+6h [2]				5.0E-6/h(2.8)
Overspeed		0.7/6.7E+5h, 1.5/6.1E+6h, 3.7/2.3E+6h [1]					6.5E-7/h(1.9)

Table 4d. Category 2 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Fails to stop			12/3.5E+6h [2]				3.6E-6/h(10)
Leakage (external)		0/6.7E+5h, 0/6.1E+6h, 0/2.3E+6h [1]					5.5E-8/h(10) [1,2]
Rupture (external)		[1]					[1,2]
Diesel-Driven Fails to start							
Fails to run							
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Ducting Leakage (external)							
Rupture (external)							
Plugs							
Heat Exchanger Air Conditioning Unit/ Chiller Fails to start							
Fails to run							
Fan Cooler Unit Fails to start							
Fails to run			0/1.4E+5h [3]				3.6E-6/h(10) [2]

Table 4d. Category 2 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Heater (Electrical) Fails to heat		1.2/4.2E+4h, 8.0/1.1E+7h [2]					8.4E-7/h(2.6)
Overheats		0.2/4.2E+4h, 1.0/1.1E+7h [2]					1.6E-7/h(10)
Heater (Gas) Fails to heat			72/8.8E+4h [4]				8.2E-4/h(10)
Overheats			1/8.8E+4h [4]				1.7E-5/h(10)
Filter Normal Plugs		0/5.8E+6h [3]	5/5.0E+5h [5]	34/6.1E+6h [1]			1.4E-6/h(5) [3]
Leakage (internal)		5.2/5.8E+6h [3]	1/5.0E+5h [5]	[1]			1.8E-6/h(5) [3]
Rupture (internal)		1.5/5.8E+6h [3]	1/5.0E+5h [5]	[1]			7.0E-7/h(5) [3]
Low-Efficiency Plugs							
Leakage (internal)							
Rupture (internal)							
HEPA Plugs							
Leakage (internal)							
Rupture (internal)							
Sand Plugs							
Leakage (internal)							
Rupture (internal)							

Table 4d. Category 2 data for HVAC/exhaust system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Baghouse Plugs							
Leakage (internal)							
Rupture (internal)							
Miscellaneous Mist Eliminator Failure							
Scrubber Failure			1/4.7E+6h [6]				3.2E-7/h(10)
Precipitator Failure							

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR2 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990. Also, S. A. Eide et al., Component External Leakage and Rupture Frequency Estimates, Idaho National Engineering Laboratory, EGG-SSRE-9639, November 1991.

All failure data except for the leakage failure mode were obtained from Tables 6 and 7 in the first reference. These tables list the aggregations of Category 2 source data from NUCLARR as it existed in August 1989. The leakage data were obtained from the second reference. These data were not in NUCLARR at the time the reference was published, but since then the data have been entered into NUCLARR.

NPRD-3 - M. J. Rossi, Nonelectronic Parts Reliability Data, Reliability Analysis Center, Rome Air Development Center, NPRD-3, 1985.

All failure data apply to a ground fixed (GF) environment, unless otherwise indicated. Commercial (C), military (M), and unknown source (?) data were used if available. Failure mode information was used to determine what % of failures were fail to open/close, spurious operation, etc. Unknown failure mode events were not considered. The NPRD-3 failures include degraded and incipient failures as well as catastrophic failures. Only catastrophic failures were used for this study. For valves, circuit breakers, relays, and switches, the following mapping of NPRD-3 failure modes into the failure modes of interest was used:

Table 4d. Category 2 data for HVAC/exhaust system.

Fail to open/close/operate - binding, breach (not for valves), contaminated, cracked/fractured, no movement, no operation, seized, stuck open, and stuck closed

Spurious operation - arcing, burned, collapsed, displaced, false response, improper flow, intermittent, opened, overheated, and shorted

Plugs - none identified

Leakage (internal) - none identified except for leaking (one-half of events applied to internal leakage for check and relief valves)

Leakage (external) - leaking

Rupture (external) - breach (valves only).

For pumps, fans, and diesel generators, the following mapping was used:

Fail to start - contaminated, cracked/fractured, no movement, no operation

Fail to run - binding, broken, displaced, false response, improper flow, intermittent, overheated, seized, shorted, stuck closed, stuck open

Overspeed (subset of fail to run) - improper flow (one-half of events used), stuck open

Fail to stop - none identified

Leakage (external) - leaking

Rupture (external) - breach (not for generator)

For vessels, piping, hoses, and jumpers, the following mapping was used:

Leakage (external) - cracked/fractured, leaking

Rupture (external) - broken, breach.

For filters, the following mapping was used:

Plug - improper flow (one-half of events used)

Leakage (internal) - improper flow (one-half of events used)

Rupture (internal) - broken, cracked/fractured, ruptured.

Table 4d. Category 2 data for HVAC/exhaust system.

For heaters, the following mapping was used:

Fail to heat - cracked/fractured, no operation, opened

Overheat - shorted.

1. General fan data used (p. 65). Failure mode information (p. 324 for centrifugal fan) indicates 27.3% of failures are fails to start, 45.5% are fails to run, 9.1% are overspeed, and 0% are external leakage or rupture.

2. Duct heater (p. 79) and electric space heater (p. 81) data used, respectively. Failure mode information (p. 287 for resistive electrical heater) indicates 61.5% of failures are fails to heat and 7.7% are overheats.

3. Air filter data used (p. 67). Failure mode information (p. 285 for general filter) indicates 0% of failures are plugs, 75% are internal leakage, and 21.9% are internal rupture.

OREDA - Offshore Reliability Data Handbook, Offshore Reliability Data (OREDA), Norway, 1984.

All failure information was taken from the critical failure mode category, unless otherwise indicated.

1. Damper data used (p. 279). Failed to reach function data used for fails closed and fails open. Function ceased while running data used for fails to respond. Leakage (degraded failure mode) data used for external leakage. Ruptured data used for external rupture.

2. Fan data used (p. 277). Failed to operate upon command and failed to function when signaled data used for fails to start. Failed while running data used for fails to run. Functioned without signal data considered similar to fails to stop.

3. Cooler (non hydrocarbon service) data used (p. 221).

4. Gas/diesel fired boiler data used (p. 283).

5. Filter data used (p. 281). Clogged data used for plugs. Internal leakage (degraded failure mode) data used for internal leakage. Ruptured data used for internal rupture.

6. Scrubber (removal of oil/condensate from hydrocarbon gas) data used (p. 147). Plugged or clogged data used for failure.

Table 4d. Category 2 data for HVAC/exhaust system.

WIN-330 - J. N. Wilkinson et al., Idaho Chemical Processing Plant Failure Rate Database, Idaho National Engineering Laboratory, WIN-330, October 1991.

All failure information was taken from Appendix C, p. 32.

1. Filter (other) data used. Failure modes not indicated.

TRITIUM - L. C. Cadwallader and M. A. Stolpe Gavett, Tritium Waste Treatment System Component Failure Data Analysis from June 18, 1984 to December 31, 1989, Idaho National Engineering Laboratory, EGG-FSP-8973, Rev. 1, November 1990; L. C. Cadwallader, M. A. Stolpe Gavett, and L. Quintana, Tritium Room Air Monitor Component Failure Data Analysis from January 1, 1984 to December 31, 1990, Idaho National Engineering Laboratory, EGG-FSP-9450, May 1991; and L. C. Cadwallader and D. P. Sanchez, Secondary Containment System Component Failure Data Analysis from 1984 to 1991, Idaho National Engineering Laboratory, EGG-FSP-10323, August 1992.

LNG1 - D. W. Johnson and J. R. Welker, Development of an Improved LNG Plant Failure Rate Data Base, Gas Research Institute, PB82-153503, September 1981.

Aggregated Results

1. Failure modes not indicated.

2. Failure rate based on zero failures and may be conservatively high.

3. Combined failure rate determined. NPRD-3 and OREDA data used to partition among failure modes.

Table 4e. *Category 2 data for electrical distribution system.*

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Electrical Distribution Generator Diesel-Driven Fails to start	83/2.2E+4d [1]	149/5.9E+5h [1]	18/5.0E+5h, 6/7.6E+2d [1]				3.9E-3/d(3.0), 4.1E-5/h(3.0) [1]
Fails to run	140/1.4E+4d [2]	[1]	82/2.2E+5h, 1/1.3E+4h [1]				9.7E-3/d(3.1), 1.9E-4/h(1.2) [1]
Motor-Driven (ac to dc) Fails to start		4/3.2E+5h [2]					1.4E-5/h(10)
Fails to run		2/3.2E+5h [2]					7.8E-6/h(10)
Gas-Turbine-Driven Fails to start		5.0/4.0E+6h, 35.5/5.4E+5h [3]	6/1.8E+5h, 51/3.4E+3d, 6/7.6E+1d, 11/2.6E+3d [2]				1.1E-2/d(3.0), 9.9E-6/h(8.4)
Fails to run		7.6/4.0E+6h, 53.4/5.4E+5h [3]	43/2.7E+5h, 7/1.3E+4h, 5/4.4E+4h [2]				2.4E-5/h(8.7)
Hydro-Turbine-Driven Fails to start							
Fails to run							
Battery Failure	6/1.5E+6h [3]	6.5/1.1E+7h [4]	4/5.9E+6h [3]				6.9E-7/h(10)
Charger Rectifier Failure	12/2.2E+6h [4]		1/2.7E+6h, 35/5.6E+6h [4]				4.6E-6/h(2.5)
Bus Metal-Enclosed Failure							

Table 4e. Category 2 data for electrical distribution system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Bare Failure							
Cable/Joint/ Termination/Jumper Cable (Copper, 1000ft) Failure							
Joint (Copper) Failure							
Termination (Copper)							
Failure							
Jumper (Power) Failure							
Circuit Breaker General Fails to open/close	25/6.3E+4d [5]	3.3/7.5E+5h, 40.1/8.9E+7h [5]	5/2.7E+7h, 9/1.8E+6h [5]				4.0E-4/d(1.4), 4.8E-7/h(4.8)
Spurious operation		0.8/7.5E+5h, 9.4/8.9E+7h [5]	2/1.2E+6h, 6/2.7E+7h, 4/1.8E+6h [5]				1.9E-7/h(4.8)
Reactor Trip Fails to open							
Spurious operation							
Relay Protective Fails to open/close		8.9/1.9E+8h, 7.9/1.8E+8h [6]					4.2E-8/h(10)
Spurious operation		33.6/1.9E+8h, 29.8/1.8E+8h [6]					1.7E-7/h(10)
Control Fails to open/close							

Table 4e. Category 2 data for electrical distribution system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Spurious							
Bistable Fails to open/close							
Spurious operation							
Switch Push-Button (Manual) Fails to open/close		1588/7.8E+8h , 0.6/5.6E+7h [7]					1.9E-6/h(10)
Spurious operation		1486/7.8E+8h , 5.6/5.6E+7h [7]					1.8E-6/h(10)
Rotary (Manual) Fails to open/close		0.08/1.1E+5h, 3.9/7.5E+7h [8]					6.0E-8/h(10)
Spurious operation		0.7/1.1E+5h, 36.6/7.5E+7h [8]					5.0E-7/h(10)
Key-Operated (Manual) Fails to open/close		0.5/2.6E+6h [9]					3.9E-7/h(10)
Spurious operation		4.2/2.6E+6h [9]					1.8E-6/h(10)
Automatic-Transfer Fails to open/close							
Spurious operation							
Limit Fails to open/close							
Spurious operation							
Fuse Fail to open		61.5/5.4E+8h [10]					1.2E-7/h(10)

Table 4e. Category 2 data for electrical distribution system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Premature opening		8.2/5.4E+8h [10]					1.6E-8/h(10)
Inverter Failure	90/3.9E+4h [6]		6/1.2E+6h [6]				1.8E-5/h(6.9)
Motor AC Fails to start		213/8.3E+6h, 4.5/6.5E+6h [11]					1.5E-5/h(3.4)
Fails to run		87.1/8.3E+6h, 1.8/6.5E+6h [11]					6.0E-6/h(3.3)
DC Fails to start		40.5/1.1E+6h, 5/1.1E+6h [12]					2.1E-5/h(3.0)
Fails to run		16.6/1.1E+6h, 2.1/1.1E+6h [12]					8.5E-6/h(2.8)
Synchro Failure		4.9/3.8E+5h [13]					1.4E-5/h(10)
Transformer Power Failure		3.0/7.8E+6h, 0/7.6E+5h [14]	0/6.9E+5h, 0/8.4E+5h [7]				3.5E-7/h(10)
Instrumentation/Control Failure							

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Table 4e. Category 2 data for electrical distribution system.

Notes

NUCLARR2 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990.

All failure data except for the leakage failure mode were obtained from Tables 6 and 7 in the first reference. These tables list the aggregations of Category 2 source data from NUCLARR as it existed in August 1989.

1. Diesel generator fail to start data used.

2. Diesel generator fail to run data used.

3. Battery data used.

4. Battery charger data used.

5. Power circuit breaker fail to operate and fail to start data used.

6. Power electronics (inverter) data used.

NPRD-3 - M. J. Rossi, Nonelectronic Parts Reliability Data, Reliability Analysis Center, Rome Air Development Center, NPRD-3, 1985.

All failure data apply to a ground fixed (GF) environment, unless otherwise indicated. Commercial (C), military (M), and unknown source (?) data were used if available. Failure mode information was used to determine what % of failures were fail to open/close, spurious operation, etc. Unknown failure mode events were not considered. For valves, circuit breakers, relays, and switches, the following mapping of NPRD-3 failure modes into the failure modes of interest was used:

Fail to open/close/operate - binding, breach (not for valves), contaminated, cracked/fractured, no movement, no operation, seized, stuck open, and stuck closed

Spurious operation - arcing, collapsed, false response, improper flow, intermittent, opened, overheated, and shorted

Plugs - none identified

Leakage (internal) - none identified except for leaking (check valve only)

Leakage (external) - breach (valves only), leaking

Degraded/incipient (not catastrophic) - degraded, drift, fatigue, improper timing, noisy, other, out of adjustment, out of specification, unstable.

Table 4e. Category 2 data for electrical distribution system.

For pumps, fans, and diesel generators, the following mapping was used:

Fail to start - contaminated, cracked/fractured, no movement, no operation

Fail to run - binding, broken, displaced, false response, improper flow, intermittent, overheated, seized, shorted, stuck closed, stuck open

Overspeed (subset of fail to run) - improper flow (one-half of events used), stuck open

Fail to stop - none identified

Leakage (external) - breach (not for diesel generator), leaking

Degraded/incipient (not catastrophic) - corroded, drift, noisy, out of adjustment, out of specification, worn out.

1. Diesel generator data used (p. 76). Failure mode information (p. 328) indicates that 100% of failures are fails to start.
2. Dc generator data used (p. 75). Failure mode information (p. 326) indicates that 44.4% of failures are fails to start and 22.2% are fails to run.
3. Turbine generator data used (p. 77). Failure mode information (p. 330) indicates that 10.5% of failures are fails to start and 15.8% are fails to run.
4. Rechargeable battery data used (p. 33). Failure mode information (p. 279) indicates that 36.4% of failures are catastrophic.
5. General circuit breaker data used (p. 43). Failure mode information (p. 283) indicates that 65.7% of failures are fails to open/close and 15.4% are spurious operation.
6. General relay data used (p. 117). Failure mode information (p. 311) indicates that 16.8% of failures are fails to open/close and 63.5% are spurious operation.
7. Push button switch data used (p. 136). General failure mode information used (p. 336). Failure mode information indicates that 7.5% of failures are fails to open/close and 70.4% are spurious operation.
8. Rotary switch data used (p. 137). See Note 7 for failure mode information.
9. Key switch data used (p. 135). See Note 7 for failure mode information.
10. Fuse data used (p. 69). Failure mode information (p. 285) indicates that 75% of failures are fails to open and 10% are premature opening.
11. Ac motor data used (p. 57). Failure mode information for dc motors used (p. 326). Failure mode information indicates that 50% of failures are fails to start and 20.5% are fails to run.
12. Dc motor data used (p. 58). See Note 11 for failure mode information.

Table 4e. Category 2 data for electrical distribution system.

13. General synchro data used (p. 141). Failure mode information (p. 331) indicates that 81.7% of failures are catastrophic.

14. General transformer data used (p. 148). Failure mode information (p. 319) indicates that 60% of failures are catastrophic.

OREDA - Offshore Reliability Data Handbook, Offshore Reliability Data (OREDA), Norway, 1984.

All failure information was taken from the critical failure mode category, unless otherwise indicated.

1. Diesel engine driven generator set data used (pp. 247 and 249). Failed while running and improper operation data used for fails to run. Operation time used for fails to run.

2. Gas fuel turbine generator data used (pp. 239, 241, 243, and 245). Failed while running and improper operation data used for fails to run. Operational time used for fails to run.

3. Battery data used (p. 263). Inadequate output and no output during emergency mode of operation data used for failure.

4. Rectifier (p. 259) and battery charger (p. 261) data used.

5. Circuit breaker data used (pp. 265, 267, and 269).

6. Inverter data used (p. 257). No output and failed to transfer data used for failure.

7. Transformer data used (pp. 253 and 255).

WIN-330 - J. N. Wilkinson et al., Idaho Chemical Processing Plant Failure Rate Database, Idaho National Engineering Laboratory, WIN-330, October 1991.

All failure information was taken from Appendix C, p. 32.

Aggregated Results

1. Combined result calculated for per hour data. OREDA data used to partition among failure modes.

Table 41. Category 2 data for instrumentation and control system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Instrumentation and Control Alarm/Annunciator Fails to alarm			11/3.2E+5h [1]				3.6E-5/h(10)
Spurious operation			1/3.2E+5h [1]				4.7E-6/h(10)
Sensor/Transmitter/ Transducer/Process Switch Temperature Failure		1.2/5.1E+6h [1]	0/1.9E+6h, 8/1.2E+6h [2]	7/1.5E+6h [1]	0/5.2E+5h [1]	2/2.6E+6h, 0/8.4E+6h [1]	8.6E-7/h(7.9)
Pressure Failure		26.2/4.6E+7h [2]	4/7.2E+6h, 8/4.3E+6h, 14/5.0E+6h, 0/3.5E+6h, 2/3.5E+6h, 3/5.5E+6h [3]	3/1.0E+6h [2]	3/5.7E+5h [2]		8.3E-7/h(3.1)
Differential Pressure Failure				2/9.2E+5h [3]			2.7E-6/h(10)
Flow Failure		38.5/1.5E+7h [3]	1/1.5E+6h, 0/1.1E+5h, 1/2.4E+5h, 0/6.6E+5h, 4/2.7E+6h, 0/4.2E+5h, 21/3.4E+6h, 0/3.4E+5h [4]	3/7.6E+5h [4]			2.9E-6/h(2.0)
Level Failure		2.3/7.6E+5h [4]	9/2.6E+7h, 4/1.2E+7h, 1/4.6E+6h [5]	9/4.1E+6h [5]	0/9.5E+4h [3]		5.3E-7/h(3.7)
Humidity Failure		2.3/2.4E+5h [5]					1.2E-5/h(10)

Table 4f. Category 2 data for instrumentation and control system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
pH Failure							
Oxygen Concentration Failure					3/3.7E+5h [4]		9.5E-6/h(10)
CO_2 Concentration Failure							
Hydrogen Concentration Failure							
Nitrogen Concentration Failure							
Hydrocarbon Concentration Failure			318/2.9E+7 h [6]			44/1.7E+7h [2]	7.9E-6/h(2.2)
Helium Concentration Failure							
Speed Failure							
Seismic Failure							
Radiation Failure				11/2.1E+6h, 18/1.4E+6h [6]	17/1.9E+5h, 2/4.6E+5h [5]		1.2E-5/h(5.7)
Indicator Failure		2.6/2.1E+5h [6]					1.5E-5/h(10)
Amplifier Failure							
Modifier/Signal Conditioner Failure							
Logic Module Failure							

Table 4f. Category 2 data for instrumentation and control system.

System/Component/Failure Mode	Failure Data (Category 2 Sources)[a]						
	NUCLARR2	NPRD-3	OREDA	WIN-330	TRITIUM	LNG1	Aggregated Results[b]
Recorder Failure							
Sampler Failure				27/2.5E+6h, 15/1.2E+6h [7]			1.2E-5/h(10)
Analyzer Failure				1/2.5E+5h [8]			6.0E-6/h(10)
Timer Failure							
Gas Chromatograph Failure					3/4.8E+4h [6]		7.3E-5/h(10)
Voltage Regulator Failure		10/3.3E+6h [7]					3.2E-6/h(10)
Transmitter Failure							
Transducer Failure		0.7/1.3E+6h [8]					9.2E-7/h(10)
Programmable Logic Controller Failure			8.2/2.7E+5h [7]				3.2E-5/h(10)

a. Failure data are listed as: X/Y, where X is the number of failures, and Y is the exposure period (h) or number of demands. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

Notes

NUCLARR2 - S. A. Eide et al., Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, Idaho National Engineering Laboratory, EGG-SSRE-8875, February 1990.

All failure data except for the leakage failure mode were obtained from Tables 6 and 7 in the first reference. These tables list the aggregations of Category 2 source data from NUCLARR as it existed in August 1989.

Table 4f. Category 2 data for instrumentation and control system.

NPRD-3 - M. J. Rossi, Nonelectronic Parts Reliability Data, Reliability Analysis Center, Rome Air Development Center, NPRD-3, 1985.

All failure data apply to a ground fixed (GF) environment, unless otherwise indicated. Commercial (C), military (M), and unknown source (?) data were used if available. Failure mode information was used to determine what % of failures were fail to open/close, spurious operation, etc. Unknown failure mode events were not considered. For valves, circuit breakers, relays, and switches, the following mapping of NPRD-3 failure modes into the failure modes of interest was used:

Fail to open/close/operate - binding, breach (not for valves), contaminated, cracked/fractured, no movement, no operation, seized, stuck open, and stuck closed

Spurious operation - arcing, collapsed, false response, improper flow, intermittent, opened, overheated, and shorted

Plugs - none identified

Leakage (internal) - none identified except for leaking (check valve only)

Leakage (external) - breach (valves only), leaking

Degraded/incipient (not catastrophic) - degraded, drift, fatigue, improper timing, noisy, other, out of adjustment, out of specification, unstable.

For pumps, fans, and diesel generators, the following mapping was used:

Fail to start - contaminated, cracked/fractured, no movement, no operation

Fail to run - binding, broken, displaced, false response, improper flow, intermittent, overheated, seized, shorted, stuck closed, stuck open

Overspeed (subset of fail to run) - improper flow (one-half of events used), stuck open

Fail to stop - none identified

Leakage (external) - breach (not for diesel generator), leaking

Degraded/incipient (not catastrophic) - corroded, drift, noisy, out of adjustment, out of specification, worn out.

1. Temperature switch data used (p. 139). General switch failure mode information used (p. 336). Failure mode information indicates 58.3% of failures are catastrophic.
2. Pressure switch data used (p. 136). See Note 1 for failure mode information.
3. Flow switch data used (p. 133). See Note 1 for failure mode information.
4. Level switch data used (p. 135). See Note 1 for failure mode information.

Table 4f. Category 2 data for instrumentation and control system.

5. Humidity switch data used (p. 134). See Note 1 for failure mode information.

6. Elapsed time indicator data used (p. 86). CRT display failure mode information used (p. 307). Failure mode information indicates 28.6% of failures are catastrophic.

7. Voltage regulator data used (p. 114). No failure mode information available.

8. General transducer data used (p. 146). Failure mode information (p. 338) indicates 13.2% of failures are catastrophic.

OREDA - Offshore Reliability Data Handbook, Offshore Reliability Data (OREDA), Norway, 1984.

All failure information was taken from the critical failure mode category, unless otherwise indicated.

1. Alarm system data used (p. 133).

2. Sensor/pneumatic switch (p. 61) sensor/electric switch (p. 63), and sensor/transducer (p. 65) data used.

3. Sensor/pneumatic switch (pp. 49 and 51), sensor/electric switch (p. 53), and sensor/transducer (pp. 55, 57, and 59) data used.

4. Sensor/pneumatic switch (pp. 67 and 69), sensor/electric switch (pp. 71 and 73), and sensor/transducer (pp. 75, 77, 79, and 81) data used.

5. Sensor/pneumatic switch (p. 83), sensor/electric switch (p. 85), and sensor/transducer (p. 87) data used.

6. Hydrocarbon gas detector data used.

7. Programmable logic controller data used (pp. 290 and 291). Failure data given by components in the controller. Assumes 1 CPU/memory with 5% of failures being critical, and 5 input and output cards with 15% of failures being critical.

WIN-330 - J. N. Wilkinson et al., Idaho Chemical Processing Plant Failure Rate Database, Idaho National Engineering Laboratory, WIN-330, October 1991.

All failure information was taken from Appendix C, p. 32.

1. Temperature (loop) data used. Fail failure mode data used.

2. Pressure (loop) data used. Fail failure mode data used.

3. Differential pressure (loop) data used. Fail failure mode data used.

Table 4f. Category 2 data for instrumentation and control system.

4. Flow (gas loop) data used. Fail failure mode data used.

5. Level (loop) data used. Fail failure mode data used.

6. Radiation (general, loop) and radiation (criticality, loop) data used. Fail failure mode data used.

7. Sampler system (non-acid and acid fluid) data used.

8. Analysis (loop) data used. Fail failure mode data used.

TRITIUM - L. C. Cadwallader and M. A. Stolpe Gavett, Tritium Waste Treatment System Component Failure Data Analysis from June 18, 1984 to December 31, 1989, Idaho National Engineering Laboratory, EGG-FSP-8973, Rev. 1, November 1990; L. C. Cadwallader, M. A. Stolpe Gavett, and L. Quintana, Tritium Room Air Monitor Component Failure Data Analysis from January 1, 1984 to December 31, 1990, Idaho National Engineering Laboratory, EGG-FSP-9450, May 1991; and L. C. Cadwallader and D. P. Sanchez, Secondary Containment System Component Failure Data Analysis from 1984 to 1991, Idaho National Engineering Laboratory, EGG-FSP-10323, August 1992.

1. Temperature monitor data used (Table A-1, first reference).

2. Pressure monitor data used (Table A-1, first reference).

3. Level monitor data used (Table A-1, first reference).

4. Oxygen monitor data used (Table A-1, first reference).

5. Radiation monitor data used (Table A-1, first reference and p. A-3, second reference).

6. Gas chromatograph data used (Table A-1, first reference).

LNG1 - D. W. Johnson and J. R. Welker, Development of an Improved LNG Plant Failure Rate Data Base, Gas Research Institute, PB82-153503, September 1981.

1. First set of data is for low temperature detector (p. 9). Second set of data is for high temperature detector (p. 9).

2. Gas detector data used (p. 9).

Table 5a. Category 3 estimates for water system.

System/Component/Failure Mode	Failure Data (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Water							
Valve (Standby or Safety)			6.0E-5/d [1]				6.0E-5/d
Manual							
Fails to open/close							
Plugs	3.8E-7/h(3)						3.8E-7/h(3)
Leakage (internal)							
Rupture (internal)							
Leakage (external)			2.0E-8/h [1]				2.0E-8/h
Rupture (external)	2.7E-8/h(10)						2.7E-8/h(10)
Check	1.3E-4/d(3)		6.0E-5/d [1]				8.8E-5/d(3.0)
Fails to open							
Fails to close							
Plugs							
Leakage (internal)			5.0E-7/h [1]				5.0E-7/h(10)
Rupture (internal)	3.8E-7/h(3)		5.0E-8/h [1]				1.9E-7/h(5.4)
Leakage (external)							
Rupture (external)	2.7E-8/h(10)						2.7E-8/h(10)
Motor-Operated	1.3E-3/d(3)		6.0E-3/d [1]				3.0E-3/d(3.5)
Fails to open/close							
Spurious operation							
Plugs	3.8E-7/h(3)		3.0E-8/h [1]				1.9E-7/h(8.1)
Leakage (internal)							
Rupture (internal)							

Table 5a. Category 3 estimates for water system.

System/Component/Failure Mode	Failure Data (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Leakage (external)			1.0E-7/h [1]				1.0E-7/h(10)
Rupture (external)	2.7E-8/h(10)						2.7E-8/h(10)
Air-Operated Fails to open/close	3.8E-4/d(3)		2.0E-3/d [1]				9.8E-4/d(3.9)
Spurious operation							
Plugs	3.8E-7/h(3)						3.8E-7/h(3)
Leakage (internal)							
Rupture (internal)							
Leakage (external)			1.0E-7/h [1]				1.0E-7/h(10)
Rupture (external)	2.7E-8/h(10)						2.7E-8/h(10)
Solenoid-Operated Fails to open/close	1.3E-3/d(3)						1.3E-3/d(3)
Spurious operation							
Plugs	3.8E-7/h(3) [1]						3.8E-7/h(3)
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)	2.7E-8/h(10)						2.7E-8/h(10)
Safety/Relief Fails to open	1.3E-5/d(3)		4.0E-3/d [1,2]				1.5E-3/d(30) [1]
Fails to reclose							
Leakage (internal)	1.3E-5/h(3)						1.3E-5/h(3)

Table 5a. Category 3 estimates for water system.

System/Component/Failure Mode	Failure Data (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Rupture (internal)			3.0E-6/h [1,2]				3.0E-6/h(10)
Leakage (external)							
Rupture (external)							
Vacuum-Breaker Fails to open	3.8E-5/d(3)						3.8E-5/d(3)
Fails to reclose							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Valve (Control) Motor-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Air-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							

Table 5a. Category 3 estimates for water system.

System/Component/Failure Mode	Failure Data (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Rupture (external)							
Solenoid-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Pump Motor-Driven Fails to start	1.3E-3/d(3)	4.3E-2/d(6.3)	4.7E-3/d [1,3]		1.0E-4/h, 1.0E-5/h [1]	5.7E-5/h [1]	7.5E-3/d(8.3), 2.4E-5/h(5.8) [2]
Fails to run	8.0E-5/h(10)		7.1E-6/h [1,3]		[1]	[1]	2.1E-5/h(6.8) [2]
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Turbine-Driven Fails to start			4.0E-3/d [1,4]		1.0E-4/h [1]	5.7E-5/h [1]	4.0E-3/d(10), 3.8E-5/h(10) [2]
Fails to run					[1]	[1]	3.8E-5/h(10) [2]
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							

Table 5a. Category 3 estimates for water system.

System/Component/Failure Mode	Failure Data (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Diesel-Driven *Fails to start*		1.9E-2/d(9.5)	5.0E-3/d [1,5]				9.8E-3/d(9.8)
Fails to run							
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Piping/Hose/Jumper Piping Leakage (external)	8.5E-9/h-ft (30), 8.5E-10/h-ft (30) [2]						2.7E-9/h-ft(30)
Rupture (external)	4.2E-10/h-ft (30), 4.2E-11/h-ft (30) [2]						1.3E-10/h-ft(30)
Plugs	4.2E-10/h-ft (30), 4.2E-11/h-ft (30) [2]						1.3E-10/h-ft(30)
Hose Leakage (external)							
Rupture (external)							
Plugs							
Jumper Leakage (external)							
Rupture (external)							
Plugs							

Table 5a. Category 3 estimates for water system.

System/Component/Failure Mode	Failure Data (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Vessel Tank (Unpressurized) Leakage (external)			1.7E-5/h [1]	1.0E-8/h			1.3E-6/h(30) [1]
Rupture (external)							
Tank (Pressurized) Leakage (external)			1.7E-6/h [1]				1.3E-7/h(30) [3]
Rupture (external)							
Flange/Gasket Leakage (external)							
Rupture (external)							
Heat Exchanger Shell/Tube Fouling (tubes)			6.3E-6/h [1,6]			1.4E-5/h [1]	9.4E-6/h(10) [4]
Plugs (tubes)			[6]			[1]	[4]
Leakage (tubes)			[6]			[1]	[4]
Rupture (tubes)							
Leakage (shell)							
Rupture (shell)							
Heater (Electrical) Fails to heat							
Overheats							
Leakage (external)							
Rupture (external)							
Strainer/Filter Plugs			2.8E-6/h(3) [6,7]				2.8E-6/h(3.0) [4]
Leakage (internal)			[6,7]				[4]

Table 5a. Category 3 estimates for water system.

System/Component/Failure Mode	Failure Data (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Rupture (internal)			[6,7]				[4]
Orifice Plugs	8.0E-7/h(3)						8.0E-7/h(3)
Miscellaneous Travelling Screen Plugs							

a. Failure rate estimates are listed as: mean frequency (error factor), where the error factor is the 95th percentile/50th percentile. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses).

Notes

WASH-1400 - Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, U. S. Nuclear Regulatory Commission, WASH-1400 (NUREG 75/014), October 1975.

All failure rates were obtained from Tables III 4-1 and 4-2, unless otherwise indicated. The median values listed in WASH-1400 were converted to mean values using the error factor indicated and assuming a lognormal distribution.

1. Equivalent estimate per hour (from air-operated valve information) used.

2. First estimate is for piping with diameters less than 3 in., and second estimate is for greater than 3 in. Leakage estimate is 20 times higher than rupture (p. III-77). Each section was assumed to be 20 ft.

CCPS - Guidelines for Process Equipment Reliability Data With Data Tables, Center for Chemical Process Safety, American Institute of Chemical Engineers, 1989.

Error factor estimates were obtained from the square root of the upper bound times the lower bound.

IEEE - IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations, Institute of Electrical and Electronic Engineers, Inc., IEEE Std 500-1984, 1983.

Recommended estimates were interpreted to be medians. Recommended estimates were converted to means using the error factor (upper bound/median) and assuming a lognormal distribution, unless otherwise indicated. If the error factor was larger than 30, it was reduced to 30.

Table 5a. Category 3 estimates for water system.

1. No upper or lower bounds given. Recommended value interpreted as a mean because of the sources used to estimate the value.

2. Safety valve data used (p. 1040).

3. Centrifugal pump data used (p. 893).

4. Turbine-driven pump data used (p. 917).

5. Diesel-driven pump data used (p. 918).

6. Mechanical restriction filter data used (p. 1401).

7. Failure modes not indicated.

LNG2 - H. Lemmerse and M. Bosman, "Data of Gas Compressors and Instrumentation - Hard to Collect, Easy to Analyse," Reliability Engineering 13 (1985), pp. 65-78.

All estimates were taken from the observed data on p. 78.

EPRI1 - R. P. Dawkins and J. A. Derdiger, Component Failure and Repair Data: Gasification-Combined-Cycle Power Generation Units, Electric Power Research Institute, Topical Report AP-2205, Research Project 239-2, February 1982.

1. Failure modes not indicated.

EPRI2 - J. A. Derdiger et al., Component Failure and Repair Data for Coal-Fired Power Units, Electric Power Research Institute, Topical Report AP-2071, Research Project 239-2, October 1981.

1. Failure modes not indicated.

Aggregated Results

1. Aggregation routine resulted in an error factor >30, so an error factor of 30 was assumed.

2. For per hour estimates without failure mode indicated, one-half was assigned to fails to start and one-half to fails to run.

3. IEEE estimates indicate pressurized tank value is one-tenth of unpressurized value.

4. Failure modes not indicated.

Table 5b. Category 3 estimates for chemical process system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Chemical Process Valve (Standby or Safety) Manual *Fails to open/close*		2.9E-4/d(8.7)					2.9E-4/d(8.7)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Check Fails to open		1.5E-4/d(3.2)					1.5E-4/d(3.2)
Fails to close		2.2E-3/d(4.9)					2.2E-3/d(4.9)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Motor-Operated Fails to open/close		5.6E-3/d(6.1)					5.6E-3/d(6.1)
Spurious operation		1.4E-6/h(4.0)					1.4E-6/h(4.0)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							

Table 5b. Category 3 estimates for chemical process system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Air-Operated Fails to open/close		2.2E-3/d(4.7)		2.4E-5/h [1]			2.2E-3/d(4.7) [1]
Spurious operation		3.6E-6/h(6.7)		[1]			3.6E-6/h(6.7) [1]
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Solenoid-Operated Fails to open/close		2.8E-3/d(5.5)					2.8E-3/d(5.5)
Spurious operation		4.1E-7/h(3.0)					4.1E-7/h(3.0)
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Safety/Relief Fails to open		4.2E-3/d(30), 2.1E-4/d(10)					7.8E-4/d(18)
Fails to reclose		5.0E-3/d(10), 5.2E-3/d(13)					5.1E-3/d(12)
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							

Table 5b. Category 3 estimates for chemical process system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Vacuum-Breaker Fails to open							
Fails to reclose							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Valve (Control) Motor-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Air-Operated Fails open				2.7E-5/h [1]			2.7E-5/h(10) [2]
Fails closed				[1]			[2]
Fails to respond				[1]			[2]
Plugs							
Leakage (external)							
Rupture (external)							
Solenoid-Operated Fails open							
Fails closed							

Table 5b. Category 3 estimates for chemical process system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Pump Motor-Driven Fails to start		1.1E-2/d(11), 1.9E-2/d(5.6)			3.0E-5/h [1]		1.6E-2/d(8.1), 1.5E-5/h [3]
Fails to run		2.9E-4/h(4.5), 1.0E-4/h(24)			[1]		6.0E-5/h(11) [3]
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Turbine-Driven Fails to start		2.6E-2/d(4.3)					2.6E-2/d(4.3)
Fails to run		8.9E-5/h(5.0)					8.9E-5/h(5.0)
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Diesel-Driven Fails to start							
Fails to run							
Overspeed							
Fails to stop							

Table 5b. Category 3 estimates for chemical process system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Leakage (external)							
Rupture (external)							
Piping/Hose/Jumper Piping Leakage (external)							
Rupture (external)		5.1E-12/h-ft (15) [1]					5.1E-12/h-ft(15)
Plugs							
Hose Leakage (external)							
Rupture (external)		2.9E-8/h-ft (15) [1]					2.9E-8/h-ft(15)
Plugs							
Jumper Leakage (external)							
Rupture (external)							
Plugs							
Vessel Tank (Unpressurized) Leakage (external)		9.9E-7/h(4.9), 1.2E-6/h(15)					1.2E-6/h(9.3)
Rupture (external)							
Tank (Pressurized) Leakage (external)		1.1E-8/h(17)					1.1E-8/h(17)
Rupture (external)							
Flange/Gasket Leakage (external)							

Table 5b. Category 3 estimates for chemical process system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Rupture (external)							
Heat Exchanger Shell/Tube Fouling (tubes)							
Plugs (tubes)							
Leakage (tubes)		2.6E-5/h(7.5)					2.6E-5/h(7.5)
Rupture (tubes)							
Leakage (shell)							
Rupture (shell)							
Heater (Electrical) Fails to heat							
Overheats							
Leakage (external)							
Rupture (external)							
Stream [illegible] Plugs			5.6E-6/h(5.0) [1,2]				5.6E-6/h(5.0) [2]
Leakage (internal)			[2]				[2]
Rupture (internal)			[2]				[2]
Orifice Plugs							
Miscellaneous Mixer/Blender Failure							
Agitator Failure					5.7E-5/h	1.0E-5/h, 1.9E-5/h, 3.0E-6/h, 7.0E-6/h, 3.8E-5/h	2.5E-5/h(10)

Table 5b. Category 3 estimates for chemical process system.							
System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Centrifuge Failure							

a. Failure rate estimates are listed as: mean frequency (error factor), where the error factor is the 95th percentile/50th percentile. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses).

Notes

WASH-1400 - Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, U. S. Nuclear Regulatory Commission, WASH-1400 (NUREG 75/014), October 1975.

All failure rates were obtained from Tables III 4-1 and 4-2, unless otherwise indicated. The median values listed in WASH-1400 were converted to mean values using the error factor indicated and assuming a lognormal distribution.

CCPS - Guidelines for Process Equipment Reliability Data With Data Tables, Center for Chemical Process Safety, American Institute of Chemical Engineers, 1989.

Error factor estimates were obtained from the square root of the upper bound times the lower bound.

1. Each section was assumed to be 20 ft.

IEEE - IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations, Institute of Electrical and Electronic Engineers, Inc., IEEE Std 500-1984, 1983.

Recommended estimates were interpreted to be medians. Recommended estimates were converted to means using the error factor (upper bound/median) and assuming a lognormal distribution, unless otherwise indicated. If the error factor was larger than 50, it was reduced to 50.

1. Strainer/filter for chemical fluid estimate used (p. 1407).

2. Failure modes not indicated.

LNG2 - H. Lemmerse and M. Bosman, "Data of Gas Compressors and Instrumentation - Hard to Collect, Easy to Analyse," Reliability Engineering 13 (1985), pp. 65-78.

All estimates were taken from the observed data on p. 78.

Table 5b. Category 3 estimates for chemical process system.

1. Failure modes not indicated.

EPRI1 - R. P. Dawkins and J. A. Derdiger, Component Failure and Repair Data: Gasification-Combined-Cycle Power Generation Units, Electric Power Research Institute, Topical Report AP-2205, Research Project 239-2, February 1982.

1. Failure modes not indicated.

Aggregated Results

1. LNG2 data not used (no information on how to partition among failure modes).

2. Failure modes not indicated.

3. Per hour estimate without failure modes indicated was divided evenly between fails to start and fails to run.

Table 5c. Category 3 estimates for compressed gas system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Compressed Gas Valve (Standby or Safety) Manual Fails to open/close							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Check Fails to open							
Fails to close							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Motor-Operated Fails to open/close							
Spurious operation							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							

Table 5c. Category 3 estimates for compressed gas system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Air-Operated Fails to open/close							
Spurious operation							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Solenoid-Operated Fails to open/close							
Spurious operation							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Safety/Relief Fails to open							
Fails to reclose							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Vacuum-Breaker Fails to open							

Table 5c. Category 3 estimates for compressed gas system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Fails to reclose							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Valve (Control) Motor-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Air-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Solenoid-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							

Table 5c. Category 3 estimates for compressed gas system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Leakage (external)							
Rupture (external)							
Compressor Motor-Driven Fails to start			6.7E-4/h(30), 4.7E-5/h [1]		3.8E-5/h [1]		1.6E-4/h(30) [1,2]
Fails to run		2.5E-3/h(19)	[1]		[1]		[2]
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Piping/Hose/Jumper/Tube Piping Leakage (external)							
Rupture (external)							
Plugs							
Hose Leakage (external)							
Rupture (external)							
Plugs							
Jumper Leakage (external)							
Rupture (external)							
Plugs							
Tube Leakage (external)							
Rupture (external)							

Table 5c. Category 3 estimates for compressed gas system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Plugs							
Vessel Tank (Pressurized) Leakage (external)							
Rupture (external)							
Cylinder (Pressurized) Leakage (external)							
Rupture (external)							
Flange/Gasket Leakage (external)							
Rupture (external)							
Heat Exchanger Shell/Tube Fouling (tubes)							
Plugs (tubes)							
Leakage (tubes)							
Rupture (tubes)							
Leakage (shell)							
Rupture (shell)							
Heater (Electrical) Fails to heat							
Overheats							
Leakage (external)							
Rupture (external)							
Vaporizer Failure							

Table 5c. Category 3 estimates for compressed gas system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Air Dryer Failure			2.6E-7/h [2]				2.6E-7/h(10) [3]
Filter Plugs			3.4E-6/h(3.4) [1]				3.4E-6/h(3.4) [2]
Leakage (internal)			[1]				[2]
Rupture (internal)			[1]				[2]
Orifice Plugs							

a. Failure rate estimates are listed as: mean frequency (error factor), where the error factor is the 95th percentile/50th percentile. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses).

Notes

WASH-1400 - Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, U. S. Nuclear Regulatory Commission, WASH-1400 (NUREG 75/014), October 1975.

All failure rates were obtained from Tables III 4-1 and 4-2, unless otherwise indicated. The median values listed in WASH-1400 were converted to mean values using the error factor indicated and assuming a lognormal distribution.

CCPS - Guidelines for Process Equipment Reliability Data With Data Tables, Center for Chemical Process Safety, American Institute of Chemical Engineers, 1989.

Error factor estimates were obtained from the square root of the upper bound times the lower bound.

IEEE - IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations, Institute of Electrical and Electronic Engineers, Inc., IEEE Std 500-1984, 1983.

Recommended estimates were interpreted to be medians. Recommended estimates were converted to means using the error factor (upper bound/median) and assuming a lognormal distribution, unless otherwise indicated. If the error factor was larger than 50, it was reduced to 50.

Table 5c. Category 3 estimates for compressed gas system.

1. Failure modes not indicated.

2. Air dryer estimate obtained from information on p. 1422 (no failures in 1.9E+6h).

LNG2 - H. Lammerse and M. Bosman, "Data of Gas Compressors and Instrumentation - Hard to Collect, Easy to Analyse," Reliability Engineering 13 (1985), pp. 65-78.

All estimates were taken from the observed data on p. 78.

EPRI1 - R. P. Dawkins and J. A. Derdiger, Component Failure and Repair Data: Gasification-Combined-Cycle Power Generation Units, Electric Power Research Institute, Topical Report AP-2205, Research Project 239-2, February 1982.

1. Failure modes not indicated.

Aggregated Results

1. CCPS estimate doubled (assumes equal failure rate estimates for fails to start and fails to run) before combining with other estimates.

2. Failure modes not indicated.

3. Failure rate estimate based on zero failures and may be conservatively high.

Table 5d. Category 3 estimates for HVAC/exhaust system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
HVAC/Exhaust							
Damper (Standby or Safety)							
Manual							
Fails to open/close							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Motor-Operated							
Fails to open/close							
Spurious operation							
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							
Air-Operated							
Fails to open/close			1.2E-6/h [1,2]				1.2E-6/h(10) [1]
Spurious operation			[1]				[1]
Plugs							
Leakage (internal)							
Rupture (internal)							
Leakage (external)							
Rupture (external)							

Table 5d. Category 3 estimates for HVAC/exhaust system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Damper (Control) Motor-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Air-Operated Fails open							
Fails closed							
Fails to respond							
Plugs							
Leakage (external)							
Rupture (external)							
Fan/Blower Motor-Driven Fails to start		2.1E-4/d(9.0)	2.5E-6/h [1,2]		1.1E-4/h [1]	8.0E-6/h, 5.0E-7/h, 1.3E-5/h [1]	2.1E-4/d(9.0), 5.0E-6/h(12) [2]
Fails to run		9.1E-6/h(3.8)	[1]		[1]	[1]	5.0E-6/h(12) [2]
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							

Table 5d. Category 3 estimates for HVAC/exhaust system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Diesel-Driven Fails to start							
Fails to run							
Overspeed							
Fails to stop							
Leakage (external)							
Rupture (external)							
Ducting Leakage (external)							
Rupture (external)							
Plugs							
Heat Exchanger Air Conditioning Unit/ Chiller Fails to start			1.0E-5/h(9.7) [1,3]				1.0E-5/h(9.7) [1]
Fails to run			[1]				[1]
Fan Cooler Unit Fails to start							
Fails to run							
Heater (Electrical) Fails to heat							
Overheats							
Heater (Gas) Fails to heat							
Overheats							

Table 5d. Category 3 estimates for HVAC/exhaust system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Filter Normal Plugs							
Leakage (internal)							
Rupture (internal)							
Low-Efficiency Plugs							
Leakage (internal)							
Rupture (internal)							
HEPA Plugs							
Leakage (internal)							
Rupture (internal)							
Sand Plugs							
Leakage (internal)							
Rupture (internal)							
Baghouse Plugs						8.6E-4/h	8.6E-4/h(10)
Leakage (internal)							
Rupture (internal)							
Miscellaneous Mist Eliminator Failure						1.1E-4/h	1.1E-4/h(10)
Scrubber Failure					5.7E-5/h [2]	6.9E-4/h [2]	2.0E-4/h(10)

Table 5d. Category 3 estimates for HVAC/exhaust system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Precipitator Failure						4.6E-5/h	4.6E-5/h(10)

a. Failure rate estimates are listed as: mean frequency (error factor), where the error factor is the 95th percentile/50th percentile. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses).

Notes

WASH-1400 - Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, U. S. Nuclear Regulatory Commission, WASH-1400 (NUREG 75/014), October 1975.

All failure rates were obtained from Tables III 4-1 and 4-2, unless otherwise indicated. The median values listed in WASH-1400 were converted to mean values using the error factor indicated and assuming a lognormal distribution.

CCPS - Guidelines for Process Equipment Reliability Data With Data Tables, Center for Chemical Process Safety, American Institute of Chemical Engineers, 1989.

Error factor estimates were obtained from the square root of the upper bound times the lower bound.

IEEE - IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations, Institute of Electrical and Electronic Engineers, Inc., IEEE Std 500-1984, 1983.

Recommended estimates were interpreted to be medians. Recommended estimates were converted to means using the error factor (upper bound/median) and assuming a lognormal distribution, unless otherwise indicated. If the error factor was larger than 50, it was reduced to 50.

1. Failure modes not indicated.

2. No upper or lower bounds given. Recommended value interpreted as a mean because of the sources used to estimate the value.

3. Chiller data used (p. 1388).

LNG2 - H. Lammerse and M. Bosman, "Data of Gas Compressors and Instrumentation - Hard to Collect, Easy to Analyse," Reliability Engineering 13 (1985), pp. 65-78.

All estimates were taken from the observed data on p. 78.

Table 5d. Category 3 estimates for HVAC/exhaust system.

EPRI1 - R. P. Dawkins and J. A. Derdiger, Component Failure and Repair Data: Gasification-Combined-Cycle Power Generation Units, Electric Power Research Institute, Topical Report AP-2205, Research Project 239-2, February 1982.

1. Failure modes not indicated.

2. Estimate for ammonia or particulate scrubber.

EPRI2 - J. A. Derdiger et al., Component Failure and Repair Data for Coal-Fired Power Units, Electric Power Research Institute, Topical Report AP-2071, Research Project 239-2, October 1981.

1. Failure modes not indicated.

2. Estimate for SO_2 scrubber.

Aggregated Results

1. Failure modes not indicated.

2. CCPS value doubled before combining with other estimates (assumes equal failure rates for fails to start and fails to run).

Table 5e. Category 3 estimates for electrical distribution system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Electrical Distribution *Generator* Diesel-Driven Fails to start	3.8E-2/d(3)	1.8E-2/d(5.0)	1.8E-2/d(30) [1]	2.0E-3/d			3.1E-2/d(11)
Fails to run	8.0E-3/h(10)	2.3E-3/h(6.7)	1.7E-4/h(19)				4.2E-3/h(24)
Motor-Driven (ac to dc) Fails to start			1.8E-7/h(4.5)				1.8E-7/h(4.5)
Fails to run			3.3E-7/h(4.3)				3.3E-7/h(4.3)
Gas-Turbine-Driven Fails to start			9.5E-5/h(25)				9.5E-5/h(25)
Fails to run			3.4E-4/h(25)				3.4E-4/h(25)
Hydro-Turbine-Driven Fails to start							
Fails to run							
Battery Failure	3.8E-6/h(3)	2.3E-6/h(4.1)	1.1E-5/h(17)				4.7E-6/h(7.0)
Charger Rectifier Failure		7.6E-6/h(10), 1.1E-6/h(2.5)	4.8E-6/h(2.1)				4.2E-6/h(3.8)
Bus Metal-Enclosed Failure			1.3E-7/h(5)				1.3E-7/h(5)
Bare Failure			8.7E-7/h(12)				8.7E-7/h(12)
Cable/Joint/ Termination/Jumper Cable (Copper, 1000ft) Failure	3.8E-6/h(3)		4.5E-6/d(7.4)				4.5E-6/d(7.4), 3.8E-6/h(3)
Joint (Copper) Failure			3.2E-6/h(30) [1]				3.2E-6/h(30)

Table 5e. Category 3 estimates for electrical distribution system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Termination (Copper) Failure	2.7E-7/h(10)		2.6E-7/h(30) [1]				2.6E-7/h(18)
Jumper (Power) Failure							
Circuit Breaker General Fails to open/close	1.3E-3/d(3)		1.3E-3/d(30) [1]				1.3E-3/d(13)
Spurious operation	1.3E-6/h(3)	1.8E-6/h(6.0), 3.8E-6/h(20)	1.7E-7/h(30) [1]				2.8E-6/h(20)
Reactor Trip Fails to open							
Spurious operation							
Relay Protective Fails to open/close	1.3E-4/d(3)	1.9E-6/h(1.1)	4.2E-6/d(2.6)				7.1E-5/d(16), 1.9E-6/h(1.1)
Spurious operation	1.3E-7/h(3)	6.0E-8/h(15)	2.6E-7/h(30) [1]				1.8E-7/h(13)
Control Fails to open/close			7.2E-6/d(1.4)				7.2E-6/d(1.4)
Spurious			3.4E-7/h(30) [1]				3.4E-7/h(30)
Bistable Fails to open/close							
Spurious operation							
Switch Push-Button (Manual) Fails to open/close	1.3E-5/d(3)		1.8E-6/h(15)				1.3E-3/d(3), 1.8E-6/h(15)
Spurious operation	8.0E-8/h(10)		9.6E-7/h(13)				2.6E-7/h(12)
Rotary (Manual) Fails to open/close			3.1E-7/h(2)				3.1E-7/h(2)

Table 5e. Category 3 estimates for electrical distribution system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Spurious operation			1.9E-7/h(2)				1.9E-7/h(2)
Key-Operated (Manual) Fails to open/close			2.3E-6/h [2]				2.3E-6/h(10) [1]
Spurious operation			[2]				[1]
Automatic-Transfer Fails to open/close							
Spurious operation							
Limit Fails to open/close	3.8E-4/d(3)		7.5E-6/h(1.6) [2]				3.8E-4/d(3), 6.0E-6/h(1.6) [2]
Spurious operation		6.3E-7/h(9.4)	[2]				1.7E-6/h(5.1) [2]
Fuse Fail to open	1.3E-5/d(3)		4.0E-6/h(10) [2]				1.3E-5/d(3), 3.5E-6/h(10) [2]
Premature opening	1.3E-6/h(3)		[2]				1.1E-6/h(6.1) [2]
Inverter Failure		2.9E-5/h(11)	2.3E-5/h(13)				2.6E-5/h(12)
Motor AC Fails to start	3.8E-4/d(3) [1]	1.5E-5/h(30) [1,2]	2.5E-5/h(30) [1]				3.8E-4/d(3), 1.8E-5/h(17) [3]
Fails to run	1.3E-5/h(3) [1]	[1]	3.3E-5/h(30) [1]				2.4E-5/h(17) [3]
DC Fails to start	3.8E-4/d(3) [1]	2.3E-5/h(2.5) [1]	1.3E-4/h(30) [1]				3.8E-4/d(3), 1.8E-5/h(8.4) [3]
Fails to run	1.3E-5/h(3) [1]	[1]	[1]				2.4E-5/h(8.4) [3]

Table 5e. Category 3 estimates for electrical distribution system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Synchro Failure							
Transformer Power Failure	1.3E-6/h(3)	2.5E-6/h(8.6)	7.7E-7/h(5.6)				1.4E-6/h(5.6)
Instrumentation/Control Failure			3.8E-7/h(2.8)				3.8E-7/h(2.8)

a. Failure rate estimates are listed as: mean frequency (error factor), where the error factor is the 95th percentile/50th percentile. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses).

Notes

WASH-1400 - Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, U. S. Nuclear Regulatory Commission, WASH-1400 (NUREG 75/014), October 1975.

All failure rates were obtained from Tables III 4-1 and 4-2, unless otherwise indicated. The median values listed in WASH-1400 were converted to mean values using the error factor indicated and assuming a lognormal distribution.

1. Type of motor not indicated.

CCPS - Guidelines for Process Equipment Reliability Data With Data Tables, Center for Chemical Process Safety, American Institute of Chemical Engineers, 1989.

Error factor estimates were obtained from the square root of the upper bound times the lower bound.

1. Failure modes not indicated.

2. Error factor reduced to 30.

Table 5e. Category 3 estimates for electrical distribution system.

IEEE - IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations, Institute of Electrical and Electronic Engineers, Inc., IEEE Std 500-1984, 1983.

Recommended estimates were interpreted to be medians. Recommended estimates were converted to means using the error factor (upper bound/median) and assuming a lognormal distribution, unless otherwise indicated. If the error factor was larger than 50, it was reduced to 50.

1. Error factor reduced to 30.

2. Failure modes not indicated.

LNG2 - H. Lemmerse and M. Bosman, "Data of Gas Compressors and Instrumentation - Herd to Collect, Easy to Analyse," Reliability Engineering 13 (1985), pp. 65-78.

All estimates were taken from the observed data on p. 78.

Aggregated Results

1. Failure modes not indicated.

2. Relay and switch results indicate approximately one-fifth of failures are spurious operation. This information was used to partition the IEEE estimate.

3. Category 2 data indicate 1 of 8.5 failures is premature opening. This information was used to partition the IEEE estimate.

Table 51. Category 3 estimates for instrumentation and control system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Instrumentation and Control Alarm/Annunciator Fails to alarm		7.7E-7/h(10) [1]	5.8E-6/h(22)				1.5E-6/h(15)
Spurious operation		[1]	3.4E-6/h(23)				8.7E-7/h(15)
Sensor/Transmitter/ Transducer/Process Switch Temperature Failure	2.7E-6/h(10) [1]	9.7E-5/h(15) [2]	1.6E-6/h(8.3)	8.0E-6/h			8.1E-6/h(14)
Pressure Failure	2.7E-6/h(10) [1]	9.1E-5/h(30) [2,3]	2.0E-6/h(16)	2.5E-5/h			6.8E-6/h(17)
Differential Pressure Failure		6.6E-5/h(16), 2.2E-4/h(15) [2]					1.2E-4/h(16)
Flow Failure		1.1E-4/h(15), 1.2E-4/h(15), 9.6E-5/h(15) [2]	9.0E-6/h(15)	1.1E-5/h			3.2E-5/h(15)
Level Failure		2.5E-6/h(15), 1.4E-4/h(16), 9.9E-5/h(14), 1.9E-4/h(15) [2]	2.1E-6/h(2.6)				6.4E-6/h(7.7)
Humidity Failure			4.2E-6/h(3.9)				4.2E-6/h(3.9)
pH Failure			5.8E-7/h(5.0) [1]				5.8E-7/h(5.0)
Oxygen Concentration Failure							
CO_2 Concentration Failure				9.8E-5/h			9.8E-5/h(10)
Hydrogen Concentration Failure							

Table 5f. Category 3 estimates for instrumentation and control system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Nitrogen Concentration Failure							
Hydrocarbon Concentration Failure							
Helium Concentration Failure							
Speed Failure			1.7E-6/h(8.1)				1.7E-6/h(8.1)
Seismic Failure			1.6E-6/h(4)				1.6E-6/h(4)
Radiation Failure			6.3E-6/h(4.7)				6.3E-6/h(4.7)
Indicator Failure		2.5E-4/h(15)	3.9E-5/h(30) [2]				1.1E-4/h(22)
Amplifier Failure							
Modifier/Signal Conditioner Failure			3.3E-7/h(2.1)				3.3E-7/h(2.1)
Logic Module Failure		1.9E-5/h(15)	1.4E-6/h(2.6) [3]				3.7E-6/h(7.7)
Recorder Failure		2.5E-5/h(15)	5.7E-5/h(30) [2]				3.8E-5/h(22)
Sampler Failure							
Analyzer Failure		1.3E-3/h(26)					1.3E-3/h(26)
Timer Failure							

Table 51. Category 3 estimates for instrumentation and control system.

System/Component/Failure Mode	Failure Estimates (Category 3 Sources)[a]						
	WASH-1400	CCPS	IEEE	LNG2	EPRI1	EPRI2	Aggregated Results[b]
Gas Chromatograph Failure							
Voltage Regulator Failure							
Transmitter Failure			1.0E-5/h(30) [2]				1.0E-5/h(30)
Transducer Failure		6.3E-5/h(15)					6.3E-5/h(15)
Programmable Logic Controller Failure							

a. Failure rate estimates are listed as: mean frequency (error factor), where the error factor is the 95th percentile/50th percentile. Numbers in brackets refer to notes listed below, arranged by source.

b. Aggregated results are mean and error factor (in parentheses).

Notes

WASH-1400 - Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, U. S. Nuclear Regulatory Commission, WASH-1400 (NUREG 75/014), October 1975.

All failure rates were obtained from Tables III 4-1 and 4-2, unless otherwise indicated. The median values listed in WASH-1400 were converted to mean values using the error factor indicated and assuming a lognormal distribution.

1. Type of instrument not indicated.

CCPS - Guidelines for Process Equipment Reliability Data With Data Tables, Center for Chemical Process Safety, American Institute of Chemical Engineers, 1989.

Error factor estimates were obtained from the square root of the upper bound times the lower bound.

1. Failure modes not indicated.

2. Transmitter estimate used.

Table 5f. Category 3 estimates for instrumentation and control system.

3. Error factor reduced to 30.

IEEE - IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations, Institute of Electrical and Electronic Engineers, Inc., IEEE Std 500-1984, 1983.

Recommended estimates were interpreted to be medians. Recommended estimates were converted to means using the error factor (upper bound/median) and assuming a lognormal distribution, unless otherwise indicated. If the error factor was larger than 50, it was reduced to 50.

1. Water chemistry instrumentation estimate used.

2. Error factor reduced to 30.

3. Totalizer estimate used.

LNG2 - H. Lammerse and M. Bosman, "Data of Gas Compressors and Instrumentation - Hard to Collect, Easy to Analyse," Reliability Engineering 13 (1985), pp. 65-78.

All estimates were taken from the observed data on p. 78.

Table 6a. Summary of results for water system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates*			
	Category 1	Category 2	Category 3	Recommended*
Water Valve (Standby or Safety) Manual Fails to open/close	3.5E-4/d(18), 3.3E-8/h(30)	1.4E-4/d(19), 7.1E-7/h(10)	6.0E-5/d(10)	3.0E-4/d(10)
Plugs	1.1E-6/h(10) [1]		3.8E-7/h(3)	5.0E-8/h(10) [1]
Leakage (internal)	5.7E-3/h(10) [1]			1.0E-6/h(10) [2]
Rupture (internal)				5.0E-8/h(30) [2]
Leakage (external)		1.0E-8/h(9.6)	2.0E-8/h(10)	1.0E-8/h(10) [3]
Rupture (external)		5.8E-10/h(10)	2.7E-8/h(10)	5.0E-10/h(30) [3]
Check Fails to open	6.0E-5/d(10)	1.8E-5/d(10), 1.3E-7/h(10)	8.8E-5/d(3.0)	5.0E-5/d(10)
Fails to close	9.8E-4/d(4.6)	5.7E-5/d(10), 3.9E-7/h(10)		1.0E-3/d(5)
Plugs				5.0E-8/h(10) [1]
Leakage (internal)	6.8E-7/h(30)	9.1E-7/h(2.9)	5.0E-7/h(5.4)	1.0E-6/h(10) [2]
Rupture (internal)			1.9E-7/h(5.4)	5.0E-8/h(30) [2]
Leakage (external)		1.5E-8/h(26)		1.0E-8/h(10) [3]
Rupture (external)		5.8E-10/h(10)	2.7E-8/h(10)	5.0E-10/h(30) [3]
Motor-Operated Fails to open/close	3.3E-3/d(6.3), 4.8E-6/h(9.6)	3.8E-3/d(1.8)	3.0E-3/d(3.5)	3.0E-3/d(5)
Spurious operation	2.3E-7/h(7.2)	1.8E-7/h(11)		3.0E-7/h(5)

Table 6a. Summary of results for water system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Plugs	5.6E-8/h(10)		1.9E-7/h(8.1)	5.0E-8/h(10) [1]
Leakage (internal)	8.3E-7/h(10)			1.0E-6/h(10) [2]
Rupture (internal)				5.0E-8/h(30) [2]
Leakage (external)		9.6E-9/h(10)	1.0E-7/h(10)	1.0E-8/h(10) [3]
Rupture (external)		5.8E-10/h(10)	2.7E-8/h(10)	5.0E-10/h(30) [3]
Air-Operated Fails to open/close	1.2E-3/d(21), 5.2E-7/h(10)	3.4E-3/d(3.8)	9.8E-4/d(3.9)	1.0E-3/d(30)
Spurious operation	1.2E-6/h(5.4)	1.2E-6/h(2.0)		1.0E-6/h(5)
Plugs	1.1E-7/h(10) [1]		3.8E-7/h(3)	5.0E-8/h(10) [1]
Leakage (internal)	1.6E-6/h(10)	6.9E-7/h(2.6)		1.0E-6/h(10) [2]
Rupture (internal)		3.0E-7/h(2.6)		5.0E-8/h(30) [2]
Leakage (external)		9.9E-9/h(7.6)	1.0E-7/h(10)	1.0E-8/h(10) [3]
Rupture (external)		5.8E-10/h(10)	2.7E-8/h(10)	5.0E-10/h(30) [3]
Solenoid-Operated Fails to open/close	7.8E-4/d(10), 7.1E-7/h(10)	1.1E-2/d(10), 7.5E-8/h(10)	1.3E-3/d(3)	1.0E-3/d(10)
Spurious operation	6.1E-7/h(10) [1]	5.6E-8/h(10)		5.0E-7/h(10)
Plugs	3.3E-4/h(10) [1]		3.8E-7/h(3)	5.0E-8/h(10) [1]

Table 6a. Summary of results for water system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates*			
	Category 1	Category 2	Category 3	Recommended*
Leakage (internal)				1.0E-6/h(10) [2]
Rupture (internal)				5.0E-8/h(30) [2]
Leakage (external)		1.3E-8/h(30)		1.0E-8/h(10) [3]
Rupture (external)		5.8E-10/h(10)	2.7E-8/h(10)	5.0E-10/h(30) [3]
Safety/Relief Fails to open	2.7E-3/d(3.3), 8.5E-8/h(10) [1]	1.2E-2/d(3.3)	1.5E-3/d(30)	3.0E-3/d(3)
Fails to reclose	2.3E-3/d(1.7)			3.0E-3/d(3)
Leakage (internal)		1.1E-6/h(2.5)	1.5E-5/h(3)	1.0E-6/h(10) [2]
Rupture (internal)			3.0E-6/h(10)	5.0E-8/h(30) [2]
Leakage (external)		1.1E-6/h(2.5)		1.0E-8/h(10) [3]
Rupture (external)		4.9E-8/h(10)		5.0E-10/h(30) [3]
Vacuum-Breaker Fails to open	1.1E-2/d(10), 4.4E-4/h(10) [1]		3.8E-5/d(3)	1.0E-2/d(10)
Fails to reclose				1.0E-2/d(10) [4]
Leakage (internal)				1.0E-6/h(10) [2]
Rupture (internal)				5.0E-8/h(30) [2]
Leakage (external)				1.0E-8/h(10) [3]

Table 6a. Summary of results for water system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Rupture (external)				5.0E-10/h(30) [3]
Explosive Fails to open	1.8E-2/d(10) [1]			1.0E-4/d(10) [5]
Leakage (internal)				1.0E-6/h(10) [2]
Rupture (internal)				5.0E-8/h(30) [2]
Leakage (external)				1.0E-8/h(10) [3]
Rupture (external)				5.0E-10/h(30) [3]
Valve (Control) Motor-Operated Fails open				3.0E-6/h(10) [6]
Fails closed				3.0E-6/h(10) [6]
Fails to respond				3.0E-6/h(10) [6]
Plugs				5.0E-8/h(10) [1]
Leakage (external)				1.0E-8/h(10) [3]
Rupture (external)				5.0E-10/h(30) [3]
Air-Operated Fails open				3.0E-6/h(10) [6]
Fails closed				3.0E-6/h(10) [6]
Fails to respond				3.0E-6/h(10) [6]

Table 6a. Summary of results for water system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates*			
	Category 1	Category 2	Category 3	Recommended*
Plugs				5.0E-8/h(10) [1]
Leakage (external)				1.0E-8/h(10) [3]
Rupture (external)				5.0E-10/h(30) [3]
Solenoid-Operated Fails open				3.0E-6/h(10) [6]
Fails closed				3.0E-6/h(10) [6]
Fails to respond				3.0E-6/h(10) [6]
Plugs				5.0E-8/h(10) [1]
Leakage (external)				1.0E-8/h(10) [3]
Rupture (external)				5.0E-10/h(30) [3]
Pump Motor-Driven Fails to start	3.7E-3/d(4.7)	8.3E-4/d(9.1), 3.7E-6/h(8.3)	7.5E-3/d(8.3), 2.4E-5/h(5.8)	3.0E-3/d(5)
Fails to run	2.2E-5/h(17)	9.4E-6/h(11)	2.1E-5/h(6.8)	3.0E-5/h(10)
Overspeed		1.9E-6/h(11)		5.0E-6/h(10)
Fails to stop	3.8E-3/d(4.4)			3.0E-3/d(5)
Leakage (external)		5.9E-8/h(30)		3.0E-8/h(10) [3]
Rupture (external)		1.7E-9/h(10)		1.0E-9/h(30) [3]
Turbine-Driven Fails to start	2.2E-2/d(3.8), 5.5E-5/h(10)	1.0E-2/d(10)	4.0E-3/d(10), 3.8E-5/h(10)	3.0E-2/d(3)

Table 6a. Summary of results for water system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Fails to run	1.4E-4/h(22)	1.0E-4/h(1.7)	3.8E-5/h(10)	1.0E-4/h(30)
Overspeed				3.0E-5/h(10) [7]
Fails to stop				3.0E-2/d(3) [7]
Leakage (external)		2.7E-8/h(10)		3.0E-8/h(10) [3]
Rupture (external)		1.6E-9/h(10)		1.0E-9/h(30) [3]
Diesel-Driven Fails to start	7.9E-3/d(5.8)	3.4E-2/d(4.0)	9.8E-3/d(9.8)	1.0E-2/d(5)
Fails to run	4.6E-3/h(7.4)	2.3E-2/h(10)		5.0E-3/h(5)
Overspeed				1.0E-3/h(5) [7]
Fails to stop				1.0E-2/d(5) [7]
Leakage (external)		2.7E-8/h(10)		3.0E-8/h(10) [3]
Rupture (external)		1.6E-9/h(10)		1.0E-9/h(30) [3]
Piping/Hose/Jumper Piping Leakage (external)		2.3E-9/h-ft(10)	2.7E-9/h-ft(30)	3.0E-9/h-ft(10) [3]
Rupture (external)		5.8E-11/h-ft(10)	1.3E-10/h-ft(30)	1.0E-10/h-ft(30) [3]
Plugs			1.3E-10/h-ft(30)	1.0E-10/h-ft(30) [8]
Hose Leakage (external)		1.7E-9/h-ft(10)		1.0E-9/h-ft(10)
Rupture (external)		1.0E-8/h-ft(10)		1.0E-8/h-ft(10)

Table 6a. Summary of results for water system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Plugs				1.0E-8/h-ft(10) [8]
Jumper Leakage (external)				1.0E-6/h(10) [9]
Rupture (external)				1.0E-8/h(30) [9]
Plugs				5.0E-8/h(10) [10]
Vessel Tank (Unpressurized) Leakage (external)	7.3E-7/h(10) [1]	2.2E-8/h(19)	1.3E-6/h(30)	1.0E-8/h(10) [3]
Rupture (external)		3.0E-9/h(19)		5.0E-10/h(30) [3]
Tank (Pressurized) Leakage (external)		1.0E-6/h(24)	1.3E-7/h(30)	1.0E-8/h(10) [3]
Rupture (external)		4.5E-8/h(23)		5.0E-10/h(30) [3]
Flange/Gasket Leakage (external)		2.1E-8/h(11)		1.0E-8/h(10) [3]
Rupture (external)		1.8E-10/h(11)		1.0E-10/h(30) [3]
Heat Exchanger Shell/Tube Fouling (tubes)			9.4E-6/h(10) [1]	1.0E-7/h(10) [11]
Plugs (tubes)	2.6E-7/h(10) [1]		[1]	3.0E-8/h(10) [12]
Leakage (tubes)	1.3E-6/h(10) [1]	1.8E-7/h(17)	[1]	1.0E-7/h(10) [3]
Rupture (tubes)		7.8E-9/h(10)		5.0E-9/h(30) [3]

Table 6a. Summary of results for water system.				
System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Leakage (shell)	3.1E-7/h(10) [1]	7.8E-9/h(10)		1.0E-8/h(10) [3]
Rupture (shell)		1.6E-9/h(10)		5.0E-10/h(30) [3]
Heater (Electrical) Fails to heat		1.8E-6/h(10)		1.0E-6/h(10)
Overheats		3.0E-7/h(10)		3.0E-7/h(10)
Leakage (external)				1.0E-7/h(10) [13]
Rupture (external)				5.0E-9/h(30) [13]
Strainer/Filter Plugs	4.0E-6/h(10)		2.8E-6/h(3.0) [1]	3.0E-6/h(10)
Leakage (internal)		2.2E-6/h(10)	[1]	3.0E-6/h(10)
Rupture (internal)		6.8E-7/h(10)	[1]	5.0E-7/h(10)
Orifice Plugs			8.0E-7/h(3)	1.0E-6/h(3)
Miscellaneous Travelling Screen Plugs	5.2E-7/h(10) [1]			5.0E-7/h(10)

a. Aggregated failure rates are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

b. For the recommended failure rate, the Category 1 result was used if available. If not, then the Category 2 result was used. If no Category 1 or 2 results were available, the Category 3 result was used. (Exceptions to this are indicated in the notes.) Mean values were rounded to 1, 3, or 5 times the appropriate power of 10. Error factors were rounded to 3, 5, 10, or 30.

Notes

Category 1

1. Failure rate based on zero failures and may be conservatively high.

Table 6a. Summary of results for water system.

Category 2

1. Failure rate based on zero failures and may be conservatively high.

Category 3

1. Failure modes not indicated.

Recommended

1. Data for manual, motor-operated, and air-operated valves combined.
2. Data for manual, check, motor-operated, and air-operated valves combined. All failures assumed to be leakage. Rupture value determined using the same partition used for external rupture.
3. Results from EGG-SSRE-9639 (Category 2 data) used. These results are believed to be the most comprehensive and consistent set of data available. Rupture values for non-PCS system used. Rupture defined as > 50 gpm.
4. Assumed to be the same as fails to open.
5. Assumed to be 10 times better than air-operated valve.
6. Control valve data for chemical process and compressed gas systems indicate approximately 3.0E-6/h for fails open, fails shut, and fails to respond.
7. Trend seen for motor-driven pump applied.
8. WASH-1400 indicates plugs is similar to external rupture in failure rate.
9. Flange/gasket values multiplied by 100.
10. Valve plugs value use
11. Data for chemical process system (Table 6b) indicate fouling failure rate is similar to tube leakage.
12. Category 1 results indicate tube plugging is one-fifth as frequent as tube leakage.
13. Vessel failure rates multiplied by 10.

Table 6b. Summary of results for chemical process system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Chemical Process Valve (Standby or Safety) Manual Fails to open/close			2.9E-4/d(8.7)	3.0E-4/d(10) [1]
Plugs				5.0E-8/h(10) [1]
Leakage (internal)				1.0E-6/h(10) [1]
Rupture (internal)				5.0E-8/h(30) [1]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Check Fails to open			1.5E-4/d(3.2)	5.0E-5/d(10) [1]
Fails to close			2.2E-3/d(4.9)	1.0E-3/d(10) [1]
Plugs				5.0E-8/h(10) [1]
Leakage (internal)				1.0E-6/h(10) [1]
Rupture (internal)				5.0E-8/h(30) [1]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Motor-Operated Fails to open/close			5.6E-3/d(6.1)	3.0E-3/d(10) [1]

Table 6b. Summary of results for chemical process system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Spurious operation			1.4E-6/h(4.0)	3.0E-7/h(10) [1]
Plugs				5.0E-8/h(10) [1]
Leakage (internal)				1.0E-6/h(10) [1]
Rupture (internal)				5.0E-8/h(10) [1]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Air-Operated Fails to open/close		1.7E-2/d(10), 2.0E-7/h(5)	2.2E-3/d(4.7)	1.0E-3/d(30) [1]
Spurious operation		2.2E-8/h(10)	3.6E-6/h(6.7)	1.0E-6/h(10) [1]
Plugs		2.2E-8/h(10)		5.0E-8/h(10) [1]
Leakage (internal)		7.3E-7/h(5)		1.0E-6/h(10) [1]
Rupture (internal)		2.2E-8/h(10)		5.0E-8/h(30) [1]
Leakage (external)		4.2E-7/h(3.6)		5.0E-7/h(10) [4]
Rupture (external)		1.8E-8/h(10)		3.0E-8/h(30) [4]
Solenoid-Operated Fails to open/close			2.8E-3/d(5.5)	1.0E-3/d(10) [1]
Spurious operation			4.1E-7/h(3.0)	5.0E-7/h(10) [1]

Table 6b. Summary of results for chemical process system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Plugs				5.0E-8/h(10) [1]
Leakage (internal)				1.0E-6/h(10) [1]
Rupture (internal)				5.0E-8/(30) [1]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Safety/Relief Fails to open			7.8E-4/d(18)	3.0E-3/d(10) [1]
Fails to reclose			5.1E-3/d(12)	3.0E-3/d(10) [1]
Leakage (internal)				1.0E-6/h(10) [1]
Rupture (internal)				5.0E-8/h(30) [1]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Vacuum-Breaker Fails to open				1.0E-2/d(10) [1]
Fails to reclose				1.0E-2/d(10) [1]
Leakage (internal)				1.0E-6/h(10) [1]
Rupture (internal)				5.0E-8/h(30) [1]

Table 6b. Summary of results for chemical process system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Explosive Fails to open				1.0E-4/d(10) [1]
Leakage (internal)				1.0E-6/h(10) [1]
Rupture (internal)				5.0E-8/h(10) [1]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Valve (Control) Motor-Operated Fails open				3.0E-6/h(10) [1]
Fails closed				3.0E-6/h(10) [1]
Fails to respond				3.0E-6/h(10) [1]
Plugs				5.0E-8/h(10) [1]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Air-Operated Fails open		6.0E-6/h(10)	2.7E-5/h [1]	3.0E-6/h(10) [1]
Fails closed		2.6E-6/h(10)	[1]	3.0E-6/h(10) [1]

Table 6b. Summary of results for chemical process system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Fails to respond			[1]	3.0E-6/h(10) [1]
Plugs				5.0E-8/h(10) [1]
Leakage (external)		1.1E-5/h(10)		5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Solenoid-Operated Fails open				3.0E-6/h(10) [1]
Fails closed				3.0E-6/h(10) [1]
Fails to respond				3.0E-6/h(10) [1]
Plugs				5.0E-8/h(10) [1]
Leakage (external)				5.0E-7/h(10) [4]
Rupture (external)				3.0E-8/h(30) [4]
Pump Motor-Driven Fails to start		8.1E-3/d(10), 8.9E-6/h(4.1)	1.6E-2/d(8.1), 1.5E-5/h	1.0E-2/d(10) [2]
Fails to run		5.8E-4/h(12)	6.0E-5/h(11)	1.0E-4/h(10) [2]
Overspeed				3.0E-5/h(10) [2]
Fails to stop				1.0E-2/d(10) [2]
Leakage (external)		9.2E-6/h(5.4)		1.0E-6/h(10) [4]

Table 6b. Summary of results for chemical process system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Rupture (external)		5.2E-8/h(10) [1]		5.0E-8/h(30) [4]
Turbine-Driven Fails to start			2.6E-2/d(4.3)	3.0E-2/d(10) [1]
Fails to run			8.9E-5/h(5.0)	1.0E-4/h(30) [1]
Overspeed				3.0E-5/h(10) [1]
Fails to stop				3.0E-2/d(10) [1]
Leakage (external)				1.0E-6/h(10) [4]
Rupture (external)				5.0E-8/h(30) [4]
Diesel-Driven Fails to start				1.0E-2/d(10) [1]
Fails to run				5.0E-3/h(10) [1]
Overspeed				1.0E-3/h(10) [1]
Fails to stop				1.0E-2/d(10) [1]
Leakage (external)				1.0E-6/h(10) [4]
Rupture (external)				5.0E-8/h(30) [4]
Piping/Hose/Jumper Piping Leakage (external)				3.0E-9/h-ft(10) [1]
Rupture (external)			5.1E-12/h-ft(15)	1.0E-10/h-ft(30) [1]

Table 6b. Summary of results for chemical process system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Plugs				1.0E-10/h-ft(30) [1]
Hose				
Leakage (external)				1.0E-9/h-ft(10) [1]
Rupture (external)			2.9E-8/h-ft(15)	1.0E-8/h-ft(10) [1]
Plugs				1.0E-8/h-ft(10) [1]
Jumper				
Leakage (external)				1.0E-6/h(10) [1]
Rupture (external)				1.0E-8/h(30) [1]
Plugs				5.0E-8/h(10) [1]
Vessel				
Tank (Unpressurized)				
Leakage (external)		2.6E-6/h(10)	1.2E-6/h(9.3)	1.0E-7/h(10) [3]
Rupture (external)				5.0E-9/h(30) [3]
Tank (Pressurized)				
Leakage (external)		3.7E-6/h(3.8)	1.1E-8/h(17)	1.0E-7/h(10) [3]
Rupture (external)		3.8E-7/h(10)		5.0E-9/h(30) [3]
Flange/Gasket				
Leakage (external)				1.0E-7/h(10) [3]
Rupture (external)				1.0E-9/h(10) [3]
Heat Exchanger				
Shell/Tube				
Fouling (tubes)		7.8E-6/h(1.3)		1.0E-6/h(10) [3]

Table 6b. Summary of results for chemical process system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Plugs (tubes)				3.0E-7/h(10) [3]
Leakage (tubes)		7.7E-6/h(1.3)	2.6E-5/h(7.5)	1.0E-6/h(10) [3]
Rupture (tubes)				5.0E-8/h(30) [3]
Leakage (shell)				1.0E-7/h(10) [3]
Rupture (shell)				5.0E-9/h(30) [3]
Heater (Electrical) Fails to heat		3.5E-5/h(5.8)		1.0E-5/h(10) [3]
Overheats		7.0E-6/h(10)		3.0E-6/h(10) [3]
Leakage (external)				1.0E-6/h(10) [3]
Rupture (external)				5.0E-8/h(30) [3]
Strainer/Filter Plugs		3.1E-6/h(11)	5.6E-6/h(5.0) [1]	3.0E-6/h(10) [1]
Leakage (internal)		7.0E-6/h(11)	[1]	3.0E-6/h(10) [1]
Rupture (internal)		7.0E-7/h(11) [1]	[1]	5.0E-7/h(10) [1]
Orifice Plugs				1.0E-6/h(10) [1]
Miscellaneous Mixer/Blender Failure				5.0E-6/h(10) [5]
Agitator Failure		6.5E-6/h(10)	2.5E-5/h(10)	5.0E-6/h(10)

Table 6b. Summary of results for chemical process system.				
System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Centrifuge Failure				5.0E-6/h(10) [5]

a. Aggregated failure rates are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

b. For the recommended failure rate, the Category 1 result was used if available. If not, then the Category 2 result was used. If no Category 1 or 2 results were available, the Category 3 result was used. (Exceptions to this are indicated in the notes.) Mean values were rounded to 1, 3, or 5 times the appropriate power of 10. Error factors were rounded to 3, 5, 10, or 30.

Notes

Category 2

1. Failure rate based on zero failure and may be conservatively high.

Category 3

1. Failure modes not indicated.

Recommended

1. Based on comparisons of (limited) chemical process system data for component groups with the much more extensive water system data (Table 6a), the water system results are appropriate.

2. Based on comparisons of (limited) chemical process system data for component groups with the much more extensive water system data (Table 6a), the water system results were multiplied by 3.

3. Based on comparisons of (limited) chemical process system data for component groups with the much more extensive water system data (Table 6a), the water system results were multiplied by 10.

4. Based on comparisons of (limited) chemical process system data for component groups with the much more extensive water system data (Table 6a), the water system results were multiplied by 50.

5. Agitator results were used.

Table 6c. Summary of results for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Compressed Gas Valve (Standby or Safety) Manual Fails to open/close		2.2E-3/d(10), 6.0E-7/h(10)		1.0E-3/d(10) [2]
Plugs				5.0E-7/h(10) [3]
Leakage (internal)				1.0E-5/h(10) [3]
Rupture (internal)				5.0E-7/h(30) [3]
Leakage (external)		1.1E-7/h(10)		1.0E-7/h(10) [3]
Rupture (external)				5.0E-9/h(30) [3]
Check Fails to open		1.1E-6/h(2.7)		1.0E-4/d(10) [2]
Fails to close		2.4E-6/h(2.7)		3.0E-3/d(10) [2]
Plugs				5.0E-7/h(10) [3]
Leakage (internal)		8.4E-6/h(10)		1.0E-5/h(10) [3]
Rupture (internal)		4.8E-7/h(10)		5.0E-7/h(30) [3]
Leakage (external)		8.4E-6/h(10)		1.0E-7/h(10) [3]
Rupture (external)		3.1E-7/h(10) [1]		5.0E-9/h(30) [3]
Motor-Operated Fails to open/close		5.3E-4/d(10)		1.0E-2/d(10) [2]

Table 6c. Summary of results for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Spurious operation				3.0E-7/h(10) [1]
Plugs				5.0E-7/h(10) [3]
Leakage (internal)				1.0E-5/h(10) [3]
Rupture (internal)				5.0E-7/h(30) [3]
Leakage (external)		1.5E-7/h(10)		1.0E-7/h(10) [3]
Rupture (external)				5.0E-9/h(30) [3]
Air-Operated Fails to open/close		3.0E-3/d(1.2)		3.0E-3/d(30) [2]
Spurious operation		1.9E-6/h(8.1)		1.0E-6/h(10) [1]
Plugs		6.5E-7/h(10)		5.0E-7/h(10) [3]
Leakage (internal)		2.5E-6/h(2.5)		1.0E-5/h(10) [3]
Rupture (internal)		4.1E-7/h(4.8)		5.0E-7/h(30) [3]
Leakage (external)		1.6E-6/h(5.5)		1.0E-7/h(10) [3]
Rupture (external)		2.0E-8/h(10) [1]		5.0E-9/h(30) [3]
Solenoid-Operated Fails to open/close		6.8E-7/h(10)		3.0E-3/d(10) [2]
Spurious operation		4.2E-7/h(10)		5.0E-7/h(10) [1]

Table 6c. Summary of results for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Plugs				5.0E-7/h(10) [3]
Leakage (internal)				1.0E-5/h(10) [3]
Rupture (internal)				5.0E-7/h(30) [3]
Leakage (external)		6.8E-6/h(10)		1.0E-7/h(10) [3]
Rupture (external)		2.6E-7/h(10) [1]		5.0E-9/h(30) [3]
Safety/Relief Fails to open				1.0E-2/d(10) [2]
Fails to reclose				1.0E-2/d(10) [2]
Leakage (internal)		9.3E-7/h(10)		1.0E-5/h(10) [3]
Rupture (internal)				5.0E-7/h(30) [3]
Leakage (external)		9.3E-7/h(10)		1.0E-7/h(10) [3]
Rupture (external)		1.2E-7/h(10) [1]		5.0E-9/h(30) [3]
Vacuum-Breaker Fails to open				3.0E-2/d(10) [2]
Fails to reclose				3.0E-2/d(10) [2]
Leakage (internal)				1.0E-5/h(10) [3]
Rupture (internal)				5.0E-7/h(30) [3]

Table 6c. Summary of results for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Leakage (external)				1.0E-7/h(10) [3]
Rupture (external)				5.0E-9/h(30) [3]
Valve (Control) Motor-Operated Fails open				3.0E-6/h(10) [1]
Fails closed				3.0E-6/h(10) [1]
Fails to respond				3.0E-6/h(10) [1]
Plugs				5.0E-7/h(10) [3]
Leakage (external)				1.0E-7/h(10) [3]
Rupture (external)				5.0E-9/h(30) [3]
Air-Operated Fails open		3.0E-6/h(6.1)		3.0E-6/h(10) [1]
Fails closed		3.0E-6/h(6.1)		3.0E-6/h(10) [1]
Fails to respond		3.0E-6/h(6.1)		3.0E-6/h(10) [1]
Plugs				5.0E-7/h(10) [3]
Leakage (external)		4.9E-6/h(3.7)		1.0E-7/h(10) [3]
Rupture (external)		1.4E-7/h(10) [1]		5.0E-9/h(30) [3]
Solenoid-Operated Fails open		1.6E-6/d [2]		3.0E-6/h(10) [1]

Table 6c. Summary of results for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Fails closed		[2]		3.0E-6/h(10) [1]
Fails to respond		[2]		3.0E-6/h(10) [1]
Plugs				5.0E-7/h(10) [3]
Leakage (external)				1.0E-7/h(10) [3]
Rupture (external)				5.0E-9/h(30) [3]
Compressor Motor-Driven Fails to start	7.5E-3/d(7.1)	3.9E-5/d(10), 8.2E-6/h(3.6)	1.6E-4/h(30)	5.0E-3/d(5)
Fails to run	5.6E-5/h(1.2)	1.3E-5/h(3.6), 4.1E-3/h(2.0)	1.6E-4/h(30)	5.0E-5/h(3)
Overspeed		2.6E-6/h(5)		1.0E-5/h(5) [5]
Fails to stop				5.0E-3/d(5) [6]
Leakage (external)		7.2E-7/h(10)		3.0E-7/h(10) [3]
Rupture (external)				1.0E-8/h(30) [3]
Piping/Hose/Jumper/Tube Piping Leakage (external)				3.0E-8/h-ft(10) [3]
Rupture (external)				1.0E-9/h-ft(30) [3]
Plugs				1.0E-9/h-ft(30) [3]

Table 6c. Summary of results for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Hose Leakage (external)				1.0E-8/h-ft(10) [3]
Rupture (external)				1.0E-7/h-ft(10) [3]
Plugs				1.0E-7/h-ft(10) [3]
Jumper Leakage (external)				1.0E-5/h(10) [3]
Rupture (external)				1.0E-7/h(30) [3]
Plugs				1.0E-7/h(30) [3]
Tube Leakage (external)				3.0E-7/h-ft(10) [7]
Rupture (external)				1.0E-8/h-ft(30) [7]
Plugs				1.0E-8/h-ft(30) [7]
Vessel Tank (Pressurized) Leakage (external)		2.3E-7/h(10)		1.0E-7/h(10) [3]
Rupture (external)		7.5E-8/h(10)		5.0E-9/h(30) [3]
Cylinder (Pressurized) Leakage (external)				1.0E-7/h(10) [8]
Rupture (external)				5.0E-9/h(30) [8]
Flange Gasket Leakage (external)				1.0E-7/h(10) [3]
Rupture (external)				1.0E-9/h(10) [3]

Table 6c. Summary of results for compressed gas system.

System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Heat Exchanger Shell/Tube Fouling (tubes)				1.0E-5/h(10) [4]
Plugs (tubes)				3.0E-6/h(10) [4]
Leakage (tubes)		4.4E-5/h(1.8)		1.0E-5/h(10) [4]
Rupture (tubes)		8.5E-7/h(10) [1]		5.0E-7/h(30) [4]
Leakage (shell)				1.0E-6/h(10) [4]
Rupture (shell)				5.0E-8/h(30) [4]
Heater (Electrical) Fails to heat		1.0E-5/h(10) [1]		1.0E-6/h(10) [1]
Overheats				3.0E-7/h(10) [1]
Leakage (external)				1.0E-6/h(10) [3]
Rupture (external)				5.0E-8/h(30) [3]
Vaporizer Failure		1.4E-4/h(10)		1.0E-4/h(10)
Air Dryer Failure	5.8E-6/h(10) [1]	8.9E-6/h(10)	2.6E-7/h [1]	5.0E-6/h(10)
Filter Plugs		1.4E-5/h(1.3) [2]	3.4E-6/h(3.4) [2]	3.0E-6/h(10) [1]
Leakage (internal)		[2]	[2]	3.0E-6/h(10) [1]
Rupture (internal)		[2]	[2]	5.0E-7/h(10) [1]

Table 6c. Summary of results for compressed gas system.				
System/Component/Failure Mode	Failure Data (Category 1 Sources)[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Orifice Plugs		2.1E-6/h(10) [1]		1.0E-6/h(10) [1]

a. Aggregated failure rates are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

b. For the recommended failure rate, the Category 1 result was used if available. If not, then the Category 2 result was used. If no Category 1 or 2 results were available, the Category 3 result was used. (Exceptions to this are indicated in the notes.) Mean values were rounded to 1, 3, or 5 times the appropriate power of 10. Error factors were rounded to 3, 5, 10, or 30.

Notes

Category 1

1. Failure rate based on zero failures and may be conservatively high.

Category 2

1. Failure rate based on zero failures and may be conservatively high.

2. Failure modes not indicated.

Category 3

1. Failure rate based on zero failures and may be conservatively high.

2. Failure modes not indicated.

Recommended

1. Based on comparisons of (limited) compressed gas system data for component groups with the much more extensive water system data (Table 6a), the water system results are appropriate.

2. Based on comparisons of (limited) compressed gas system data for component groups with the much more extensive water system data (Table 6a), the water system results were multiplied by 3.

3. Based on comparisons of (limited) compressed gas system data for component groups with the much more extensive water system data (Table 6a), the water system results were multiplied by 10.

Table 6c. Summary of results for compressed gas system.

4. Based on comparisons of (limited) compressed gas system data for component groups with the much more extensive water system data (Table 6a), the water system results were multiplied by 100.

5. Similar to the water system results (Table 6a), overspeed was assumed to be one-fifth of fails to run.

6. Similar to the water system results (Table 6a), fails to stop was assumed to be comparable to fails to start.

7. Water system piping results were multiplied by 100.

8. Tank results used.

Table 6d. Summary of results for HVAC/exhaust system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
HVAC/Exhaust Damper (Standby or Safety) Manual Fails to open/close				3.0E-3/d(10) [2]
Plugs				5.0E-7/h(10) [2]
Leakage (internal)				1.0E-5/h(10) [2]
Rupture (internal)				5.0E-7/h(30) [2]
Leakage (external)				1.0E-7/h(10) [2]
Rupture (external)				5.0E-9/h(30) [2]
Motor-Operated Fails to open/close				3.0E-2/d(10) [2]
Spurious operation				3.0E-6/h(10) [2]
Plugs				5.0E-7/h(10) [2]
Leakage (internal)				1.0E-5/h(10) [2]
Rupture (internal)				5.0E-7/h(10) [2]
Leakage (external)				1.0E-7/h(10) [2]
Rupture (external)				5.0E-9/h(30) [2]
Air-Operated Fails to open/close	9.9E-3/d(6.1)		1.2E-6/h [1]	1.0E-2/d(30) [2]

Table 6d. Summary of results for HVAC/exhaust system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Spurious operation	8.2E-6/h(4.2)		[1]	1.0E-5/h(10) [2]
Plugs				5.0E-7/h(10) [2]
Leakage (internal)				1.0E-5/h(10) [2]
Rupture (internal)				5.0E-7/h(10) [2]
Leakage (external)				1.0E-7/h(10) [2]
Rupture (external)				5.0E-9/h(30) [2]
Damper (Control) Motor-Operated Fails open				3.0E-6/h(10) [1]
Fails closed				3.0E-6/h(10) [1]
Fails to respond				3.0E-6/h(10) [1]
Plugs				5.0E-7/h(10) [2]
Leakage (external)				1.0E-7/h(10) [2]
Rupture (external)				5.0E-9/h(30) [2]
Air-Operated Fails open		8.0E-6/h(10) [2]		3.0E-6/h(10) [1]
Fails closed		[2]		3.0E-6/h(10) [1]
Fails to respond		9.0E-7/h(10)		3.0E-6/h(10) [1]

Table 6d. Summary of results for HVAC/exhaust system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates*			
	Category 1	Category 2	Category 3	Recommended*
Plugs				5.0E-7/h(10) [2]
Leakage (external)		4.1E-7/h(10)		1.0E-7/h(10) [2]
Rupture (external)		2.5E-7/h(10)		5.0E-9/h(30) [2]
Fan/Blower Motor-Driven Fails to start	4.4E-3/d(5.4)	3.3E-6/h(2.9)	2.1E-4/d(9.0), 5.0E-6/h(12)	5.0E-3/d(5)
Fails to run	2.9E-5/h(2.4)	5.0E-6/h(2.8)	5.0E-6/h(12)	3.0E-5/h(3)
Overspeed		6.5E-7/h(1.9)		5.0E-6/h(10) [4]
Fails to stop		3.6E-6/h(10)		5.0E-3/d(10) [5]
Leakage (external)		5.5E-8/h(10) [1]		3.0E-7/h(10) [2]
Rupture (external)				1.0E-8/h(30) [2]
Diesel-Driven Fails to start				1.0E-2/d(10) [1]
Fails to run				5.0E-3/h(10) [1]
Overspeed				1.0E-3/h(10) [1]
Fails to stop				1.0E-2/d(10) [1]
Leakage (external)				3.0E-7/h(10) [2]
Rupture (external)				1.0E-8/h(10) [2]

Table 6d. Summary of results for HVAC/exhaust system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Ducting Leakage (external)				3.0E-7/h-ft(10) [3]
Rupture (external)				1.0E-8/h-ft(30) [3]
Plugs				1.0E-8/h-ft(30) [3]
Heat Exchanger Air Conditioning Unit/ Chiller Fails to start	1.4E-2/d(10)		1.0E-5/h(9.7) [1]	1.0E-2/d(10)
Fails to run	2.4E-5/h(10)		[1]	3.0E-5/h(10)
Fan Cooler Unit Fails to start	8.4E-3/d(7.2)			1.0E-2/d(5)
Fails to run	8.8E-6/h(2.9)	3.6E-6/h(10)		1.0E-5/h(3)
Heater (Electrical) Fails to heat		8.4E-7/h(2.6)		1.0E-6/h(3)
Overheats		1.6E-7/h(10)		3.0E-7/h(10) [6]
Heater (Gas) Fails to heat		8.2E-4/h(10)		1.0E-3/h(10)
Overheats		1.7E-5/h(10)		3.0E-4/h(10) [6]
Filter Normal Plugs		1.4E-6/h(5)		3.0E-6/h(10) [1]
Leakage (internal)		1.8E-6/h(5)		3.0E-6/h(10) [1]
Rupture (internal)		7.0E-7/h(5)		5.0E-7/h(10) [1]
Low-Efficiency Plugs				3.0E-6/h(10) [7]

Table 6d. Summary of results for HVAC/exhaust system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Leakage (internal)				3.0E-6/h(10) [7]
Rupture (internal)				5.0E-7/h(10) [7]
HEPA Plugs				3.0E-6/h(10) [7]
Leakage (internal)				3.0E-6/h(10) [7]
Rupture (internal)				5.0E-7/h(10) [7]
Sand Plugs				3.0E-6/h(10) [7]
Leakage (internal)				3.0E-6/h(10) [7]
Rupture (internal)				5.0E-7/h(10) [7]
Baghouse Plugs			8.6E-4/h	3.0E-5/h(10) [8]
Leakage (internal)				3.0E-5/h(10) [8]
Rupture (internal)				5.0E-6/h(10) [8]
Miscellaneous Mist Eliminator Failure			1.1E-4/h	1.0E-4/h(10)
Scrubber Failure		3.2E-7/h(10)	2.0E-4/h	1.0E-6/h(10) [9]
Precipitator Failure			4.6E-5/h	5.0E-5/h(10)

Table 6d. Summary of results for HVAC/exhaust system.

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a. Aggregated failure rates are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

b. For the recommended failure rate, the Category 1 result was used if available. If not, then the Category 2 result was used. If no Category 1 or 2 results were available, the Category 3 result was used. (Exceptions to this are indicated in the notes.) Mean values were rounded to 1, 3, or 5 times the appropriate power of 10. Error factors were rounded to 3, 5, 10, or 30.

Notes

Category 2

1. Failure rate based on zero failures and may be conservatively high.

Category 3

1. Failure modes not indicated.

Recommended

1. Water system results used as appropriate.
2. Based on comparisons of (limited) HVAC/exhaust system data for component groups with the much more extensive water system data for comparable component groups (Table 6a), the water system results were multiplied by 10.
3. Water system piping results were multiplied by 100.
4. Similar to the water system results (Table 6a), overspeed was assumed to be one-fifth of fails to run.
5. Similar to the water system results (Table 6a), fails to stop was assumed to be comparable to fails to start.
6. Similar to the water system results (Table 6a), overheats was assumed to be one-fifth as likely as fails to heat.
7. Normal filter results were used.
8. Based on the Category 3 information, the normal filter results were multiplied by 10.
9. Based on the Category 3 information, the Category 2 result (limited data) was increased.

Table 6e. Summary of results for electrical distribution system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Electric Power Generator Diesel-Driven Fails to start	1.3E-2/d(2.2)	3.9E-3/d(3.0), 4.1E-5/h(3)	3.1E-2/d(11)	1.0E-2/d(3)
Fails to run	4.1E-3/h(3.3)	9.7E-3/d(3.1), 1.9E-4/h(1.2)	4.2E-3/h(24)	5.0E-3/h(3)
Motor-Driven (ac to dc) Fails to start		1.4E-5/h(10)	1.8E-7/h(4.5)	1.0E-5/h(10)
Fails to run	2.1E-5/h(10)	7.8E-6/h(10)	3.3E-7/h(4.3)	3.0E-5/h(10)
Gas-Turbine-Driven Fails to start	3.8E-2/d(10)	1.1E-2/d(3.0), 9.9E-6/h(8.4)	9.5E-5/h(25)	3.0E-2/d(10)
Fails to run	2.6E-4/h(10)	2.4E-5/h(8.7)	3.4E-4/h(25)	3.0E-4/h(10)
Hydro-Turbine-Driven Fails to start	3.1E-3/d(10)			3.0E-3/d(10)
Fails to run				3.0E-4/h(10) [1]
Battery Failure	8.0E-3/d(1.2), 8.4E-6/h(3.7)	6.9E-7/h(10)	4.7E-6/h(7.0)	1.0E-5/h(3)
Charger Rectifier Failure	1.8E-5/h(1.7)	4.6E-6/h(2.5)	4.2E-6/h(3.8)	1.0E-5/h(3)
Bus Metal-Enclosed Failure	1.1E-7/h(10)		1.3E-7/h(5)	1.0E-7/h(5)
Bare Failure			8.7E-7/h(12)	1.0E-6/h(10)
Cable/Joint/ Termination/Jumper Cable (Copper, 1000ft) Failure			4.5E-6/h(7.4), 3.8E-6/h(3)	3.0E-6/h(3)

Table 6e. Summary of results for electrical distribution system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Joint (Copper) Failure			3.2E-6/h(30)	3.0E-6/h(30)
Termination (Copper) Failure			2.6E-7/h(18)	3.0E-7/h(10)
Jumper (Power) Failure				5.0E-6/h(10) [2]
Circuit Breaker General Fails to open/close	5.6E-4/d(4.5)	4.0E-4/d(1.4), 4.8E-7/h(4.8)	1.3E-3/d(13)	5.0E-4/d(5)
Spurious operation	3.8E-7/h(10)	1.9E-7/h(4.8)	2.8E-6/h(20)	3.0E-7/h(10)
Reactor Trip Fails to open				5.0E-3/d(5) [3]
Spurious operation				3.0E-6/h(10) [3]
Relay Protective Fails to open/close	1.2E-3/d(10)	4.2E-8/h(10)	7.1E-5/d(16), 1.9E-6/h(1.1)	1.0E-3/d(10)
Spurious operation		1.7E-7/h(10)	1.8E-7/h(13)	1.0E-7/h(10)
Control Fails to open/close			7.2E-6/d(1.4)	1.0E-4/d(10) [4]
Spurious operation			3.4E-7/h(30)	3.0E-7/h(30)
Bistable Fails to open/close				1.0E-5/d(10) [3]
Spurious operation				3.0E-7/h(10) [3]
Switch Push Button (Manual) Fails to open/close		1.9E-6/h(10)	1.3E-3/d(3), 1.8E-6/h(15)	1.0E-6/h(10)
Spurious operation		1.8E-6/h(10)	2.6E-7/h(12)	1.0E-6/h(10)

Table 6a. Summary of results for electrical distribution system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates*			
	Category 1	Category 2	Category 3	Recommended*
Rotary (Manual) Fails to open/close		6.0E-8/h(10)	3.1E-7/h(2)	5.0E-8/h(10)
Spurious operation		5.0E-7/h(10)	1.9E-7/h(2)	5.0E-7/h(10)
Key-Operated (Manual) Fails to open/close		3.9E-7/h(10)	2.3E-6/h [1]	3.0E-7/h(10)
Spurious operation		1.8E-6/h(10)	[1]	1.0E-6/h(10)
Automatic-Transfer Fails to open/close	2.0E-2/d(10)			1.0E-6/h(10) [5]
Spurious operation				1.0E-6/h(10)
Limit Fails to open/close	4.0E-5/d(10), 9.2E-7/h(10)		3.8E-4/d(3), 6.0E-6/h(1.6)	1.0E-6/h(10)
Spurious operation			1.7E-6/h(5.1)	1.0E-6/h(5)
Fuse Fail to open		1.2E-7/h(10)	1.3E-5/d(3), 3.5E-6/h(10)	1.0E-7/h(10)
Premature opening		1.6E-8/h(10)	1.1E-6/h(6.1)	1.0E-8/h(10)
Inverter Failure	7.9E-3/d(10), 1.2E-5/h(1.9)	1.8E-5/h(6.9)	2.6E-5/h(12)	1.0E-5/h(3)
Motor AC Fails to start		1.5E-5/h(3.4)	3.8E-4/d(3), 1.8E-5/h(17)	3.0E-4/d(3) [6]
Fails to run		6.0E-6/h(3.3)	2.4E-5/h(1.7)	5.0E-6/h(3)
DC Fails to start		2.1E-5/h(3.0)	3.8E-4/d(3), 1.8E-5/h(8.4)	3.0E-4/d(3) [6]
Fails to run		8.5E-6/h(2.8)	2.4E-5/h(8.4)	1.0E-5/h(3)
Synchro Failure		1.4E-5/h(10)		1.0E-5/h(10)
Transformer Power Failure	8.2E-7/h(10)	3.5E-7/h(10)	1.4E-6/h(5.6)	1.0E-6/h(10)

Table 6a. Summary of results for electrical distribution system.				
System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Instrumentation/Control Failure	8.9E-7/h(10)		3.8E-7/h(2.8)	1.0E-6/h(10)

a. Aggregated failure rates are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

b. For the recommended failure rate, the Category 1 result was used if available. If not, then the Category 2 result was used. If no Category 1 or 2 results were available, the Category 3 result was used. (Exceptions to this are indicated in the notes.) Mean values were rounded to 1, 3, or 5 times the appropriate power of 10. Error factors were rounded to 3, 5, 10, or 30.

Notes

Category 3

1. Failure modes not indicated.

Recommended

1. Gas turbine results used.
2. Jumper modeled as 2 electrical joints. Therefore, the joint result was multiplied by 2.
3. Estimate taken from Reference 35, Table 4.
4. Based on Category 3 estimate, multiply the protective relay result by 10.
5. Category 1 data include only 1 failure and very few demands. The highest result from the other switches was used.
6. Per demand result is desired. The Category 3 per hour estimate is similar to the Category 2 estimate (from data), so the Category 3 per demand estimate was assumed to be appropriate.

Table 6f. Summary of results for instrumentation and control system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[a]
Instrumentation and Control		3.6E-5/h(10)	1.5E-6/h(15)	3.0E-5/h(10)
Alarm/Annunciator				
Fails to alarm				
Spurious operation		4.7E-6/h(10)	8.7E-7/h(15)	5.0E-6/h(10)
Sensor/Transmitter/ Transducer/Process Switch	2.8E-4/d(3.5), 1.1E-6/h(3.3)	8.6E-7/h(7.9)	8.1E-6/h(14)	1.0E-6/h(3)
Temperature				
Failure				
Pressure	2.8E-4/d(3.5), 1.1E-6/h(3.3)	8.3E-7/h(3.1)	6.8E-6/h(17)	1.0E-6/h(3)
Failure				
Differential Pressure		2.7E-6/h(10)	1.2E-4/h(16)	3.0E-6/h(10)
Failure				
Flow		2.9E-6/h(2.0)	3.2E-5/h(15)	3.0E-6/h(3)
Failure				
Level		5.3E-7/h(3.7)	6.4E-6/h(7.7)	5.0E-7/h(3)
Failure				
Humidity		1.2E-5/h(10)	4.2E-6/h(3.9)	1.0E-5/h(10)
Failure				
pH			5.8E-7/h(5.0)	5.0E-7/h(5)
Failure				
Oxygen Concentration		9.5E-6/h(10)		1.0E-5/h(10)
Failure				
CO_2 Concentration			9.8E-5/h(10)	1.0E-4/h(10)
Failure				
Hydrogen Concentration				1.0E-5/h(3) [1]
Failure				
Nitrogen Concentration				1.0E-5/h(3) [1]
Failure				
Hydrocarbon Concentration		7.9E-6/h(2.2)		1.0E-5/h(3)
Failure				

Table 6f. Summary of results for instrumentation and control system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Helium Concentration Failure				1.0E-5/h(3) [1]
Speed Failure			1.7E-6/h(8.1)	1.0E-6/h(10)
Seismic Failure			1.6E-6/h(4)	1.0E-6/h(5)
Radiation Failure			6.3E-6/h(4.7)	5.0E-6/h(5)
Indicator Failure		1.5E-5/h(10)	1.1E-4/h(22)	1.0E-5/h(10)
Amplifier Failure				5.0E-6/h(10) [2]
Modifier/Signal Conditioner Failure			3.3E-7/h(2.1)	3.0E-7/h(3)
Logic Module Failure			3.7E-6/h(7.7)	3.0E-6/h(5)
Recorder Failure			3.8E-5/h(22)	3.0E-5/h(30)
Sampler Failure		1.2E-5/h(10)		1.0E-5/h(10)
Analyzer Failure		6.0E-6/h(10)	1.3E-3/h(26)	5.0E-6/h(10)
Timer Failure				5.0E-6/h(10) [3]
Gas Chromatograph Failure		7.3E-5/h(10)		5.0E-5/h(10)
Voltage Regulator Failure		3.2E-6/h(10)		3.0E-6/h(10)
Transmitter Failure	2.2E-6/h(1.4)		1.0E-5/h(30)	3.0E-6/h(10)

Table 61. Summary of results for instrumentation and control system.

System/Component/Failure Mode	Aggregated and Recommended Failure Rates[a]			
	Category 1	Category 2	Category 3	Recommended[b]
Transducer Failure		9.2E-7/h(10)	6.3E-5/h(15)	1.0E-6/h(10)
Programmable Logic Controller Failure		3.2E-5/h(10)		3.0E-5/h(10)

a. Aggregated failure rates are mean and error factor (in parentheses). The error factor is the 95th percentile/50th percentile.

b. For the recommended failure rate, the Category 1 result was used if available. If not, the Category 2 result was used. If no Category 1 or 2 results were available, the Category 3 result was used. (Exceptions to this are indicated in the notes.) Mean Values were rounded to 1, 3, or 5 times the appropriate power of 10. Error factors were rounded to 3, 5, 10, or 30.

Notes

Recommended

1. O_2 result used.

2. Result obtained from Reference 35, Table 4.

3. Representative estimate, based on the other results in the table.

Table 7. Naming scheme component codes.

Code	Component
ACU	Air conditioning unit/chiller
ADR	Air dryer
AGI	Agitator
ALR	Alarm/annunciator
AMP	Amplifier
ANA	Analyzer
AOD	Air-operated damper
AOV	Air-operated valve
ATS	Automatic transfer switch
BAG	Baghouse filter
BAT	Battery
BUB	Bus, bare
BUM	Bus, metal-enclosed
CAD	Control damper, air-operated
CAV	Control valve, air-operated
CBL	Cable
CBR	Circuit breaker
CKV	Check valve
CMD	Control damper, motor-operated
CMV	Control valve, motor-operated
COC	CO_2 concentration sensor/transmitter/ transducer/switch
CSV	Control valve, solenoid-operated
CTF	Centrifuge
DCT	Duct
DDF	Diesel-driven fan
DDG	Diesel-driven generator
DPS	Differential pressure sensor/transmitter/ transducer/switch
DST	Density sensor/transmitter/ transducer/switch
EXV	Explosive valve
FCU	Fan cooler unit
FLG	Flange
FLL	Filter, low-efficiency
FLS	Filter, sand
FLT	Filter
FST	Flow sensor/transmitter/ transducer/switch
FUS	Fuse
GCR	Gas chromatograph
GTG	Gas-turbine-driven generator
HCC	Hydrocarbon concentration sensor/ transmitter/transducer/switch
HDG	Hydro-turbine-driven generator
HEC	Helium concentration sensor/transmitter/ transducer/switch
HOS	Hose
HPA	HEPA filter
HST	pH sensor/transmitter transducer/switch
HTE	Heater, electrical
HTG	Heater, gas
HTX	Heat exchanger
HYC	Hydrogen concentration sensor/transmitter/ transducer/switch
IND	Indicator
INV	Inverter
JNT	Joint
JPR	Jumper
LMS	Limit switch
LOG	Logic module
LST	Level sensor/transmitter/ transducer/switch
MDC	Motor-driven compressor
MDF	Motor-driven fan
MDG	Motor-driven generator
MDP	Motor-driven pump
MIX	Mixer/blender
MOD	Motor-operated damper
MOV	Motor-operated valve
MRA	Motor, ac
MRD	Motor, dc
MTE	Mist eliminator
NIC	Nitrogen concentration sensor/transmitter/ transducer/switch
ORF	Orifice
OXC	Oxygen concentration sensor/transmitter/ transducer/switch
PCP	Precipitator
PIP	Pipe
PLC	Programmable logic controller
PST	Pressure sensor/transmitter/ transducer/switch
RCT	Rectifier
REC	Recorder
RLC	Relay, control
RLP	Relay, protective
RST	Radiation sensor/transmitter/ transducer/switch
SAM	Sampler
SBR	Scrubber
SCR	Modifier/signal conditioner
SET	Seismic sensor/transmitter/ transducer/switch
SOV	Solenoid-operated valve
SRV	Safety relief valve
SST	Speed sensor/transmitter/ transducer/switch
SYN	Synchro
TFI	Transformer, instrumentation and control
TFP	Transformer, power
TKP	Tank, pressurized
TKU	Tank, unpressurized
TMN	Termination
TMR	Timer
TRO	Transducer
TRM	Transmitter
TRS	Traveling screen
TST	Temperature sensor/transmitter/ transducer/switch
TUB	Tube
UST	Humidity sensor/transmitter/ transducer/switch
VAP	Vaporizer
VBV	Vacuum breaker valve
VRG	Voltage regulator
XDM	Manual damper
XSK	Manual switch, key-operated
XSP	Manual switch, push-button
XSR	Manual switch, rotary
XVM	Manual valve

Table 8. Naming scheme failure mode codes.

Code	Failure Mode
CC	Fails to open (closed, fails closed)
CO	Spurious opening (closed, fails open)
FA	Failure (no specific failure mode implied)
FC	Fails closed (only for control valves and dampers)
FL	Fouling
FH	Fails to heat
FO	Fails open (only for control valves and dampers)
FR	Fails to run
FS	Fails to start
LE	Leak (external)
LI	Leak (internal)
NR	No response (upon demand)
NS	Fails to stop
OC	Spurious closing (open, fails closed)
OH	Overheats
OO	Fails to close (open, fails open)
OS	Overspeed
PG	Plug
RE	Rupture (external)
RI	Rupture (internal)
SO	Spurious operation

Table 9. Naming scheme system codes.

Code	Type of System
C	Chemical process
E	Electrical distribution
G	Compressed gas
H	HVAC/exhaust
I	Instrumentation and control
W	Water

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