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Enhanced Component Performance Study: Emergency Diesel Generators 1998–2022

July 2023

Zhegang Ma
Regulatory Support, Idaho National Laboratory

Idaho National Laboratory

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Idaho National Laboratory
Regulatory Support Department
Idaho Falls, Idaho 83415

http://www.inl.gov

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ABSTRACT

This report presents an enhanced performance evaluation of the emergency power system (EPS) and high-pressure core spray (HPCS) emergency diesel generators (EDGs) at U.S. commercial nuclear power plants. This report evaluates component performance over time using (1) Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS) data from 1998 through 2022 and (2) maintenance unavailability performance data from Mitigating Systems Performance Index (MSPI) Basis Document data from 2002 through 2022. The objective is to show estimates of current failure probabilities and rates related to EDGs, trend these data on an annual basis, determine if the current data are consistent with the probability distributions currently recommended for use in Nuclear Regulatory Commission (NRC) probabilistic risk assessments, show how the reliability data differ for different EDG manufacturers and for EDGs with different ratings; and summarize the subcomponents, causes, detection methods, and recovery associated with each EDG failure mode. The EDG failure modes considered are fail to start (FTS), fail to load and run (FTLR), and fail to run after one hour of operation (FTR>1H). Engineering analyses were performed with respect to time-period and failure mode without regard to the actual number of EDGs at each plant. The factors analyzed include subcomponent, failure cause, detection method, recovery, manufacturer, and EDG rating.

The following increasing trends were identified for EDGs for the most recent 10-year period:

- HPCS EDG FTS failure probability
- EPS and HPCS EDG frequency of start demands (demands per reactor year)
- EPS and HPCS EDG frequency of FTLR demands.

The following decreasing trends were identified for EDGs for the most recent 10-year period:

- EPS EDG FTS failure probability
- EPS EDG FTLR failure probability
- EPS EDG unavailability
- EPS and HPCS EDG frequency of FTLR events (failures per reactor year).

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ACRONYMS

AOV	air-operated valve
CCF	common-cause failure
CNID	constrained noninformative prior distribution
EDG	emergency diesel generator
EPIX	Equipment Performance and Information Exchange
EPS	emergency power supply
ESF	engineered safety feature
FTLR	fail to load and run
FTR	fail to run
FTR>1H	fail to run after one hour of operation
FTS	fail to start
HPCS	high-pressure core spray
ICES	INPO Consolidated Events Database
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
IRIS	Industry Reporting and Information System
LOOP	loss-of-offsite-power
MDP	motor-driven pump
MOV	motor-operated valve
MSPI	Mitigating Systems Performance Index
NPRDS	Nuclear Plant Reliability Data System
NRC	Nuclear Regulatory Commission
OLS	ordinary least squares
PMT	post maintenance testing
PRA	probabilistic risk assessment
SPAR	standardized plant analysis risk
TDP	turbine-driven pump
UA	unavailability

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Enhanced Component Performance Study: Emergency Diesel Generators 1998–2022

1. INTRODUCTION

This report presents an enhanced performance evaluation of emergency diesel generators (EDGs) at U.S. commercial nuclear power plants from 1998 through 2022. The objective is to show estimates of current failure probabilities and rates related to EDGs, trend these data on an annual basis, determine if the current data are consistent with the probability distributions currently recommended for use in NRC probabilistic risk assessments, show how the reliability data differ for different EDG manufacturers and for EDGs with different ratings; and summarize the subcomponents, causes, detection methods, and recovery associated with each EDG failure mode. This year's update continues with the three changes implemented in the 2016 update that are different from prior updates: (1) the update results are based on calendar year instead of the federal fiscal year, (2) the failure events included in the update are "hard" failures (i.e., the p-values indicating the likelihood the component would have failed during a 24-hour mission are 1.0). Previous updates (2015 and before) included lesser p-values indicating a degraded condition that probably would have caused failure during a 24-hour mission but were not quite hard failures at their outset, and (3) the discussion of EDG repair times, which was previously included in the annual loss-of-offsite-power (LOOP) updates (see https://nrcoe.inl.gov/LOSP/), is included in the EDG update.

The enhanced component performance studies are conducted for the following component types: air-operated valves (AOVs), EDGs, motor-driven pumps (MDPs), motor-operated valves (MOVs), and turbine-driven pumps (TDPs). The EDG performance analysis was first conducted in 2007 with data from 1998 through 2006 [1] and then updated annually in a series of reports, with the last one being documented in INL/RPT-22-66601, *Enhanced Component Performance Study: Emergency Diesel Generators 1998-2020* [2]. The Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases webpage provides the link to the historical and current results of component performance studies (http://nrcoe.inl.gov/CompPerf). An overview of the trending methods, glossary of terms, and abbreviations is documented in the paper *Overview and Reference* [3] that can also be found from https://nrcoe.inl.gov/.

The data used in this study are based on the operating experience failure reports from Institute of Nuclear Power Operations (INPO) *Industry Reporting and Information System (IRIS)* [4], formerly the Equipment Performance and Information Exchange Database (EPIX) and INPO Consolidated Events Database (ICES) [5]. Maintenance unavailability (UA) performance data came from the Reactor Oversight Process program's Mitigating Systems Performance Index (MSPI) program and IRIS [6]. Previously, the study relied on operating experience obtained from licensee event reports, Nuclear Plant Reliability Data System (NPRDS), and EPIX. The IRIS database (which includes the MSPI designated devices as a subset) has matured to the point where both component availability and reliability can be estimated with a high degree of accuracy.

The EDG failure modes considered are fail to start (FTS), fail to load and run (FTLR), and fail to run after one hour of operation (FTR>1H). Annual failure probabilities (failures per demand) are provided for FTS and FTLR events and annual failure rates (failures per run hour) are provided for FTR>1H events. EDG train maintenance unavailability probabilities are also considered. In addition to the presentation of the component failure mode data and the UA data, an 8-hour component total unreliability is calculated and trended. Each of the estimates is trended for the most recent 10-year period. Yearly estimates have been provided for the entire study period. The results are reported separately for emergency power system (EPS) and high-pressure core spray (HPCS) EDGs.

While this report provides an overview of operational data and evaluates component performance over time, it makes no attempt to estimate values for use in probabilistic risk assessments (PRAs) or Standardized Plant Analysis Risk (SPAR) models. The *2020 Parameter Update* documented in INL/EXT-21-65055 [7] is the most recent update to NUREG/CR-6928, *Industry-Average Performance for Components and Initiating Events at U.S Commercial Nuclear Power Plants* [8], using data through 2020 and provides component unreliability estimates for SPAR models. Estimates from that report are included herein for comparison. Those estimates are labelled "SPAR 2020" in the associated tables and figures.

Section 2 of this report presents the summary of findings from the study, with particular emphasis on the existence of any statistically significant increasing or decreasing trends in component performances. Section 3 provides the annual estimates of failure probabilities and rates related to EDGs as well as the trending of the estimates. Section 4 provides EDG train UA estimates and their trends (Sections 4.1 and 4.2), as well as the discussion of EDG repair times (Section 4.3). Section 5 provides the annual estimates of total unreliability (8-hour mission) and the trending of the estimates for EDGs.

Section 6 presents various engineering analyses performed for EDGs with respect to time and failure modes. In Section 6.1, the same failures used in Section 3 are used to compute estimates of overall failure frequencies per reactor year (with EPS and HPCS EDG failures combined). Frequencies of demands per plant reactor year are also provided for each year and for each of the possible failure modes. As in Section 3, each of the estimates is trended for the most recent 10-year period. The frequencies show general industry performances and are not based on the number of EDGs at each plant.

In Sections 6.2 through 6.4, various subsets of the EDG data are compared with the distributions currently recommended for PRA use in the *2020 Parameter Update*. First, the subset of failure events and demands from this report that occurred on unplanned demands (engineered safety feature [ESF] actuations) is compared for consistency with the *2020 Parameter Update* data. This evaluation provided a check on the ongoing use of the EDG data in the *2020 Parameter Update* (which includes failures from testing demands that raises the concern on whether the testing data could adequately predict EDG performance during unplanned demands). In Section 6.3, data from each EDG manufacturer is compared. Finally, in Section 6.4, EDG failure groupings based on EDG ratings are compared.

Section 6.5 provides breakdowns of the failures for each failure mode for the two plant systems with EDGs. The analyses are based on the following factors: subcomponent, failure cause, detection method, and recovery.

Section 7 provides additional information on the EDG assembly component boundaries and failure modes. Section 8 presents the plot data for various figures in previous sections.

2. SUMMARY OF FINDINGS

The results of this study are summarized in this section. Of particular interest is the existence of any statistically significant[a] increasing trends.

2.1 Increasing Trends

1.1.1 Extremely Statistically Significant

- An extremely statistically significant **increasing trend** was identified in the **frequency of start demands** (demands per reactor year) estimates for **EPS and HPCS EDGs** with a p-value of 0.0000 (see Figure 11). The same trend was observed in the *2020 EDG Update* study [2].
- An extremely statistically significant **increasing trend** in the **frequency of FTLR demands** estimates for **EPS and HPCS EDGs** was identified with a p-value of 0.0001 (see Figure 12). The same trend was observed in the *2020 EDG Update* study.

1.1.2 Highly Statistically Significant

- None.

1.1.3 Statistically Significant

- None.

2.2 Decreasing Trends

1.1.4 Extremely Statistically Significant

- None.

1.1.5 Highly Statistically Significant

- A highly statistically significant **decreasing trend** in the **EPS EDG UA** estimates was identified with a p-value of 0.0022 (see Figure 7). This is a new trend that was not observed in the *2020 EDG Update* study.
- A highly statistically significant **decreasing trend** in the **frequency of FTR > 1H events** estimates for **EPS and HPCS EDGs** was identified with a p-value of 0.0045 (see Figure 16). This is a new trend that was not observed in the *2020 EDG Update* study.

1.1.6 Statistically Significant

- A statistically significant **decreasing trend** in the **EPS EDG FTLR failure probability** estimates was identified with a p-value of 0.0199 (see Figure 2). The same trend was observed in the *2020 EDG Update* study as highly statistically significant.
- A statistically significant **decreasing trend** in the **frequency of FTLR events** estimates for **EPS and HPCS EDGs** was identified with a p-value of 0.0441 (see Figure 15). The same trend was observed in the *2020 EDG Update* study as highly statistically significant.

a. Statistically significant is defined in terms of the p-value. A p-value is a probability indicating whether to accept or reject the null hypothesis that there is no trend in the data. P-values of less than or equal to 0.05 indicate that we are 95% confident there is a trend in the data (reject the null hypothesis of no trend.) By convention, we use the Michelin Guide scale: p-value < 0.05 (statistically significant), p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant).

2.3 Consistency Check Results

An ongoing concern in the nuclear risk assessment field is whether industry failure rate estimates that are largely derived from test data adequately predict component performance during unplanned ESF demands. Section 6.2 provides results of a consistency check that compares industry failure estimates obtained via simulation tests on parameters from the *2020 Parameter Update* against operational failure counts obtained from actual EDG performance with ESF demands. These consistency checks show that the FTS, FTLR, and FTR>1H failure observations in the non-test, operational ESF demand data lie within the corresponding industry-average failure estimate distributions, provided in the *2020 Parameter Update* (Table 2) that were based on both test and actual non-test operational ESF demands.

Section 6.3 provides the results of consistency checks by EDG manufacturer. Two manufacturer's ESF EPS EDG failure counts lie in the upper 95% of the uncertainty range of the industry-average estimate. However, these manufacturers have very few EPS EDGs, and so the data are limited. The remaining manufacturers' failure counts lie within the 5% to 95% interval of the industry-average estimate uncertainty band.

Section 6.4 shows the results of the consistency check by EDG load rating. The failure counts by rating all lie within the 5% to 95% interval of the industry-average estimate uncertainty band.

3. FAILURE PROBABILITIES AND FAILURE RATES

3.1 Overview

The failure probabilities and failure rates of EDGs have been calculated from the operating experience for FTS, FTLR, and FTR>1H. The EDG data set obtained from IRIS includes EDGs in the systems listed in Table 1. Table 2 shows failure probability and failure rate estimates for the EPS EDG from the *2020 Parameter Update* [7] for reference. Table 3 shows the failure probability and failure rate estimates from the *2020 Parameter Update* for the HPCS EDG, also for reference.

Table 1. EDG systems.

System	Description	EDG Count
EPS	Emergency power supply	234
HPCS	High-pressure core spray	8
	Total	242

The EDGs do not operate all the time. They are standby components required to operate when called upon, both when the reactor is critical and during shutdown periods. The demands and run hours are reported on a quarterly or semi-annual basis through the MSPI program. All demand types are considered—testing, non-testing, and those ESF demands that require the EDG to mitigate a bus under-voltage condition.

Table 2. Industry-wide distributions of p (failure probability) and λ (hourly rate) in the *2020 Parameter Update* for EPS EDGs [7].

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTS	1.53E-3	2.19E-3	2.22E-3	3.02E-3	Beta	23.80	1.07E+04
FTLR	1.05E-3	3.01E-3	3.31E-3	6.60E-3	Gamma	3.61	1.09E+03
FTR>1H	3.90E-4	1.08E-3	1.18E-3	2.31E-3	Gamma	3.83	3.25E+03

Table 3. Industry-wide distributions of p (failure probability) and λ (hourly rate) in the *2020 Parameter Update* for HPCS EDGs [7].

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTS	7.87E-4	1.97E-3	2.13E-3	4.00E-3	Beta	4.50	2.11E+03
FTR	2.58E-4	7.55E-4	8.34E-4	1.67E-3	Gamma	3.50	4.20E+03

3.2 EDG Failure Probability and Failure Rate Trends

This section estimates industry-wide annual failure probabilities and failure rates for EDGs in the entire study period which covers 1998 through 2022. The estimates are trended for the most recent 10-year period.

The failure probability and failure rate estimates in this section were obtained from a Bayesian update process. The means from the posterior distributions were plotted for each year. The 5th and 95th percentiles from the posterior distributions are also provided and give an indication of the relative uncertainty in the estimated parameters from year to year. When there are no failures, the interval is larger than the interval for years when there are one or more failures because of the form of the posterior variance. Each update utilizes a relatively "flat" constrained noninformative prior distribution (CNID) which has wide bounds [3, 9]. CNID is a compromise between an informative prior and the Jeffreys noninformative prior. The mean of the CNID uses prior belief and is based on a pooling of the component or event type data for the years going into the plot (i.e., the most recent 10-year period), but the dispersion is defined to correspond to little information (i.e., relatively flat by set) so that the prior distributions do not create large changes in the data.

For **failure rates** or Poisson data, the CNID is a gamma distribution, with the mean (μ) given by prior belief and calculated as:

$$\mu = \frac{\sum f_i + 0.5}{\sum T_i} \tag{1}$$

where f_i and T_i are the failures and operating/standby time for the i^{th} year, respectively. The CNID shape parameter (α) is a constant number of 0.5. The posterior distribution mean for the i^{th} year (μ_i) can be calculated as:

$$\mu_i = \frac{f_i + 0.5}{\frac{0.5}{\mu} + T_i} \tag{2}$$

For **failure probabilities** or binomial data, the CNID is a beta distribution, with the mean given by prior belief and calculated as:

$$\mu = \frac{\sum f_i + 0.5}{\sum D_i + 1} \tag{3}$$

where f_i and D_i are the failures and demands for the i^{th} year, respectively. The CNID shape parameter (α) is a number between 0.3 and 0.5 based on the mean μ (see Table C.8 of [9]). The posterior distribution mean for the i^{th} year (μ_i) can be calculated as:

$$\mu_i = \frac{f_i + \alpha}{\frac{\alpha}{\mu} + D_i} \tag{4}$$

The horizontal curves plotted around the regression lines in the graphs form 90% simultaneous confidence bands for the fitted lines. The bounds are larger than ordinary confidence bands for the individual coefficients because they form a confidence band for the entire line. In the lower left-hand corner of the trend figures, the regression p-values are reported. They come from a statistical test to assess evidence against the slope of the regression line being zero. Low p-values indicate strong evidence that the slopes are not zero and, therefore, suggest a trend does exist. P-values of less than or equal to 0.05 indicate strong evidence that there is a trend in the data (reject the null hypothesis of no trend). By convention, this study uses the Michelin Guide scale: p-value < 0.05 (statistically significant), p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant).

The regression methods are all based on ordinary least squares (OLS), which minimize the residuals or the square of the vertical distance between the annual data points and the fitted regression line. The p-values assume normal distributions for the residuals, with the same variability in the residuals across the years. In the case where the data involve failure counts, the iterative reweighted least squares method is used to account for the fact that count data are not expected to have a constant variance (for example, the variance for Poisson-distributed counts is equal to the expected number of counts, which is expected to vary proportionally to the expected number of counts). Further information on the trending methods is provided in Section 2 of *Overview and Reference* [3].

A final feature of the trend graphs includes the baseline industry values from the *2020 Parameter Update* (see Table 2) which are shown as “SPAR 2020” in the graphs for comparison.

Figure 1 to Figure 6 provide the plots for industry-wide failure probabilities/rates of EPS and HPCS EDGs. The data for these plots are provided in Section 8:

- Figure 1 shows the failure probability estimate trends for EPS EDG FTS
- Figure 2 shows the failure probability estimate trends for EPS EDG FTLR
- Figure 3 shows the failure rate estimate trends for EPS EDG FTR>1H
- Figure 4 shows the failure probability estimate trends for HPCS EDG FTS
- Figure 5 shows the failure probability estimate trends for HPCS EDG FTLR
- Figure 6 shows the failure rate estimate trends for HPCS EDG FTR>1H

The following trends were identified for EPS or HPCS EDG failure probabilities/rates for FTS, FTLR, and FTR>1H events in the most recent 10-year period:

- **Increasing trend** in the **HPCS EDG FTS failure probability** estimates, which is statistically significant with a p-value of 0.0235 (see Figure 4). This is a new trend that was not observed in the *2020 EDG Update* study
- **Decreasing trend** in the **EPS EDG FTS failure probability** estimates, which is statistically significant with a p-value of 0.0215 (see Figure 1). This is a new trend that was not observed in the *2020 EDG Update* study
- **Decreasing trend** in the **EPS EDG FTLR failure probability** estimates, which is highly statistically significant with a p-value of 0.0062 (see Figure 2). This is a new trend that was not observed in the *2020 EDG Update* study.

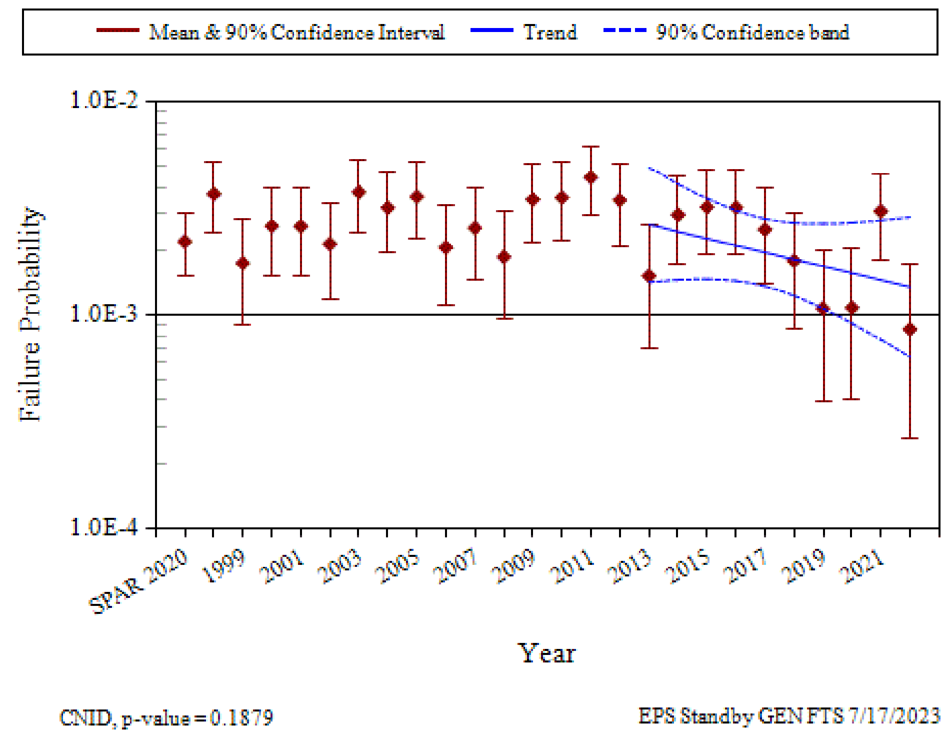

Figure 1. Failure probability estimate trend for EPS EDG FTS.

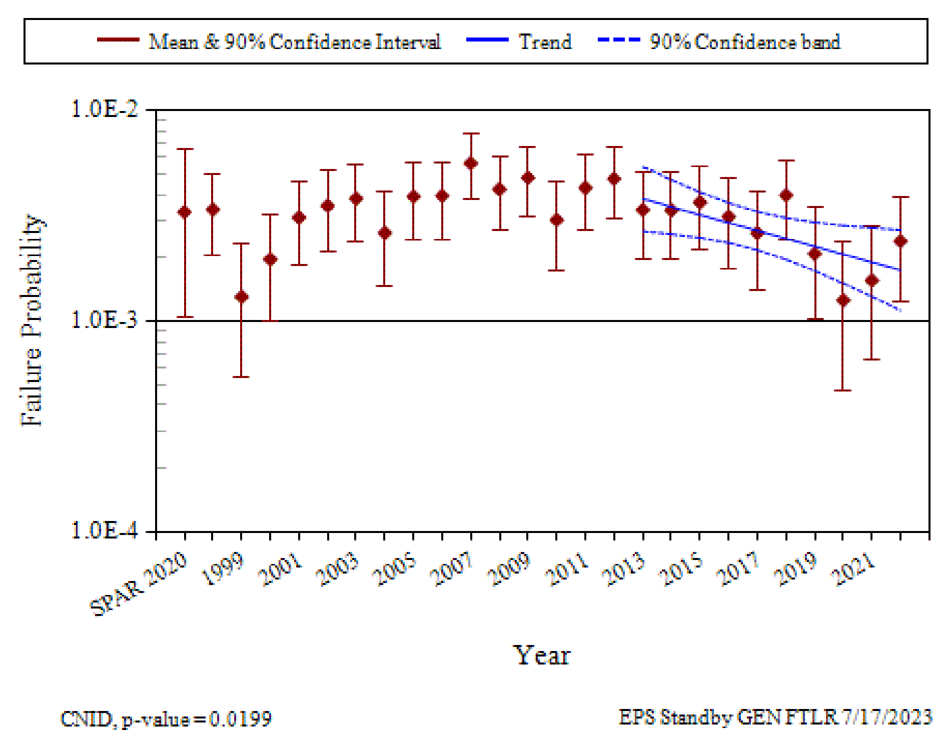

Figure 2. Failure probability estimate trend for EPS EDG FTLR.

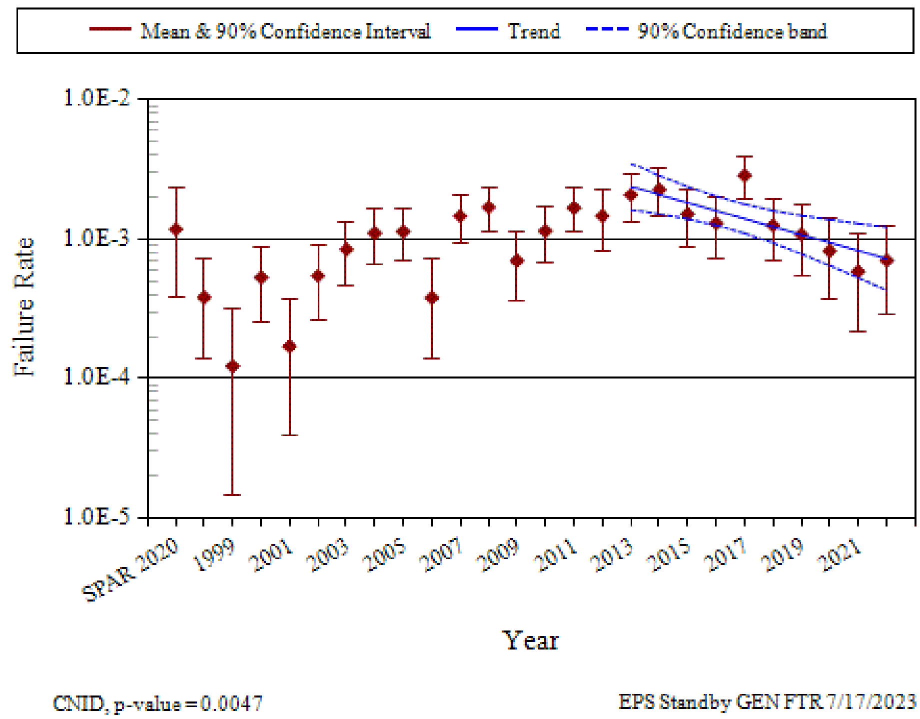

Figure 3. Failure rate estimate trend for EPS EDG FTR>1H.

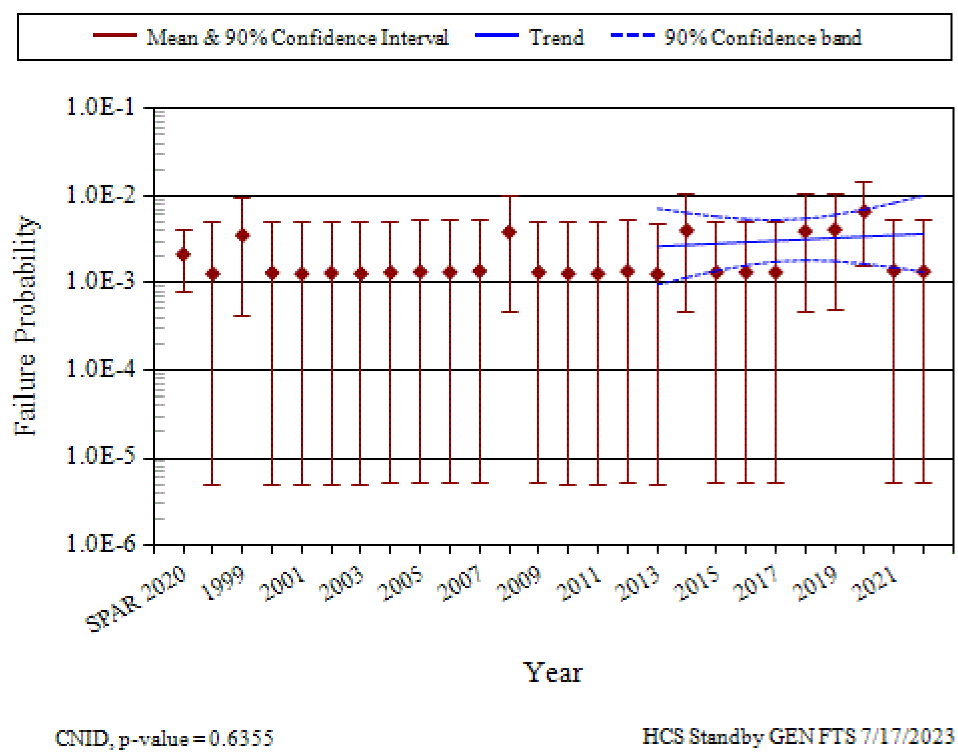

Figure 4. Failure probability estimate trend for HPCS EDG FTS.

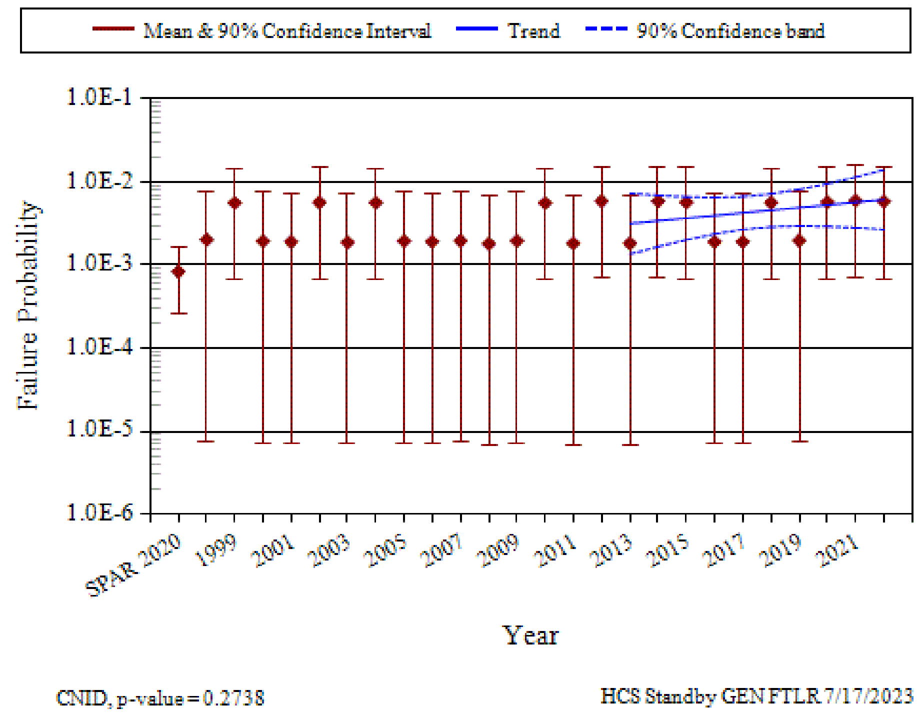

Figure 5. Failure probability estimate trend for HPCS EDG FTLR.

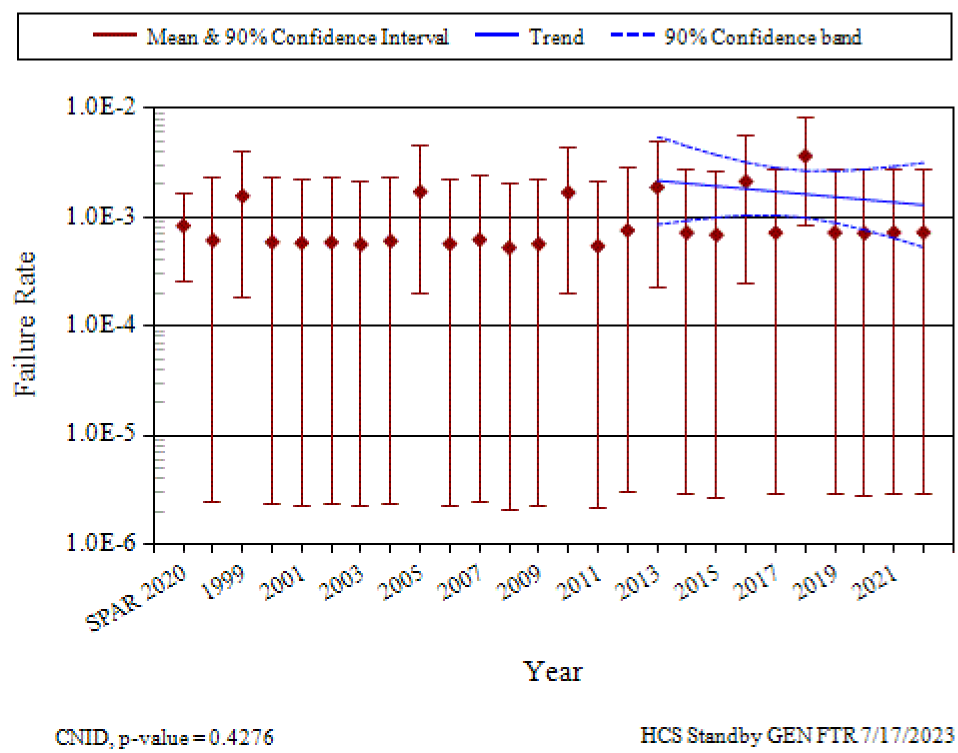

Figure 6. Failure rate estimate trend for HPCS EDG FTR>1H.

4. EDG UNAVAILABILITY AND REPAIR TIMES

4.1 EDG Unavailability Overview

The industry-wide test or maintenance UA of EDG trains has been calculated from operating experience. UA data are for EDG trains, which can include more than just the EDG. However, in most cases the EDG contributes the majority of the UA reported. Table 4 shows overall results for the EDG from the *2020 Parameter Update* [7] based on UA data from the IRIS database (which includes the MSPI designated devices as a subset). In the calculations, planned and unplanned unavailable hours for a train are combined.

Table 4. Industry-average unavailability estimates in the *2020 Parameter Update* [7] for EPS and HPCS EDGs.

Description	Distribution	Mean	α	β
EDG Test or Maintenance (EPS)	Normal	1.51E-2	0.0151	0.0070
EDG Test or Maintenance (HPCS)	Normal	1.33E-2	0.0133	0.0037

4.2 EDG Unavailability Trends

The graphs that follow provide overall maintenance unavailability, planned (such as test), and unplanned data for the 1998–2022 period. Note that these data do not supersede the data in Table 4 for use in risk assessments.

Trends in EDG train unavailability are shown in Figure 7 and Figure 8. Data tables for these figures are presented in Section 8. The EDGs in systems EPS and HPCS are trended. The yearly unavailability and reactor critical hour data were obtained from the Reactor Oversight Process program (1998 to 2001) and MSPI EPS and HPCS indicators (2002 to 2022). The total EDG downtimes during operation for each plant and year were summed and divided by the corresponding number of EDG-reactor critical hours. Unavailability data for plant shutdown periods are not reported.

A change in reporting requirements for UA occurred in 2002. The Reactor Oversight Process program data (1998–2001) did not include EDG overhaul outages while plants were in critical operation, while the MSPI (2002–2022) requires plants to report such outages. The difference in the annual means of these two groups is not statistically significant.

The mean and variance for each year is the sample mean and variance calculated from the plant-level UAs for that year. The vertical bar spans the calculated 5th to 95th percentiles of the beta distribution with matching means.

For the trend graphs, a least squares fit is sought for the linear or logit model depending upon which is more appropriate. Section 3 in *Overview and Reference* [3] provides further information. In the lower left-hand corner of the trend figures, the regression method and the p-value are reported. A review of the p-values identified a highly statistically significant **decreasing trend** in the **EPS EDG UA** for the most recent 10-year period with a p-value of 0.0022 (see Figure 7). This is a new trend that was not observed in the *2020 EDG Update* study [2].

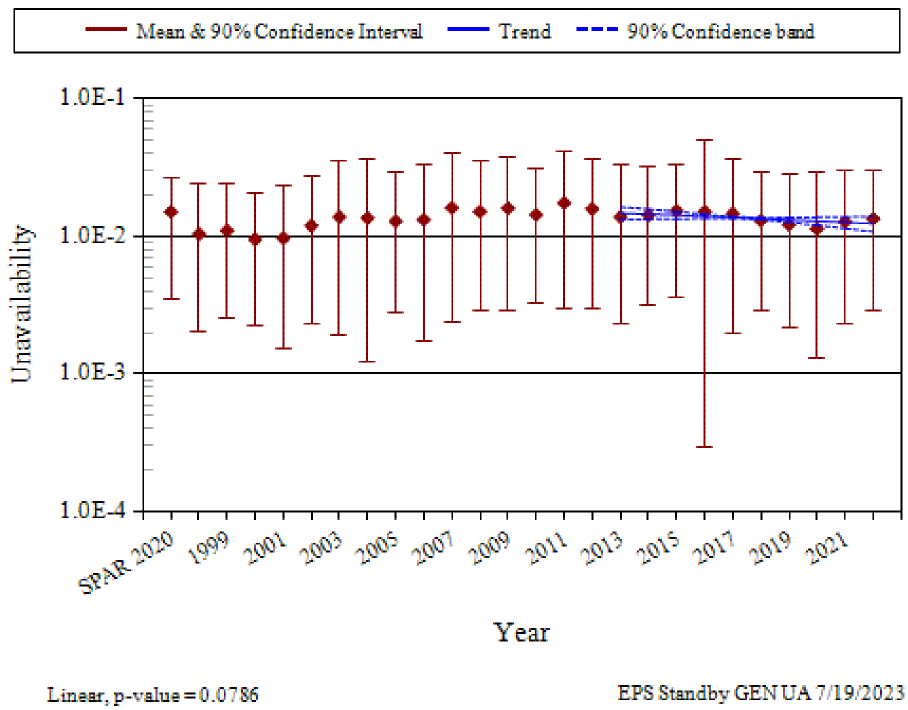

Figure 7. EPS EDG UA trend.

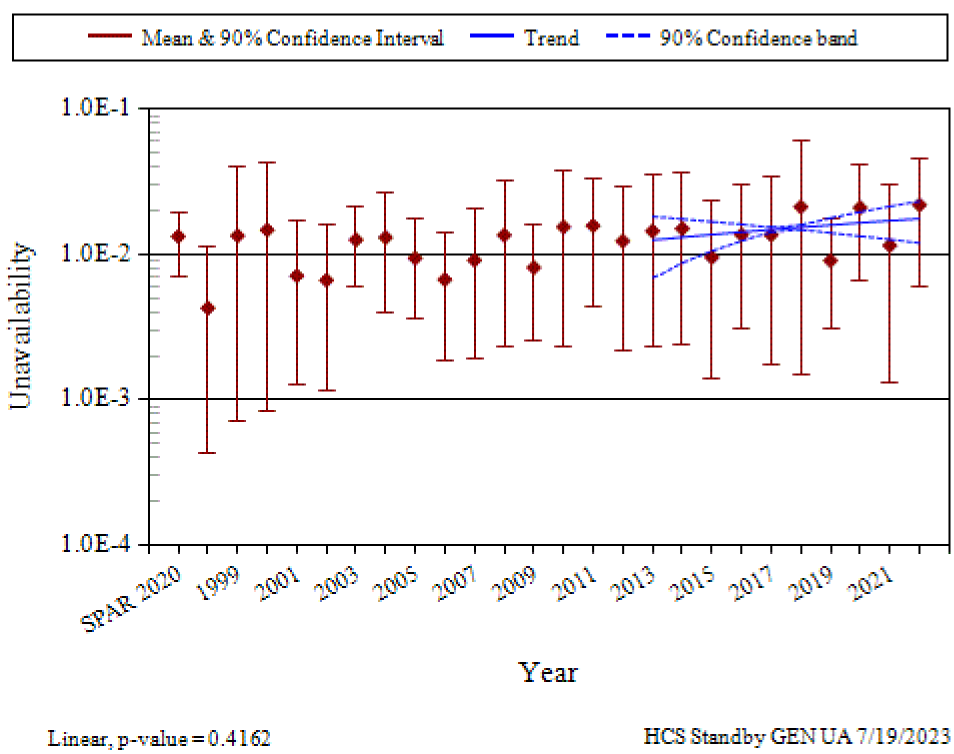

Figure 8. HPCS EDG UA trend.

4.3 Emergency Diesel Generator Repair Times

The data for repair times performed under actual emergency conditions are not available so repair durations were based on the number of hours of unplanned unavailability that have been reported for each EDG from 2013 to 2022. The hourly unplanned unavailability is reported to the NRC in the MSPI data. This MSPI data were not reported prior to 2006.

A Weibull distribution was fitted to the unplanned unavailability durations. The Weibull fit parameters are provided in Table 5 along with those values in the *2020 and 2018 EDG Updates* [2, 10] for comparison. The probability an EDG unplanned outage duration exceeds a given time (*t*) is listed in Table 6. The correspondence between fitted and observed distributions is very good at short to moderate repair times but not as good at very long repair times (well beyond typical PRA missions), such as when the outage spans hundreds of hours. In that situation, the long right tail of the repair time distribution is fit better by a lognormal distribution than a Weibull.

Table 5. Weibull curve fit parameters.

Parameter	This Update	*2020 EDG Update* [2]	*2018 EDG Update* [10]
Mean	33.9	37.1	34.2
Median	14.7	15.7	15.4
Weibull(α)	0.667	0.656	0.68
Weibull(β)	25.49	27.46	26.3

Table 6. Probability of exceeding selected EDG repair times.

Recovery Time (hr)	Weibull Model Probability		
	This Update	*2020 EDG Update* [2]	*2018 EDG Update* [10]
0.5	0.930	0.930	0.935
1	0.891	0.892	0.898
1.5	0.860	0.862	0.868
2	0.787	0.791	0.841
3	0.748	0.754	0.796
4	0.714	0.721	0.758
5	0.683	0.692	0.724
6	0.656	0.665	0.694
7	0.630	0.641	0.667
8	0.607	0.618	0.641
9	0.585	0.597	0.618
10	0.565	0.578	0.596
11	0.546	0.559	0.576
12	0.528	0.542	0.557
13	0.512	0.526	0.539
14	0.496	0.510	0.522
15		0.496	0.506
16		0.482	0.491

Recovery Time (hr)		Weibull Model Probability	
	This Update	*2020 EDG Update* [2]	*2018 EDG Update* [10]
17		0.469	0.476
18		0.456	0.462
19		0.444	0.449
20		0.432	0.436
21		0.421	0.424
22		0.411	0.413
23		0.400	0.402
24		0.391	0.391

5. EDG UNRELIABILITY TRENDS

Trends in total component unreliability are shown in Figure 9 and Figure 10. Plot data for these figures are provided in Section 8. Total unreliability is defined as the union of UA, FTS, FTLR, FTR>1H. The probability of FTR>1H is calculated for 7 hours to provide the results for an 8-hour mission.[b] The trends are shown at the system-specific level across the industry. The trending method is described in more detail in Section 4 of *Overview and Reference* [3]. In the lower left-hand corner of the trend figures, the regression method and the p-value are reported. A review of the p-values identifies **no statistically significant trends** in the **EDG total unreliability** estimates for the most recent 10-year period.

Because there are no total unreliability estimates in the *2020 Parameter Update*, there is no baseline industry values shown in Figure 9 and Figure 10 for comparison.

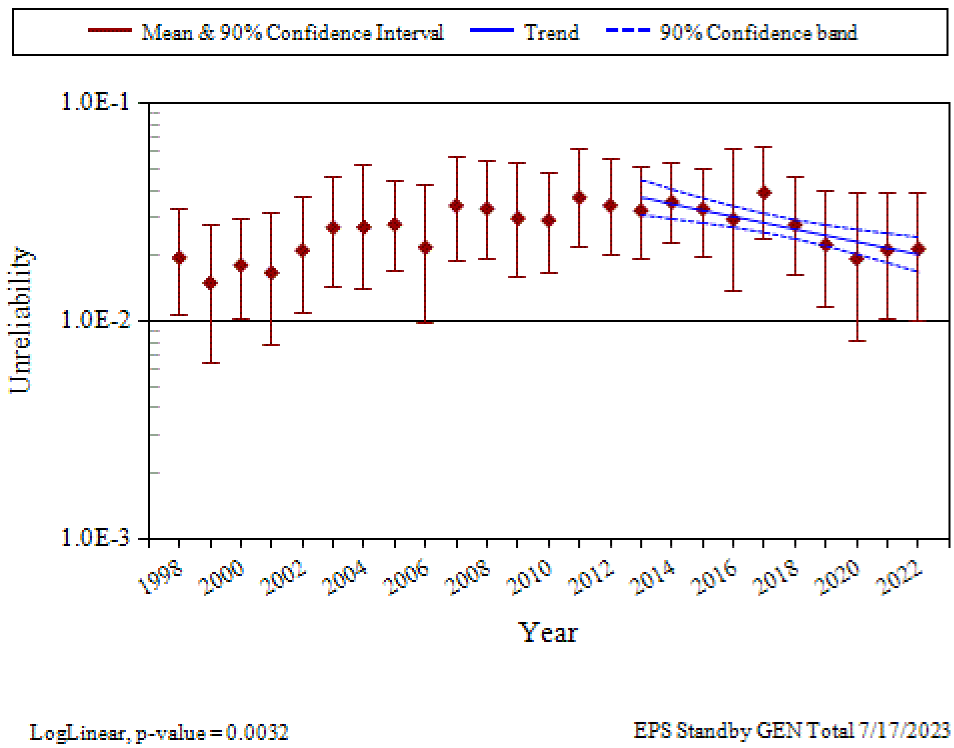

Figure 9. EPS EDG unreliability trend (8-hour mission).

[b] 8-hour mission is used in the analysis in order to account for the fact that recovery of offsite power during LOOP and station blackout sequences most likely occur well before the 24-hour PRA mission time.

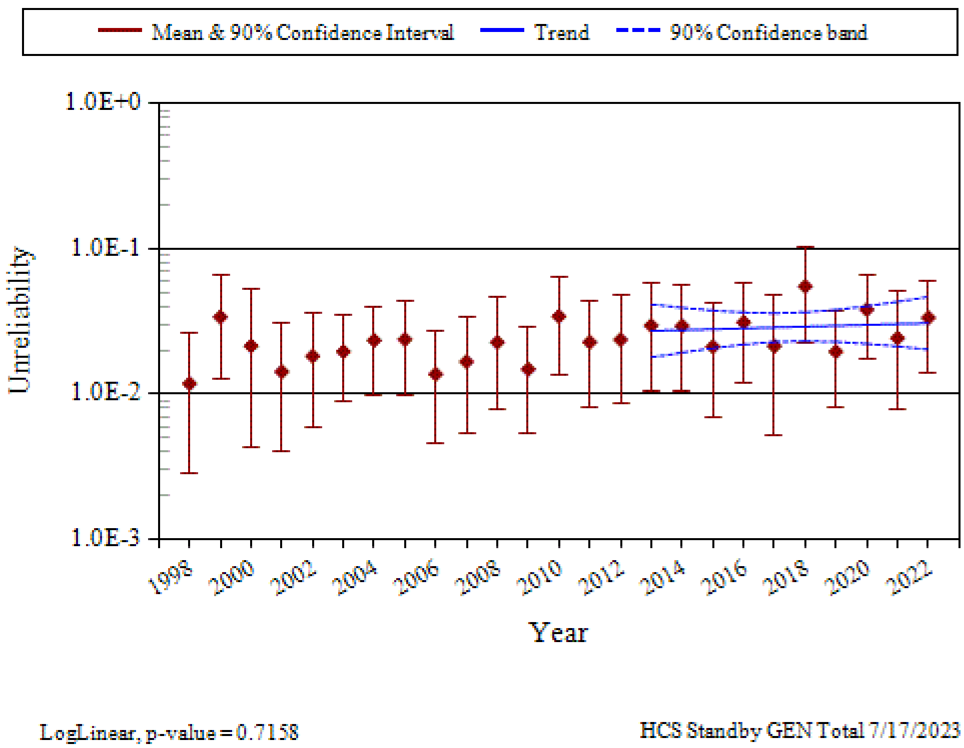

Figure 10. HPCS EDG unreliability trend (8-hour mission).

6. ENGINEERING ANALYSIS

This section presents the engineering analysis for factors that could influence the component trends. Engineering trends of component failures and demands are presented in Section 6.1. Differences between testing and actual unplanned demands are considered in Section 6.2. Differences among manufacturers are presented in Section 6.3, and differences among EDG ratings are presented in Section 6.4. Finally, engineering analyses performed with respect to failure mode are presented in Section 6.5. The factors analyzed include subcomponent, failure cause, detection method, manufacturer, and EDG rating.

6.1 Engineering Trends

This section presents frequency trends for EPS and HPCS EDG failures and demands. The data are normalized by reactor year for plants that report data for these EDGs with no consideration for plant system (EPS versus HPCS) or for the number of EDGs at a plant. The trends provide an overview of the demand counts and failure counts associated with each failure mode across the years.

Figure 11 to Figure 16 provide the plot for frequency (per reactor year) of EDG start and load and run demands, run > 1H hours, FTS events, FTLR events, and FTR>1H events:

- Figure 11 shows the trend for EPS and HPCS EDG frequency of start demands
- Figure 12 shows the trend for EPS and HPCS EDG frequency of load and run demands
- Figure 13 shows the trend for the EPS and HPCS EDG frequency of run > 1H hours
- Figure 14 shows the trend for EPS and HPCS EDG frequency of FTS events
- Figure 15 shows the trend EPS and HPCS EDG frequency of FTLR events
- Figure 16 shows the trend for the EPS and HPCS EDG frequency of FTR>1H events.

The data for the figures listed above are provided in Section 8. EPS and HPCS systems are trended together for each figure. The rate methods described in Section 2 of *Overview and Reference* are used [3].

In the lower left-hand corner of the trend figures, the regression p-values are reported. A review of these p-values identified the following trends for the most recent 10-year period:

- **Increasing trend** in the **EPS and HPCS EDG frequency of start demands**, which is highly statistically significant with a p-value of 0.0083 (see Figure 11). This is a new trend that was not observed in the *2020 EDG Update* study [2]
- **Increasing trend** in the **EPS and HPCS EDG frequency of FTLR demands**, which is statistically significant with a p-value of 0.0228 (see Figure 12). The same trend was observed in the *2020 EDG Update* study
- **Decreasing trend** in the **EPS and HPCS EDG frequency of FTLR events**, which is highly statistically significant with a p-value of 0.0096 (see Figure 15). This is a new trend that was not observed in the *2020 EDG Update* study.

Table 7 through Table 9 provides a summary of the total failure event count for each of the years a trend line is plotted. Table 7 summarizes the failures by system and year for the FTS failure mode. Table 8 summarizes the failures by system and year for the FTLR failure mode. Table 9 summarizes the failures by system and year for the FTR>1H failure mode. The data in Table 7 through Table 9 show failure events resulting from FTLR and FTR>1H occur in roughly equal numbers, while FTS failures occur somewhat less frequently. Furthermore, HPCS EDGs are about 3% of the EDG population, but account for only 1-2% of the failure counts throughout the trending period.

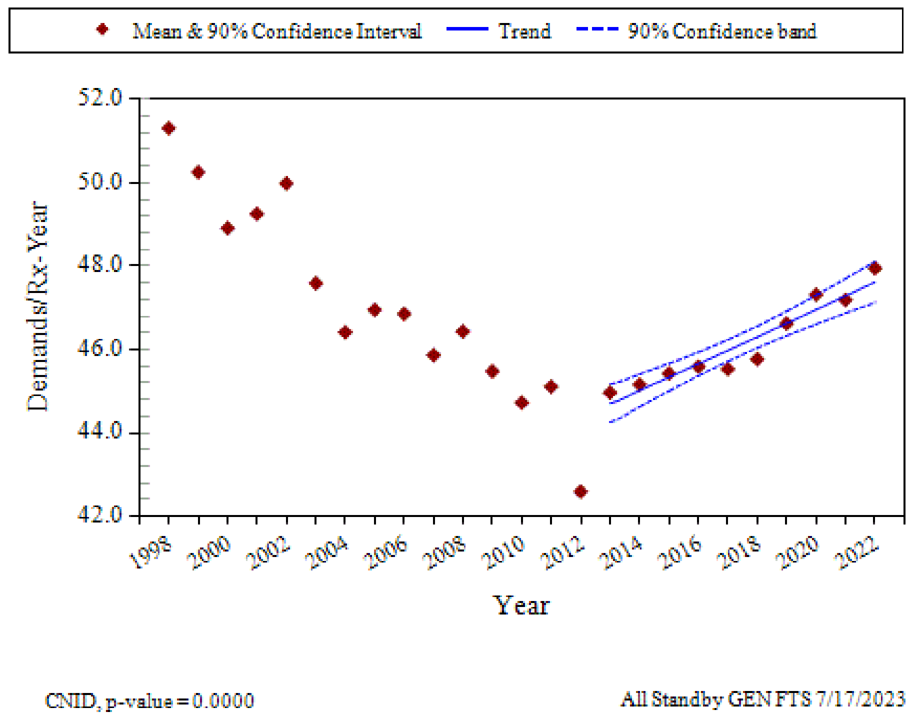

Figure 11. Frequency of start demands (demands per reactor year) for EPS and HPCS EDGs.

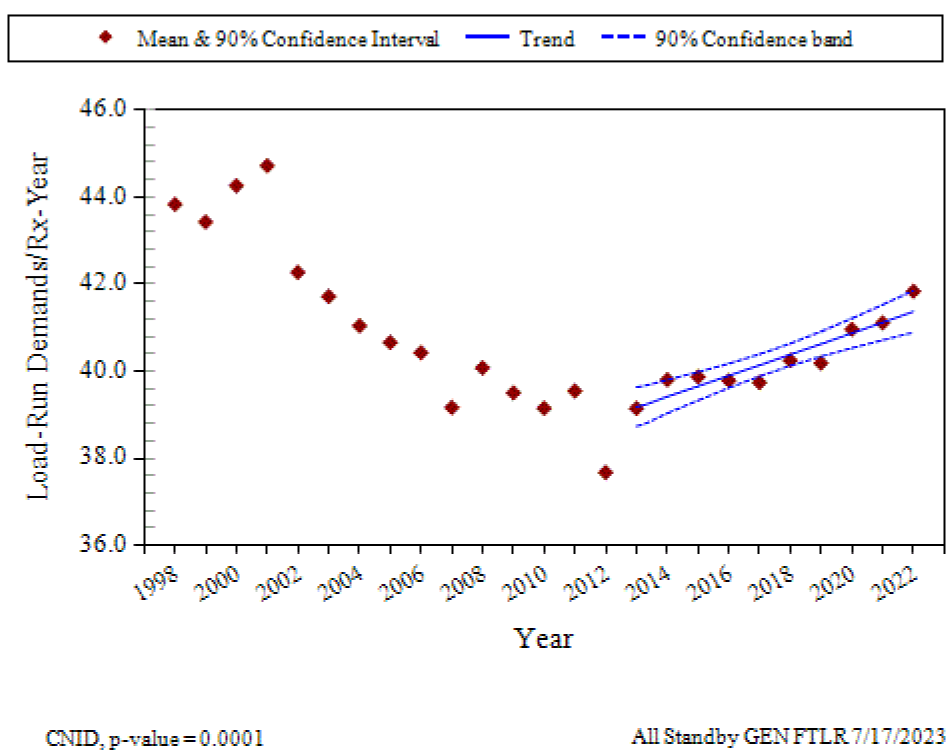

Figure 12. Frequency of FTLR demands (demands per reactor year) trend for EPS and HPCS EDGs.

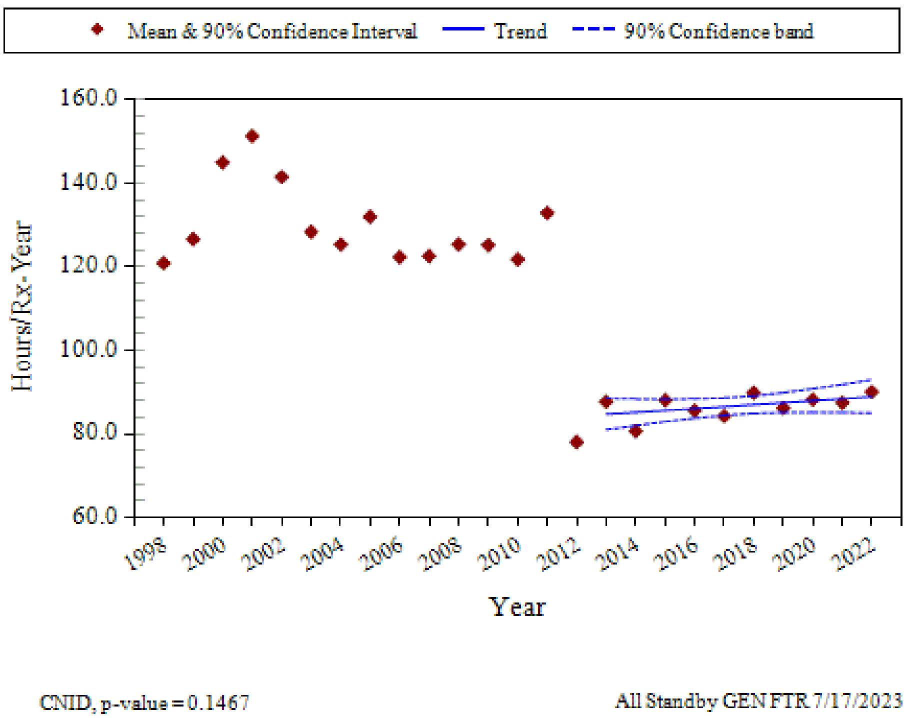

Figure 13. Frequency of run > 1H hours (hours per reactor year) trend for EPS and HPCS EDGs.

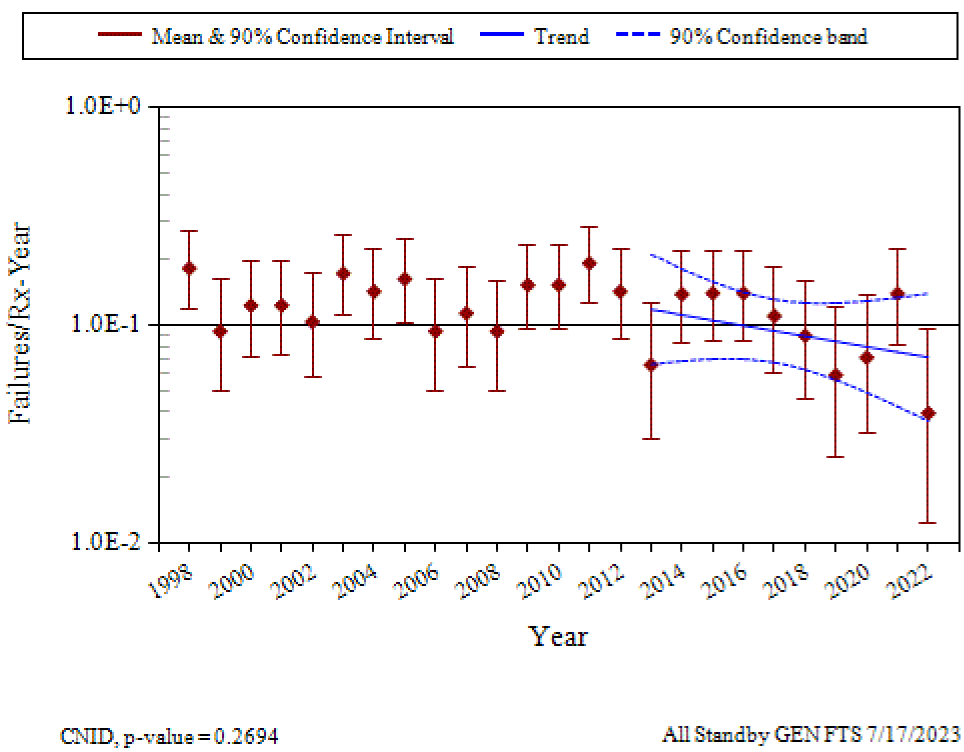

Figure 14. Frequency of FTS events (events per reactor year) trend for EPS and HPCS EDGs.

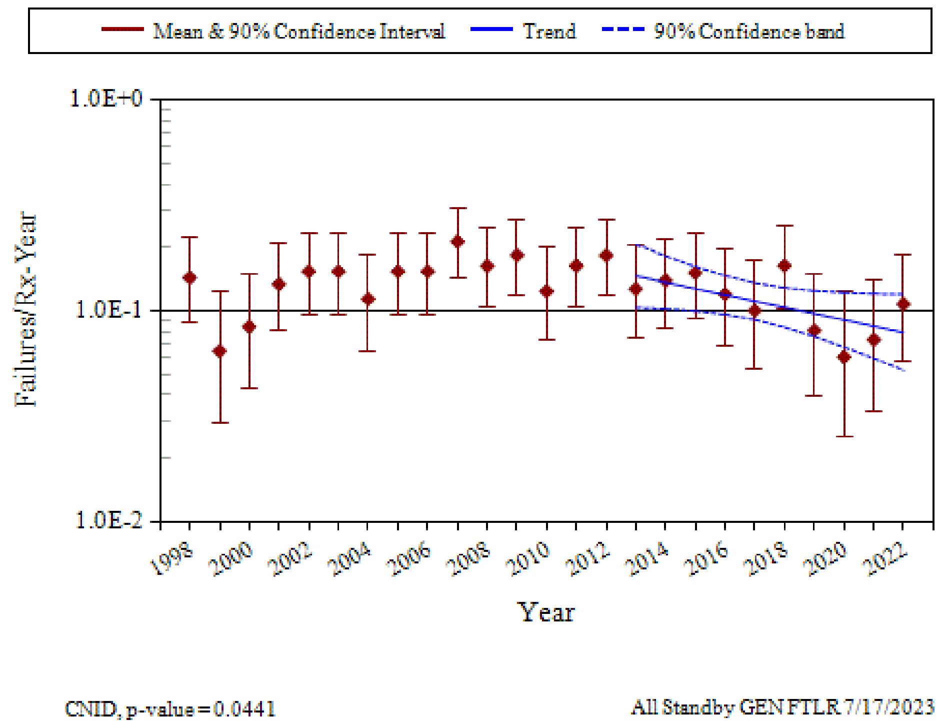

Figure 15. Frequency of FTLR events (events per reactor year) trend for EPS and HPCS EDGs.

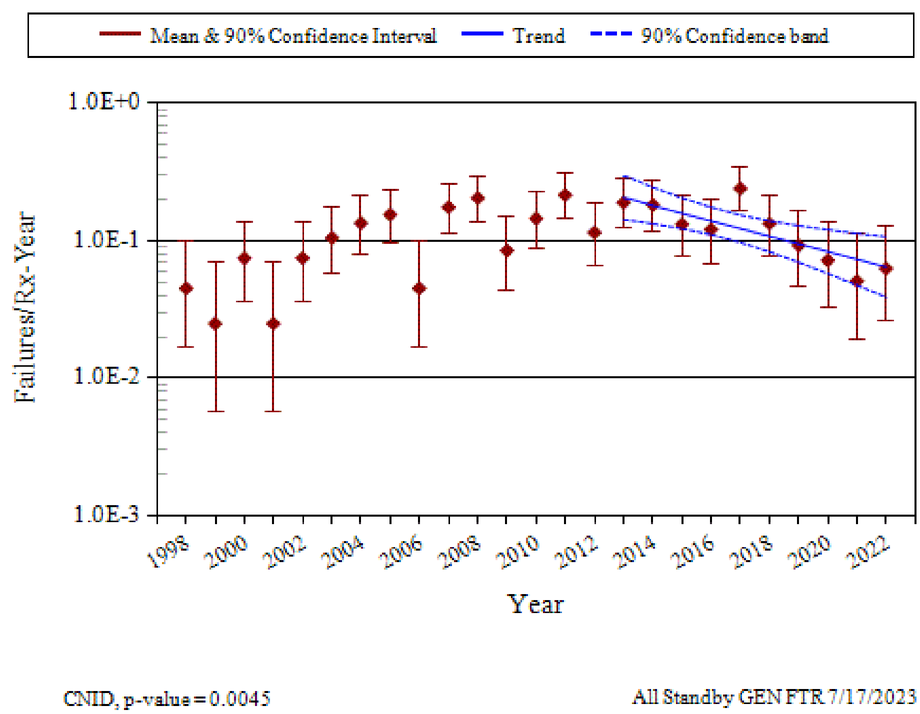

Figure 16. Frequency of FTR>1H events (events per reactor year) trend for EPS and HPCS EDGs.

Table 7. Summary of EDG failure counts for the FTS failure mode over time by system.

System	EDG Count	EDG Percent	Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
EPS	234	96.7 %	6	12	13	13	10	7	4	4	12	3	84	94.4%
HPCS	8	3.3 %		1				1	1	2			5	5.6%
Total	242	100%	6	13	13	13	10	8	5	6	12	3	89	100.0%

Table 8. Summary of EDG failure counts for the FTLR failure mode over time by system.

System	EDG Count	EDG Percent	Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
EPS	234	96.7%	12	12	13	11	9	14	7	4	5	8	95	94.1%
HPCS	8	3.3%		1	1			1		1	1	1	6	5.9%
Total	242	100%	12	13	14	11	9	15	7	5	6	9	101	100.0%

Table 9. Summary of EDG failure counts for the FTR>1H failure mode over time by system.

System	EDG Count	EDG Percent	Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
EPS	234	96.7%	17	17	12	10	22	10	8	6	4	5	111	96.5%
HPCS	8	3.3%	1			1		2					4	3.5%
Total	242	100%	18	17	12	11	22	12	8	6	4	5	115	100.0%

6.2 Comparison of IRIS EPS EDG Unplanned Demand Results with Industry Results

Because the IRIS EPS EDG data are dominated by test demands (over 95% of the demands are typically from tests), there is a concern on whether the test data could adequately predict EPS EDG performance during unplanned demands. This comparison evaluates the same dataset for standby components used for the overall trends shown in this document but limits the failure data to those that are discovered during an ESF demand reported in IRIS. The data are further limited to 2003 to present since the ESF demand reporting in IRIS is inconsistent prior to 2003.

IRIS failure records were reviewed to identify actual unplanned EPS EDG demands involving bus under-voltage conditions. Such events require the associated EPS EDG to start, load onto the bus, and power the bus until normal power is recovered to the bus. There are additional EPS EDG unplanned demands in which a bus under-voltage condition did not exist. In these cases, the EPS EDG did not have to load and power the bus. Such unplanned demands do not fully exercise the mission of the EPS EDGs and therefore were not counted.

The EPS EDG unplanned demand data covering 2003–2022 are summarized in Table 10. Consistency between the unplanned demand data and the *2020 Parameter Update* (Table 2) was evaluated using the predictive distribution approach outlined in NUREG/CR-6823, “Handbook of Parameter Estimation for Probabilistic Risk Assessment,” Sections 6.2.3.5 and 6.3.3.4 [9].

The unplanned demand data were aggregated at the industry level (failures and demands). The industry-average failure mode distribution (from Table 2) was sampled and the predicted number of events was evaluated using the binomial distribution with industry-average failure probability and associated number of demands. This process was repeated 1,000 times, each time obtaining the total number of failures predicted by the industry-average failure parameters. Then the actual number of observed unplanned demand failures (listed in the Observed Failures column of Table 10) was compared with this sample to determine the probability of observing this number of failures or greater. If the probability was greater than 0.05 and less than 0.95, then the Table 2 industry-average distribution obtained from the IRIS data analysis is consistent with the observed unplanned demand performance.

Table 10. EPS EDG unplanned demand performance comparison with industry-average performance from IRIS data.

Failure Modes	Plants	Demands or Hours	Observed Failures	Expected Failures	Probability of ≥ Observed Failures	Consistent with Industry-Average Performance[a]
FTS	95	597	0	1.3	1.00	Yes[b]
FTLR	95	347	1	1.1	0.64	Yes
FTR>1H	95	5346	4	6.3	0.74	Yes

Note:

a. If the probability of observing the actual failures or greater is ≥ 0.05 and ≤ 0.95, then the observed performance is considered to be consistent with the industry-average performance estimate.

b. In this case P(X=0) = 0.25 which is considered consistent with the industry average data.

These consistency checks show that the FTS, FTLR, and FTR>1H failure observations, in the non-test operational ESF demand data, lie within the corresponding industry-average estimate distributions provided in the *2020 Parameter Update* (Table 2) that were based on both test and non-test operational ESF demands.

6.3 EPS EDG Performance by Manufacturer

Table 11 presents the results of summarizing EPS EDG performance by manufacturer. IRIS contains information on EPS EDG manufacturers, but over the years some manufacturers have changed names or have been acquired by others. Therefore, to identify the original manufacturer, the IRIS information was supplemented by other EPS EDG reports. The results are a second consistency check against the industry-average distributions in Table 2. The comparison was made for the combination of all three failure modes.

Two manufacturer’s EPS EDG failure observations lie in the upper 95% of the uncertainty range of the industry-average distribution. However, these two manufacturers involve very few EPS EDGs. The rest of the manufacturers’ failure observations lie within the 5% to 95% interval.

Table 11. EPS EDG manufacturer performance compared with industry-average performance—FTS, FTLR, and FTR>1H combined.

Manufacturer	Code	EPS EDGs	Observed Failures	Expected Failures	Probability ≥ Observed Failures	Consistent with Industry-Average Performance[a]
ALCO Power	AP	24	74	83.6	0.66	Yes
Cooper Bessemer	CB	37	81	135.0	0.94	Yes
Electro Motive/General Motors	EM/GM	69	220	242.6	0.60	Yes
Fairbanks Morse/Colt	FM/C	67	277	243.2	0.29	Yes
Nordberg	NB	8	40	32.9	0.26	Yes

Manufacturer	Code	EPS EDGs	Observed Failures	Expected Failures	Probability ≥ Observed Failures	Consistent with Industry-Average Performance[a]
SAC/Compair Luchard/ Jeumont Schndr	SC/JS	3	25	8.9	0.00	No
TransAmerica DeLaval	TD	20	92	74.4	0.19	Yes
Worthington Corp	WC	4	38	12.0	0.00	No

Note:

a. If the probability of observing the failures or greater is ≥ 0.05 and ≤ 0.95, then the industry-average estimate is considered consistent with the observed failure count.

6.4 EPS EDG Performance by Rating

Table 12 presents the results of the evaluation of EPS EDG performance by rating. The results are a consistency check of the industry-average distributions in Table 2 against observed performance by EDG rating. The comparison was made for the combination of all three failure modes. The failure observations for ratings all lie within the 5% to 95% interval of the industry-average distribution and are therefore consistent with the industry-average failure rate estimates.

Table 12. EPS EDG rating performance compared with industry-average performance—FTS, FTLR, and FTR>1H combined.

Rating	EPS EDGs	Observed Failures	Expected Failures	Probability ≥ Observed Failures	Consistent with Industry-Average Performance[a]
50-249 KW	2	7	9.8	0.79	Yes
1,000-4,999 KW	170	622	616.4	0.43	Yes
5,000-99,999 KW	58	216	211.6	0.43	Yes
100,000-499,999 KW	2	2	4.8	0.93	Yes

Note:

a. If the probability of observing the actual failures or greater is ≥ 0.05 and ≤ 0.95, then the industry-average estimate is considered consistent with the observed failure count.

6.5 EPS EDG Engineering Analysis by Failure Modes

The engineering analysis of the EPS EDG failure breakdown by failure mode and other factors such as subcomponents, failure causes, detection methods, and recovery possibility are presented in this section (there are too few HPCS EDGs to perform similar analyses on them). The failure modes are determined as a result of the IRIS data review by INL staff. See Section 7 for further description of failure modes.

EPS EDG subcomponent contributions to the three failure modes are presented in Figure 17. The subcomponent contributions are similar to those used in the common-cause failure (CCF) database. **For FTS**, the **instrumentation and control**, generator, starting air, and engine piece parts are the top contributors to failures. **For FTLR**, the **instrumentation and control** and breaker are dominating contributors to failures. **For FTR>1H**, high contributors include the **cooling,** engine, fuel oil, and instrumentation and control.

EPS EDG failure cause group contributions to the three failure modes are presented in Figure 18. The cause groups are similar to those used in the CCF database. Table 13 shows the breakdown of the cause groups with the specific causes that were coded during the data collection. The most likely causes are **component** issues and **human** errors. The Component cause group includes the causes that were related to something internal to the component or an aging or worn-out part, which were categorized as the Internal cause group in previous studies [2]. The Human cause group is primarily influenced by maintenance and operating procedures and practices.

EPS EDG failure detection methods for the three failure modes are presented in Figure 19. A failure can be detected during inspection, testing, post maintenance testing (PMT), non-test demand, or ESF demand. The most likely detection method is **test demand**, which is the prevalent detection method for most standby components. The inspection failure detection method is also important in the FTS failure mode.

EPS EDG recovery results for the three failure modes are presented in Figure 20. Most EPS EDG failures were judged as unrecoverable. The overall **non-recovery to recovery ratio** is approximately **14:1**, meaning that 14 of every 15 failures were not recovered.

Table 13. Component failure cause groups.[c]

Group	Specific Cause	Description
Component	Internal to component, piece-part	Used when the cause of a failure is a non-specific result of a failure internal to the component that failed other than aging or wear.
	Set point drift	Used when the cause of a failure is the result of set point drift or adjustment.
	Age/wear	Used when the cause of the failure is a non-specific aging or wear issue.
Design	Construction/installation error or inadequacy	Used when a construction or installation error is made during the original or modification installation. This includes specification of an incorrect component or material.
	Design error or inadequacy	Used when a design error is made.
	Manufacturing error or inadequacy	Used when a manufacturing error is made during component manufacture.
Environment	Ambient environmental stress	Used when the cause of a failure is the result of an environmental condition from the location of the component.
	Internal environment	The internal environment led to the failure. Debris/foreign material as well as an operating medium chemistry issue.
	Extreme environmental stress	Used when the cause of a failure is the result of an environmental condition that places a higher-than-expected load on the equipment and is transitory in nature.
Human	Accidental action (unintentional or undesired human errors)	Used when a human error (during the performance of an activity) results in an unintentional or undesired action.
	Human action procedure	Used when the correct procedure is not followed, or the wrong procedure is followed, for example, when a missed step or incorrect step in a surveillance procedure results in a component failure.
	Inadequate maintenance	Used when a human error (during the performance of maintenance) results in an unintentional or undesired action.
	Inadequate procedure	Used when the cause of a failure is the result of an inadequate procedure operating or maintenance.

c The cause groups have been re-arranged to align with those currently used in the CCF database.

Group	Specific Cause	Description
Other	State of other component	Used when the cause of a failure is the result of a component state that is not associated with the component that failed. An example would be the diesel failed due to empty fuel storage tanks.
	Other (stated cause does not fit other categories)	Used when the cause of a failure is provided, but it does not meet any one of the descriptions.
	Unknown	Used when the cause of the failure is not known.

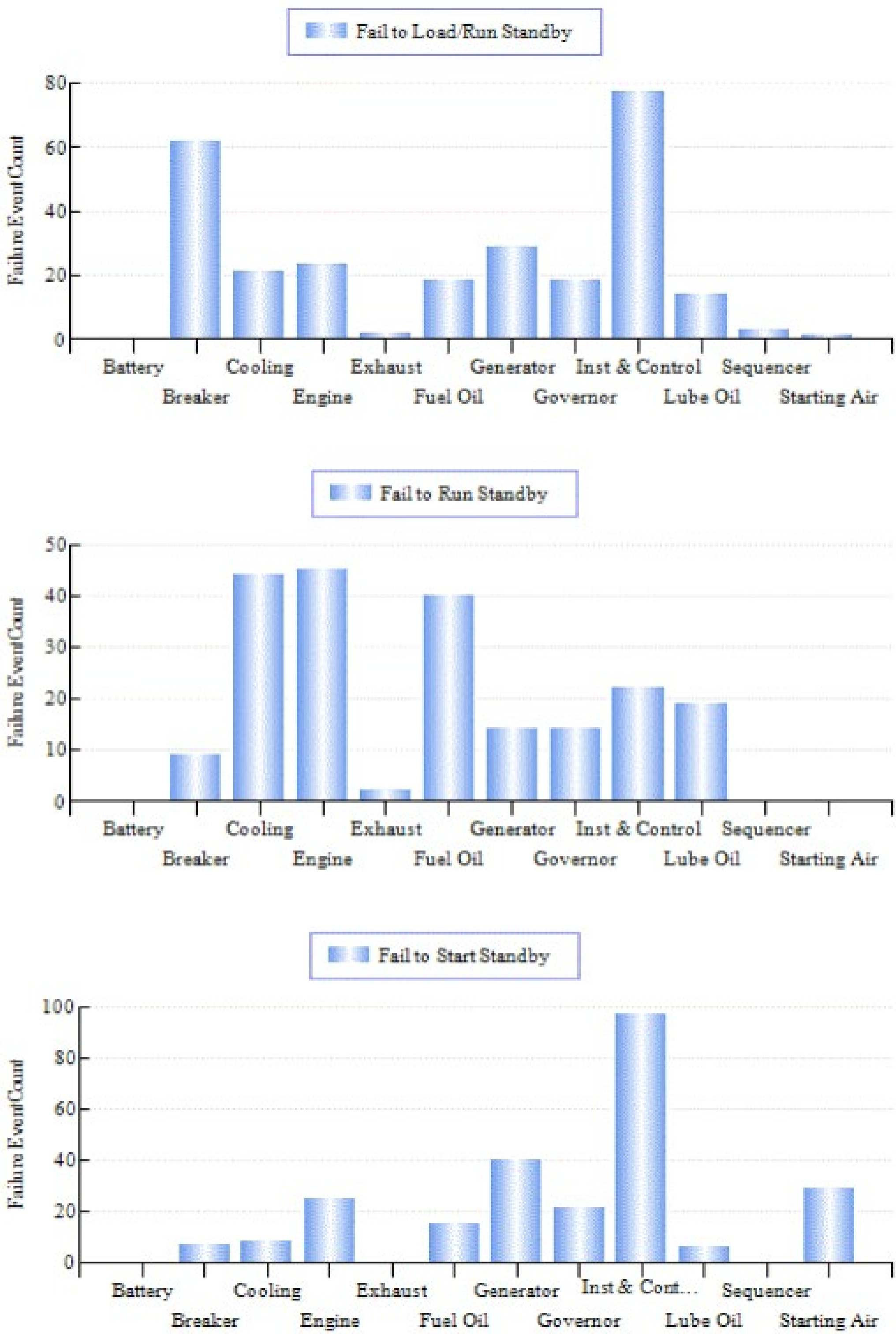

Figure 17. EPS EDG failure breakdown by subcomponent and failure mode.

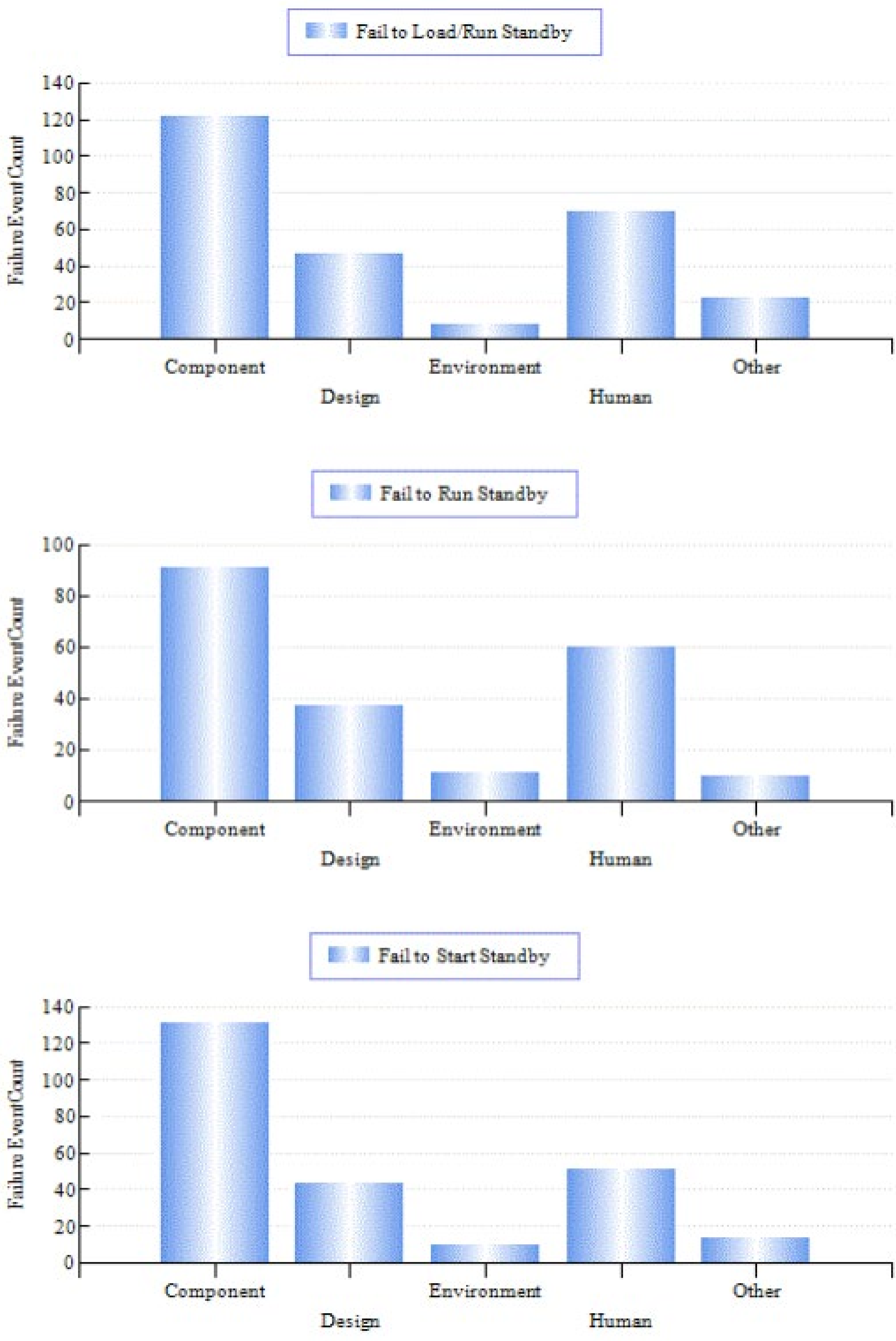

Figure 18. EPS EDG breakdown by cause group and failure mode.

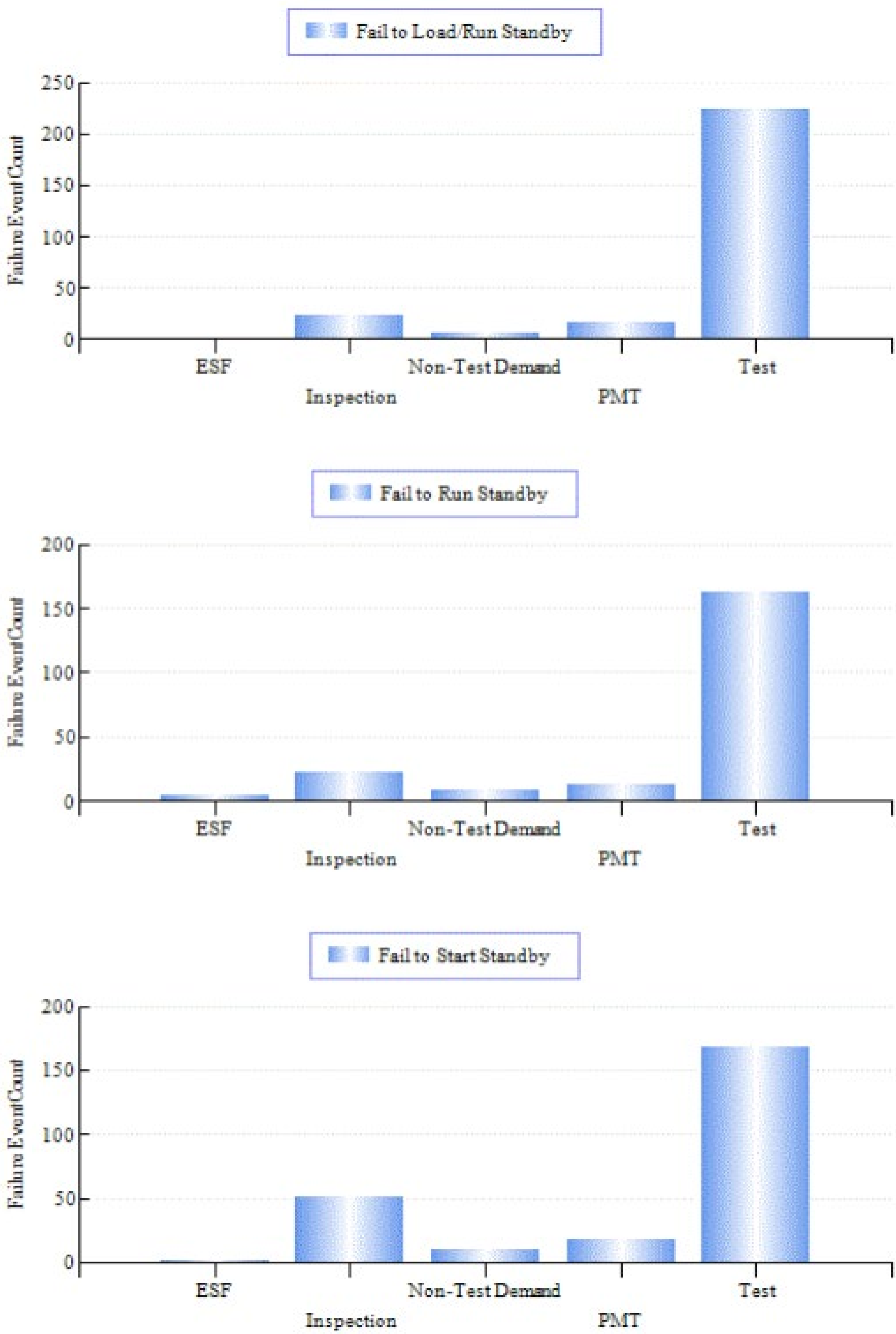

Figure 19. EPS EDG component failure distribution failure mode and method of detection.

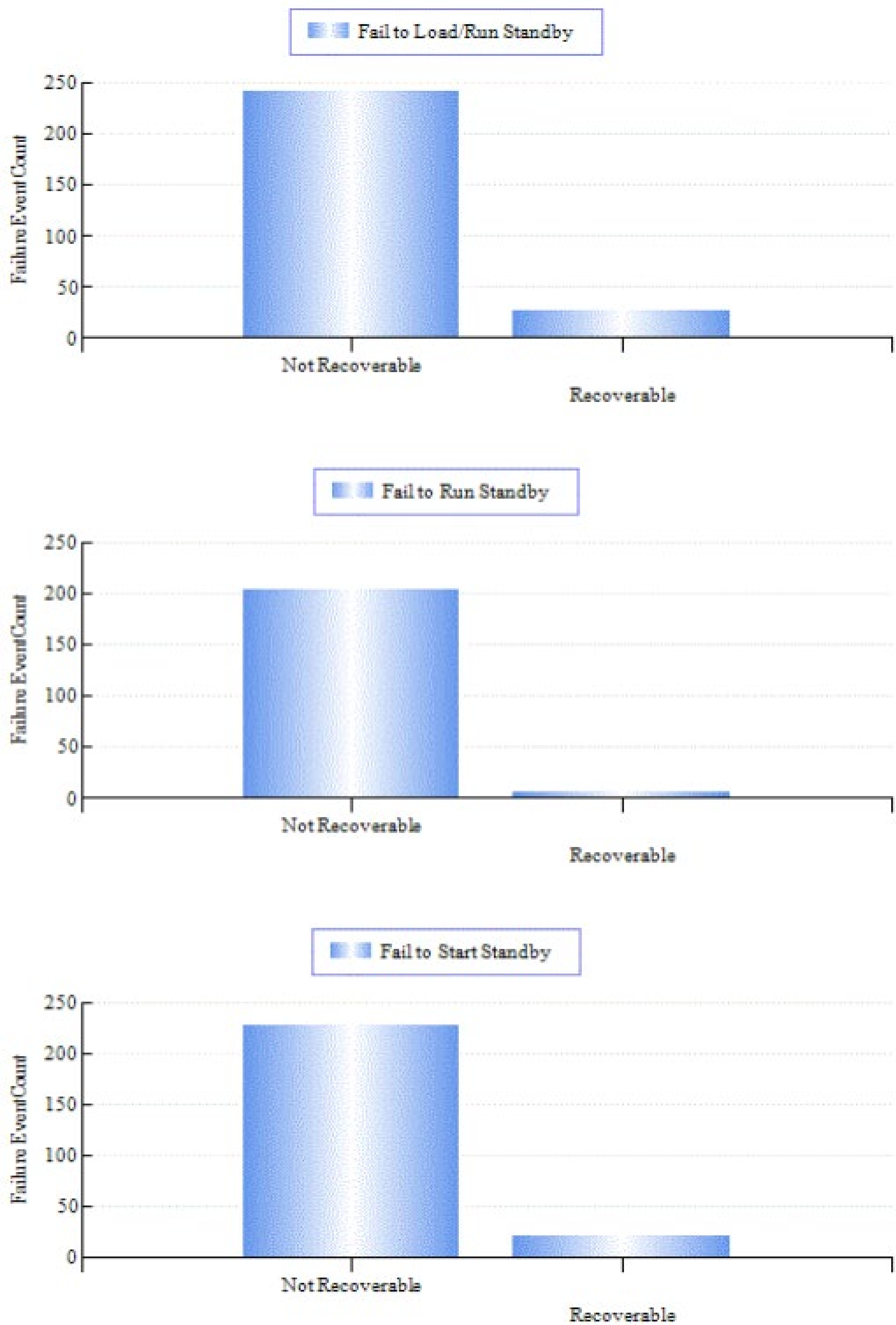

Figure 20. EPS EDG component failure distribution by failure mode and recovery determination.

Figure 21 shows the percentage of failure events for the three failure modes segregated by EPS EDG manufacturer as indicated in the IRIS database. Table 14 shows the distribution of the various manufacturers of EPS EDGs in the IRIS database and the total failure count associated with each. Based on the information given in Figure 21, EPS EDG manufacturers do not appear to be correlated to any particular failure mode pattern.

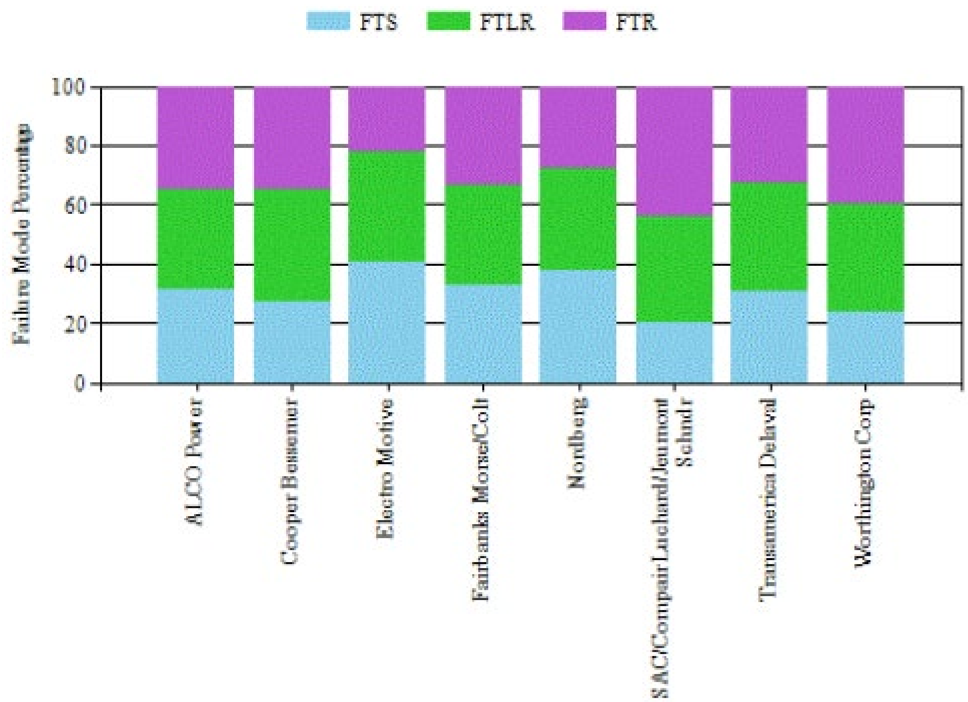

Figure 21. EPS EDG failure distribution by manufacturer.

Table 14. EPS EDG manufacturer population and total failure count.

Manufacturer	Code	EPS EDGs	EDG Percent	Total Failure Count	Percent of Failures
ALCO Power	AP	24	10.3%	74	8.7%
Cooper Bessemer	CB	37	15.9%	81	9.6%
Electro Motive	EM/GM	69	29.7%	220	26.0%
Fairbanks Morse/Colt	FM/C	67	28.9%	277	32.7%
Nordberg	NB	8	3.4%	40	4.7%
SAC/Compair Luchard/Jeumont Schndr	SC/JS	3	1.3%	25	3.0%
Transamerica Delaval	TD	20	8.6%	92	10.9%
Worthington Corp	WC	4	1.7%	38	4.5%
Totals	–	232	100%	847	100%

Figure 22 shows the percentage of failure events for the three failure modes segregated by EPS EDG rating as indicated in the IRIS database. Table 15 shows the distribution of the various rated EPS EDGs in the IRIS database used in this study. The larger EDG differs from the others in not yet having any FTS events, but the operational experience for this EDG is much shorter than for other EDGs.

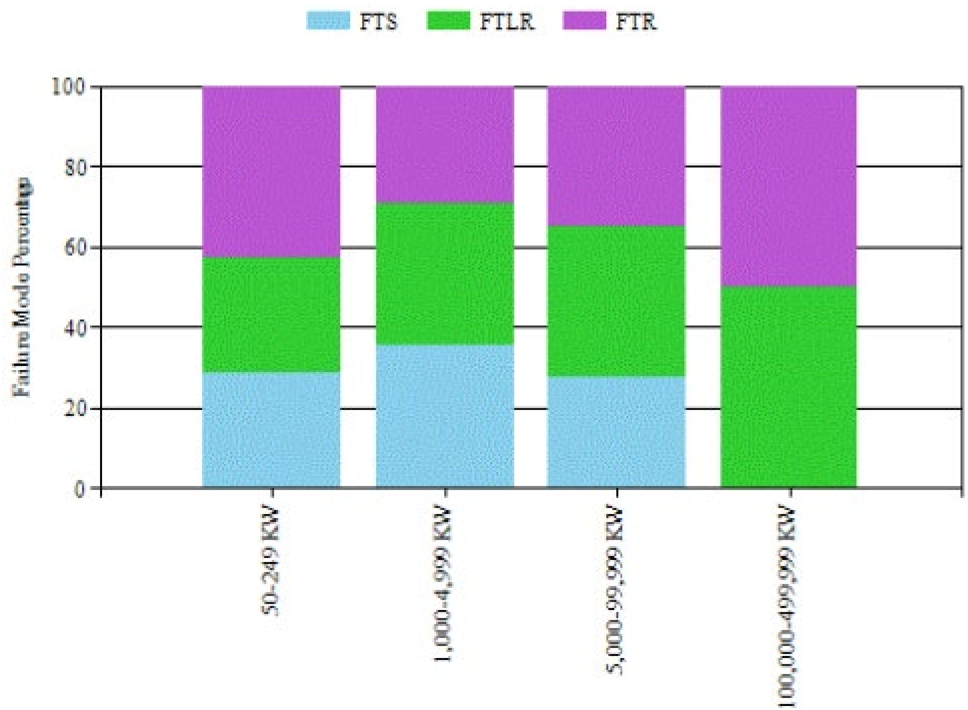

Figure 22. EPS EDG component failure modes by EPS EDG rating.

Table 15. EPS EDG population by rating.

EPS EDG Rating	Device Count	Device Percent	Total Failure Count	Percent of Failures
50-249 KW	2	0.9%	7	0.8%
1,000-4,999 KW	170	73.3%	622	73.4%
5,000-99,999 KW	58	25.0%	216	25.5%
100,000-499,999 KW	2	0.9%	2	0.2%
Total	232	100%	847	100.0%

7. EDG ASSEMBLY DESCRIPTION

The EDGs are those within the Class 1E ac electrical power system at U.S. commercial nuclear power plants and those in the HPCS systems. Station blackout EDGs are not included.

The EDG includes the diesel engine with all components in the exhaust path, electrical generator, generator exciter, output breaker, combustion air, lube oil systems, fuel oil system, and starting compressed air system, and local instrumentation and control circuitry. The sequencer is excluded from the EDG component. For the service water system providing cooling to the EDGs, only the devices providing control of cooling flow to the EDG heat exchangers are included. Room heating and ventilating is not included.

The EDG failure modes include FTS, FTLR, and FTR>1H. These failure modes were used in NUREG/CR-6928 and are similar to those used in the MSPI Program. There is some uncertainty concerning when the run hours should start to be counted; for example, should they start as soon as the EDG is started or should they start only after the output circuit breaker has closed? For this study, the run hours start as soon as the EDG is started, which is the way data have been reported in IRIS. The total run hours are partitioned by failure mode, with the first hour being used for FTLR, and the remaining hours assigned to FTR>1H.

Guidelines for determining whether a component failure event reported in IRIS is to be included in FTS, FTLR, or FTR>1H are similar to those used in the MSPI Program. In general, any circumstance in which the component is not able to meet the performance requirements defined in the PRA is counted. This includes conditions revealed through testing, operational demands, unplanned demands, or discovery (see INPO 19-002 [4] for examples of operational demands, or operational non-test demands). Run failures that occur beyond the typical 24-hour mission time in PRAs are included. However, certain events are excluded: slow engine starting times that do not exceed the PRA success criteria, conditions that are annunciated immediately in the control room without a demand, and run events representing degraded conditions that are shown to not have caused an actual run failure within 24 hours. Events occurring during maintenance or post maintenance testing that are related to the actual maintenance activities are excluded. Finally, in contrast to the MSPI Program, a general guideline on slow starting times is to include only those slow starts requiring more than 20 seconds as FTS events, similar to what was done for the CCF database and the EPS system study. (In the MSPI Program, most licensees chose to use technical specification requirements for fast starts as their success criteria—typically less than 10 seconds to start.) All EDG events within IRIS were reviewed to ensure that they were binned to the correct failure mode—FTS, FTLR, FTR>1H, or no failure. However, even given detailed descriptions of failure events, this binning still required some judgment and involves some uncertainty.

Guidelines for counting demands and run hours are similar to those in the MSPI Program. Start and load/run demands include those resulting from tests, operational demands, and unplanned demands. Demands during maintenance and post maintenance testing are excluded. Similarly, run hours include those from tests, operational demands, and unplanned demands. Note that the test demands and run hours dominate the totals, compared with operational and unplanned demands and run hours.

8. DATA TABLES

In this section, the plot data for Figure 1 to Figure 16 in previous sections are provided in Table 16 to Table 31, respectively.

Figure	Table	Analysis
Figure 1	Table 16	Failure probability estimate trend for EPS EDG FTS
Figure 2	Table 17	Failure probability estimate trend for EPS EDG FTLR
Figure 3	Table 18	Failure rate estimate trend for EPS EDG FTR>1H
Figure 4	Table 19	Failure probability estimate trend for HPCS EDG FTS
Figure 5	Table 20	Failure probability estimate trend for HPCS EDG FTLR
Figure 6	Table 21	Failure rate estimate trend for HPCS EDG FTR>1H
Figure 7	Table 22	EPS EDG UA trend
Figure 8	Table 23	HPCS EDG UA trend
Figure 9	Table 24	EPS EDG unreliability trend (8-hour mission)
Figure 10	Table 25	HPCS EDG unreliability trend (8-hour mission)
Figure 11	Table 26	Frequency of start demands (demands per reactor year) trend for EPS and HPCS EDGs
Figure 12	Table 27	Frequency of FTLR demands (demands per reactor year) trend for EPS and HPCS EDGs
Figure 13	Table 28	Frequency of run > 1H hours (hours per reactor year) trend for EPS and HPCS EDG
Figure 14	Table 29	Frequency of FTS events (events per reactor year) trend for EPS and HPCS EDGs
Figure 15	Table 30	Frequency of FTLR events (events per reactor year) trend for EPS and HPCS EDGs
Figure 16	Table 31	Frequency of FTR>1H events (events per reactor year) trend for EPS and HPCS EDGs

Table 16. Plot data for Figure 1, failure probability estimate trend for EPS EDG FTS.

Year	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	1.53E-03	3.02E-03	2.22E-03
1998	18	4,773	--	--	--	2.42E-03	5.24E-03	3.72E-03
1999	8	4,637	--	--	--	8.98E-04	2.85E-03	1.76E-03
2000	12	4,563	--	--	--	1.54E-03	3.95E-03	2.62E-03
2001	12	4,574	--	--	--	1.53E-03	3.94E-03	2.62E-03
2002	10	4,653	--	--	--	1.20E-03	3.37E-03	2.17E-03
2003	17	4,416	--	--	--	2.43E-03	5.39E-03	3.79E-03
2004	14	4,328	--	--	--	1.96E-03	4.70E-03	3.20E-03
2005	16	4,374	--	--	--	2.28E-03	5.18E-03	3.61E-03
2006	9	4,361	--	--	--	1.11E-03	3.31E-03	2.08E-03
2007	11	4,277	--	--	--	1.46E-03	3.93E-03	2.57E-03
2008	8	4,318	--	--	--	9.61E-04	3.06E-03	1.88E-03
2009	15	4,227	--	--	--	2.18E-03	5.08E-03	3.50E-03
2010	15	4,142	--	--	--	2.22E-03	5.18E-03	3.57E-03
2011	19	4,178	--	--	--	2.93E-03	6.22E-03	4.45E-03
2012	14	3,972	--	--	--	2.12E-03	5.10E-03	3.48E-03
2013	6	4,049	2.66E-03	1.43E-03	4.91E-03	6.94E-04	2.63E-03	1.53E-03
2014	12	4,019	2.47E-03	1.47E-03	4.13E-03	1.73E-03	4.46E-03	2.96E-03
2015	13	3,994	2.29E-03	1.48E-03	3.54E-03	1.93E-03	4.78E-03	3.22E-03
2016	13	4,011	2.13E-03	1.45E-03	3.11E-03	1.92E-03	4.76E-03	3.21E-03
2017	10	3,959	1.97E-03	1.37E-03	2.84E-03	1.40E-03	3.93E-03	2.53E-03
2018	7	3,964	1.83E-03	1.24E-03	2.71E-03	8.73E-04	3.00E-03	1.80E-03
2019	4	3,973	1.70E-03	1.08E-03	2.68E-03	3.99E-04	2.03E-03	1.08E-03
2020	4	3,941	1.58E-03	9.18E-04	2.72E-03	4.02E-04	2.05E-03	1.09E-03
2021	12	3,857	1.47E-03	7.70E-04	2.79E-03	1.80E-03	4.64E-03	3.08E-03
2022	3	3,868	1.36E-03	6.41E-04	2.89E-03	2.67E-04	1.73E-03	8.62E-04
Total	282	105,430	--	--	--	--	--	--

Table 17. Plot data for Figure 2, failure probability estimate trend for EPS EDG FTLR.

Year	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	1.05E-03	6.60E-03	3.31E-03
1998	14	4,098	--	--	--	2.08E-03	4.99E-03	3.40E-03
1999	5	4,039	--	--	--	5.45E-04	2.34E-03	1.31E-03
2000	8	4,140	--	--	--	1.01E-03	3.21E-03	1.98E-03
2001	13	4,168	--	--	--	1.86E-03	4.63E-03	3.12E-03
2002	14	3,930	--	--	--	2.16E-03	5.19E-03	3.54E-03
2003	15	3,876	--	--	--	2.39E-03	5.56E-03	3.83E-03
2004	10	3,821	--	--	--	1.46E-03	4.10E-03	2.64E-03
2005	15	3,784	--	--	--	2.44E-03	5.69E-03	3.92E-03
2006	15	3,756	--	--	--	2.46E-03	5.73E-03	3.95E-03
2007	21	3,642	--	--	--	3.80E-03	7.77E-03	5.64E-03
2008	16	3,718	--	--	--	2.69E-03	6.10E-03	4.25E-03
2009	18	3,673	--	--	--	3.14E-03	6.79E-03	4.81E-03
2010	11	3,625	--	--	--	1.73E-03	4.64E-03	3.04E-03
2011	16	3,659	--	--	--	2.73E-03	6.19E-03	4.31E-03
2012	17	3,509	--	--	--	3.06E-03	6.77E-03	4.76E-03
2013	12	3,525	3.81E-03	2.68E-03	5.41E-03	1.98E-03	5.10E-03	3.39E-03
2014	12	3,543	3.49E-03	2.60E-03	4.69E-03	1.97E-03	5.08E-03	3.37E-03
2015	13	3,501	3.21E-03	2.50E-03	4.11E-03	2.21E-03	5.47E-03	3.68E-03
2016	11	3,494	2.94E-03	2.37E-03	3.66E-03	1.79E-03	4.81E-03	3.15E-03
2017	9	3,451	2.70E-03	2.19E-03	3.33E-03	1.40E-03	4.17E-03	2.63E-03
2018	14	3,483	2.48E-03	1.97E-03	3.11E-03	2.43E-03	5.83E-03	3.97E-03
2019	7	3,419	2.27E-03	1.74E-03	2.96E-03	1.01E-03	3.49E-03	2.10E-03
2020	4	3,407	2.08E-03	1.52E-03	2.86E-03	4.66E-04	2.37E-03	1.26E-03
2021	5	3,352	1.91E-03	1.31E-03	2.78E-03	6.52E-04	2.80E-03	1.57E-03
2022	8	3,369	1.75E-03	1.13E-03	2.72E-03	1.23E-03	3.91E-03	2.41E-03
Total	303	91,980	--	--	--	--	--	--

Table 18. Plot data for Figure 3, failure rate estimate trend for EPS EDG FTR>1H.

Year	Failures	Run Time (hr)	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	3.90E-04	2.31E-03	1.18E-03
1998	4	11,285	--	--	--	1.41E-04	7.19E-04	3.83E-04
1999	1	11,694	--	--	--	1.45E-05	3.21E-04	1.23E-04
2000	7	13,607	--	--	--	2.58E-04	8.87E-04	5.32E-04
2001	2	14,162	--	--	--	3.91E-05	3.78E-04	1.71E-04
2002	7	13,233	--	--	--	2.65E-04	9.12E-04	5.47E-04
2003	10	11,931	--	--	--	4.67E-04	1.32E-03	8.46E-04
2004	13	11,733	--	--	--	6.61E-04	1.64E-03	1.11E-03
2005	14	12,293	--	--	--	6.93E-04	1.67E-03	1.14E-03
2006	4	11,365	--	--	--	1.40E-04	7.14E-04	3.80E-04
2007	17	11,458	--	--	--	9.41E-04	2.09E-03	1.47E-03
2008	20	11,615	--	--	--	1.13E-03	2.35E-03	1.70E-03
2009	8	11,637	--	--	--	3.58E-04	1.14E-03	7.02E-04
2010	13	11,299	--	--	--	6.86E-04	1.70E-03	1.15E-03
2011	21	12,332	--	--	--	1.13E-03	2.31E-03	1.68E-03
2012	11	7,352	--	--	--	8.36E-04	2.25E-03	1.47E-03
2013	17	7,913	2.37E-03	1.63E-03	3.47E-03	1.34E-03	2.97E-03	2.09E-03
2014	17	7,228	2.08E-03	1.52E-03	2.86E-03	1.46E-03	3.23E-03	2.27E-03
2015	12	7,788	1.83E-03	1.40E-03	2.38E-03	8.84E-04	2.28E-03	1.51E-03
2016	10	7,584	1.60E-03	1.26E-03	2.03E-03	7.19E-04	2.03E-03	1.30E-03
2017	22	7,390	1.40E-03	1.10E-03	1.78E-03	1.95E-03	3.92E-03	2.86E-03
2018	10	7,875	1.23E-03	9.41E-04	1.61E-03	6.94E-04	1.96E-03	1.26E-03
2019	8	7,389	1.08E-03	7.85E-04	1.48E-03	5.51E-04	1.75E-03	1.08E-03
2020	6	7,405	9.45E-04	6.47E-04	1.38E-03	3.74E-04	1.42E-03	8.25E-04
2021	4	7,186	8.29E-04	5.29E-04	1.30E-03	2.17E-04	1.10E-03	5.87E-04
2022	5	7,321	7.26E-04	4.31E-04	1.22E-03	2.93E-04	1.26E-03	7.05E-04
Total	263	252,074	--	--	--	--	--	--

Table 19. Plot data for Figure 4, failure probability estimate trend for HPCS EDG FTS.

Year	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	7.87E-04	4.00E-03	2.13E-03
1998	0	153	--	--	--	4.87E-06	4.91E-03	1.28E-03
1999	1	187	--	--	--	4.13E-04	9.17E-03	3.53E-03
2000	0	145	--	--	--	4.97E-06	5.02E-03	1.30E-03
2001	0	154	--	--	--	4.86E-06	4.90E-03	1.27E-03
2002	0	146	--	--	--	4.96E-06	5.01E-03	1.30E-03
2003	0	152	--	--	--	4.87E-06	4.92E-03	1.28E-03
2004	0	139	--	--	--	5.04E-06	5.09E-03	1.32E-03
2005	0	133	--	--	--	5.12E-06	5.17E-03	1.34E-03
2006	0	136	--	--	--	5.08E-06	5.13E-03	1.33E-03
2007	0	126	--	--	--	5.23E-06	5.28E-03	1.37E-03
2008	1	152	--	--	--	4.51E-04	1.00E-02	3.85E-03
2009	0	138	--	--	--	5.06E-06	5.11E-03	1.33E-03
2010	0	151	--	--	--	4.89E-06	4.94E-03	1.28E-03
2011	0	152	--	--	--	4.87E-06	4.92E-03	1.28E-03
2012	0	128	--	--	--	5.20E-06	5.25E-03	1.36E-03
2013	0	158	2.63E-03	9.63E-04	7.16E-03	4.80E-06	4.85E-03	1.26E-03
2014	1	136	2.73E-03	1.16E-03	6.38E-03	4.70E-04	1.04E-02	4.01E-03
2015	0	140	2.83E-03	1.38E-03	5.79E-03	5.03E-06	5.08E-03	1.32E-03
2016	0	138	2.94E-03	1.60E-03	5.40E-03	5.06E-06	5.11E-03	1.33E-03
2017	0	139	3.05E-03	1.76E-03	5.28E-03	5.05E-06	5.10E-03	1.32E-03
2018	1	144	3.17E-03	1.83E-03	5.49E-03	4.61E-04	1.02E-02	3.93E-03
2019	1	129	3.29E-03	1.78E-03	6.06E-03	4.79E-04	1.06E-02	4.09E-03
2020	2	139	3.41E-03	1.66E-03	7.00E-03	1.52E-03	1.46E-02	6.62E-03
2021	0	122	3.54E-03	1.50E-03	8.31E-03	5.29E-06	5.34E-03	1.39E-03
2022	0	131	3.67E-03	1.34E-03	1.00E-02	5.16E-06	5.21E-03	1.35E-03
Total	7	3,566	--	--	--	--	--	--

Table 20. Plot data for Figure 5, failure probability estimate trend for HPCS EDG FTLR.

Year	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	2.58E-04	1.67E-03	8.34E-04
1998	0	110	--	--	--	7.52E-06	7.79E-03	2.02E-03
1999	1	131	--	--	--	6.58E-04	1.46E-02	5.62E-03
2000	0	121	--	--	--	7.21E-06	7.47E-03	1.94E-03
2001	0	125	--	--	--	7.08E-06	7.34E-03	1.91E-03
2002	1	128	--	--	--	6.65E-04	1.48E-02	5.68E-03
2003	0	129	--	--	--	6.99E-06	7.24E-03	1.88E-03
2004	1	130	--	--	--	6.60E-04	1.47E-02	5.64E-03
2005	0	120	--	--	--	7.24E-06	7.50E-03	1.95E-03
2006	0	125	--	--	--	7.10E-06	7.36E-03	1.91E-03
2007	0	118	--	--	--	7.29E-06	7.56E-03	1.96E-03
2008	0	140	--	--	--	6.71E-06	6.95E-03	1.80E-03
2009	0	119	--	--	--	7.27E-06	7.54E-03	1.96E-03
2010	1	133	--	--	--	6.53E-04	1.45E-02	5.58E-03
2011	0	138	--	--	--	6.76E-06	7.01E-03	1.82E-03
2012	1	117	--	--	--	6.92E-04	1.54E-02	5.91E-03
2013	0	137	3.16E-03	1.37E-03	7.30E-03	6.76E-06	7.01E-03	1.82E-03
2014	1	118	3.40E-03	1.67E-03	6.92E-03	6.90E-04	1.53E-02	5.89E-03
2015	1	127	3.66E-03	2.01E-03	6.65E-03	6.66E-04	1.48E-02	5.69E-03
2016	0	126	3.94E-03	2.37E-03	6.55E-03	7.05E-06	7.31E-03	1.90E-03
2017	0	125	4.24E-03	2.69E-03	6.69E-03	7.08E-06	7.34E-03	1.90E-03
2018	1	129	4.57E-03	2.89E-03	7.19E-03	6.61E-04	1.47E-02	5.64E-03
2019	0	116	4.91E-03	2.97E-03	8.13E-03	7.33E-06	7.60E-03	1.97E-03
2020	1	125	5.29E-03	2.92E-03	9.54E-03	6.71E-04	1.49E-02	5.73E-03
2021	1	114	5.69E-03	2.81E-03	1.15E-02	7.01E-04	1.56E-02	5.99E-03
2022	1	121	6.12E-03	2.67E-03	1.40E-02	6.83E-04	1.52E-02	5.83E-03
Total	11	3,123	--	--	--	--	--	--

Table 21. Plot data for Figure 6, failure rate estimate trend for HPCS EDG FTR>1H.

Year	Failures	Run Time (hr)	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	2.58E-04	1.67E-03	2.58E-04
1998	0	317	--	--	--	2.41E-06	2.35E-03	6.12E-04
1999	1	459	--	--	--	1.83E-04	4.07E-03	1.56E-03
2000	0	348	--	--	--	2.32E-06	2.26E-03	5.89E-04
2001	0	361	--	--	--	2.28E-06	2.23E-03	5.80E-04
2002	0	350	--	--	--	2.31E-06	2.26E-03	5.88E-04
2003	0	390	--	--	--	2.21E-06	2.16E-03	5.61E-04
2004	0	331	--	--	--	2.37E-06	2.31E-03	6.02E-04
2005	1	376	--	--	--	2.01E-04	4.46E-03	1.71E-03
2006	0	378	--	--	--	2.24E-06	2.19E-03	5.69E-04
2007	0	306	--	--	--	2.44E-06	2.38E-03	6.20E-04
2008	0	452	--	--	--	2.07E-06	2.02E-03	5.25E-04
2009	0	380	--	--	--	2.23E-06	2.18E-03	5.68E-04
2010	1	391	--	--	--	1.97E-04	4.38E-03	1.68E-03
2011	0	424	--	--	--	2.13E-06	2.08E-03	5.41E-04
2012	0	161	--	--	--	2.97E-06	2.90E-03	7.56E-04
2013	1	297	2.16E-03	8.57E-04	5.44E-03	2.21E-04	4.90E-03	1.88E-03
2014	0	193	2.04E-03	9.31E-04	4.48E-03	2.84E-06	2.77E-03	7.21E-04
2015	0	228	1.93E-03	9.96E-04	3.73E-03	2.70E-06	2.64E-03	6.87E-04
2016	1	205	1.82E-03	1.04E-03	3.19E-03	2.50E-04	5.54E-03	2.13E-03
2017	0	194	1.72E-03	1.04E-03	2.84E-03	2.83E-06	2.77E-03	7.20E-04
2018	2	185	1.62E-03	9.91E-04	2.67E-03	8.35E-04	8.07E-03	3.65E-03
2019	0	194	1.53E-03	8.90E-04	2.65E-03	2.83E-06	2.76E-03	7.20E-04
2020	0	203	1.45E-03	7.66E-04	2.74E-03	2.79E-06	2.73E-03	7.11E-04
2021	0	191	1.37E-03	6.42E-04	2.92E-03	2.84E-06	2.78E-03	7.23E-04
2022	0	190	1.29E-03	5.29E-04	3.16E-03	2.85E-06	2.78E-03	7.24E-04
Total	7	7,506	--	--	--	--	--	--

Table 22. Plot data for Figure 7, EPS EDG UA trend.

Year	UA Hours	Critical Hours	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	3.48E-03	2.67E-02	1.51E-02
1998	21,235	1,874,166	--	--	--	2.01E-03	2.42E-02	1.04E-02
1999	22,769	2,005,223	--	--	--	2.55E-03	2.42E-02	1.10E-02
2000	18,409	2,042,467	--	--	--	2.27E-03	2.08E-02	9.53E-03
2001	19,233	2,075,373	--	--	--	1.54E-03	2.36E-02	9.72E-03
2002	24,631	2,093,196	--	--	--	2.31E-03	2.78E-02	1.20E-02
2003	28,961	2,047,203	--	--	--	1.91E-03	3.49E-02	1.39E-02
2004	29,617	2,099,392	--	--	--	1.24E-03	3.71E-02	1.36E-02
2005	26,350	2,070,016	--	--	--	2.81E-03	2.90E-02	1.29E-02
2006	28,713	2,083,212	--	--	--	1.73E-03	3.36E-02	1.33E-02
2007	34,106	2,104,115	--	--	--	2.41E-03	3.99E-02	1.62E-02
2008	31,755	2,089,978	--	--	--	2.87E-03	3.53E-02	1.52E-02
2009	33,204	2,059,429	--	--	--	2.86E-03	3.79E-02	1.61E-02
2010	30,037	2,081,690	--	--	--	3.32E-03	3.16E-02	1.44E-02
2011	36,401	2,023,478	--	--	--	2.95E-03	4.18E-02	1.75E-02
2012	32,470	1,977,596	--	--	--	3.02E-03	3.68E-02	1.59E-02
2013	30,642	2,007,371	1.48E-02	1.33E-02	1.64E-02	2.29E-03	3.34E-02	1.39E-02
2014	28,292	2,027,147	1.46E-02	1.34E-02	1.58E-02	3.15E-03	3.19E-02	1.43E-02
2015	30,706	2,008,809	1.43E-02	1.34E-02	1.52E-02	3.65E-03	3.36E-02	1.54E-02
2016	29,859	2,025,233	1.40E-02	1.35E-02	1.45E-02	2.95E-04	5.06E-02	1.51E-02
2017	30,465	1,997,343	1.38E-02	1.36E-02	1.39E-02	2.00E-03	3.69E-02	1.47E-02
2018	25,798	1,990,438	1.35E-02	1.33E-02	1.37E-02	2.85E-03	2.92E-02	1.30E-02
2019	24,498	1,975,944	1.32E-02	1.27E-02	1.37E-02	2.19E-03	2.88E-02	1.22E-02
2020	21,822	1,887,082	1.29E-02	1.21E-02	1.38E-02	1.30E-03	2.96E-02	1.14E-02
2021	24,031	1,824,673	1.27E-02	1.15E-02	1.39E-02	2.35E-03	2.99E-02	1.28E-02
2022	23,836	1,807,766	1.24E-02	1.08E-02	1.39E-02	2.93E-03	3.02E-02	1.35E-02
Total	687,841	50,278,341	--	--	--	--	--	--

Table 23. Plot data for Figure 8, HPCS EDG UA trend.

Year	UA Hours	Critical Hours	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	7.13E-03	1.94E-02	1.33E-02
1998	255	42,029	--	--	--	4.24E-04	1.15E-02	4.27E-03
1999	760	55,565	--	--	--	7.09E-04	3.99E-02	1.35E-02
2000	959	65,705	--	--	--	8.40E-04	4.33E-02	1.48E-02
2001	474	65,093	--	--	--	1.27E-03	1.69E-02	7.13E-03
2002	431	65,329	--	--	--	1.14E-03	1.59E-02	6.66E-03
2003	825	65,040	--	--	--	6.07E-03	2.11E-02	1.26E-02
2004	855	65,589	--	--	--	4.00E-03	2.63E-02	1.31E-02
2005	610	64,383	--	--	--	3.59E-03	1.75E-02	9.42E-03
2006	453	66,949	--	--	--	1.85E-03	1.40E-02	6.71E-03
2007	592	64,512	--	--	--	1.92E-03	2.07E-02	9.14E-03
2008	861	65,262	--	--	--	2.31E-03	3.24E-02	1.36E-02
2009	519	63,966	--	--	--	2.54E-03	1.63E-02	8.13E-03
2010	1,050	67,158	--	--	--	2.34E-03	3.80E-02	1.55E-02
2011	991	62,329	--	--	--	4.37E-03	3.29E-02	1.58E-02
2012	815	64,557	--	--	--	2.20E-03	2.92E-02	1.24E-02
2013	952	64,142	1.26E-02	6.95E-03	1.82E-02	2.33E-03	3.51E-02	1.45E-02
2014	1,012	66,677	1.31E-02	8.76E-03	1.75E-02	2.39E-03	3.66E-02	1.51E-02
2015	627	65,277	1.37E-02	1.06E-02	1.68E-02	1.40E-03	2.37E-02	9.56E-03
2016	884	62,704	1.43E-02	1.24E-02	1.61E-02	3.09E-03	3.03E-02	1.37E-02
2017	827	63,353	1.48E-02	1.42E-02	1.55E-02	1.76E-03	3.45E-02	1.36E-02
2018	1,346	64,262	1.54E-02	1.48E-02	1.60E-02	1.46E-03	6.04E-02	2.12E-02
2019	593	65,338	1.60E-02	1.41E-02	1.78E-02	3.04E-03	1.77E-02	9.08E-03
2020	1,332	65,659	1.65E-02	1.34E-02	1.97E-02	6.53E-03	4.20E-02	2.10E-02
2021	739	65,168	1.71E-02	1.27E-02	2.15E-02	1.33E-03	3.00E-02	1.15E-02
2022	1,455	66,249	1.76E-02	1.20E-02	2.33E-02	6.01E-03	4.57E-02	2.19E-02
Total	20,217	1,592,295	--	--	--	--	--	--

Table 24. Plot data for Figure 9, EPS EDG unreliability trend (8-hour mission).

Year	Regression Curve Data Points			Plot Trend Error Bar Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	--	--	--	1.07E-02	3.31E-02	1.96E-02
1999	--	--	--	6.49E-03	2.79E-02	1.50E-02
2000	--	--	--	1.02E-02	2.94E-02	1.81E-02
2001	--	--	--	7.82E-03	3.13E-02	1.67E-02
2002	--	--	--	1.08E-02	3.68E-02	2.12E-02
2003	--	--	--	1.45E-02	4.60E-02	2.70E-02
2004	--	--	--	1.40E-02	5.17E-02	2.71E-02
2005	--	--	--	1.69E-02	4.39E-02	2.79E-02
2006	--	--	--	9.88E-03	4.26E-02	2.19E-02
2007	--	--	--	1.91E-02	5.65E-02	3.40E-02
2008	--	--	--	1.94E-02	5.44E-02	3.30E-02
2009	--	--	--	1.59E-02	5.30E-02	2.97E-02
2010	--	--	--	1.68E-02	4.78E-02	2.92E-02
2011	--	--	--	2.18E-02	6.15E-02	3.71E-02
2012	--	--	--	2.02E-02	5.52E-02	3.41E-02
2013	3.70E-02	3.08E-02	4.45E-02	1.94E-02	5.08E-02	3.23E-02
2014	3.46E-02	2.96E-02	4.05E-02	2.27E-02	5.36E-02	3.54E-02
2015	3.24E-02	2.84E-02	3.69E-02	1.96E-02	5.05E-02	3.28E-02
2016	3.03E-02	2.71E-02	3.39E-02	1.37E-02	6.17E-02	2.94E-02
2017	2.84E-02	2.56E-02	3.14E-02	2.41E-02	6.33E-02	3.91E-02
2018	2.65E-02	2.40E-02	2.93E-02	1.62E-02	4.58E-02	2.78E-02
2019	2.48E-02	2.22E-02	2.78E-02	1.16E-02	3.96E-02	2.25E-02
2020	2.32E-02	2.04E-02	2.65E-02	8.05E-03	3.87E-02	1.94E-02
2021	2.17E-02	1.86E-02	2.54E-02	1.03E-02	3.92E-02	2.13E-02
2022	2.03E-02	1.69E-02	2.44E-02	1.01E-02	3.89E-02	2.16E-02

Table 25. Plot data for Figure 10, HPCS EDG unreliability trend (8-hour mission).

Year	Regression Curve Data Points			Plot Trend Error Bar Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	--	--	--	2.89E-03	2.62E-02	1.18E-02
1999	--	--	--	1.26E-02	6.52E-02	3.39E-02
2000	--	--	--	4.33E-03	5.21E-02	2.14E-02
2001	--	--	--	4.02E-03	3.04E-02	1.42E-02
2002	--	--	--	5.88E-03	3.61E-02	1.82E-02
2003	--	--	--	9.03E-03	3.47E-02	1.95E-02
2004	--	--	--	9.92E-03	4.02E-02	2.34E-02
2005	--	--	--	9.85E-03	4.39E-02	2.37E-02
2006	--	--	--	4.56E-03	2.68E-02	1.37E-02
2007	--	--	--	5.32E-03	3.37E-02	1.67E-02
2008	--	--	--	7.86E-03	4.63E-02	2.27E-02
2009	--	--	--	5.45E-03	2.85E-02	1.48E-02
2010	--	--	--	1.34E-02	6.42E-02	3.43E-02
2011	--	--	--	8.11E-03	4.35E-02	2.27E-02
2012	--	--	--	8.68E-03	4.80E-02	2.36E-02
2013	2.72E-02	1.79E-02	4.13E-02	1.06E-02	5.82E-02	2.96E-02
2014	2.75E-02	1.93E-02	3.93E-02	1.06E-02	5.63E-02	2.94E-02
2015	2.79E-02	2.07E-02	3.76E-02	6.95E-03	4.24E-02	2.12E-02
2016	2.83E-02	2.20E-02	3.65E-02	1.17E-02	5.90E-02	3.11E-02
2017	2.87E-02	2.28E-02	3.61E-02	5.23E-03	4.86E-02	2.13E-02
2018	2.91E-02	2.31E-02	3.66E-02	2.26E-02	1.02E-01	5.51E-02
2019	2.95E-02	2.29E-02	3.80E-02	8.03E-03	3.67E-02	1.95E-02
2020	2.99E-02	2.22E-02	4.03E-02	1.73E-02	6.54E-02	3.81E-02
2021	3.03E-02	2.13E-02	4.32E-02	7.83E-03	5.08E-02	2.42E-02
2022	3.07E-02	2.02E-02	4.67E-02	1.39E-02	6.03E-02	3.35E-02

Table 26. Plot data for Figure 11, frequency of start demands (demands per reactor year) trend for EPS and HPCS EDGs.

Year	Demands	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	4,926	96.0	--	--	--	5.01E+01	5.25E+01	5.13E+01
1999	4,824	96.0	--	--	--	4.91E+01	5.15E+01	5.03E+01
2000	4,708	96.3	--	--	--	4.77E+01	5.01E+01	4.89E+01
2001	4,728	96.0	--	--	--	4.81E+01	5.04E+01	4.92E+01
2002	4,798	96.0	--	--	--	4.88E+01	5.12E+01	5.00E+01
2003	4,568	96.0	--	--	--	4.64E+01	4.88E+01	4.76E+01
2004	4,468	96.3	--	--	--	4.53E+01	4.76E+01	4.64E+01
2005	4,507	96.0	--	--	--	4.58E+01	4.81E+01	4.69E+01
2006	4,498	96.0	--	--	--	4.57E+01	4.80E+01	4.69E+01
2007	4,403	96.0	--	--	--	4.47E+01	4.70E+01	4.59E+01
2008	4,470	96.3	--	--	--	4.53E+01	4.76E+01	4.64E+01
2009	4,365	96.0	--	--	--	4.43E+01	4.66E+01	4.55E+01
2010	4,293	96.0	--	--	--	4.36E+01	4.59E+01	4.47E+01
2011	4,330	96.0	--	--	--	4.40E+01	4.63E+01	4.51E+01
2012	4,100	96.3	--	--	--	4.15E+01	4.37E+01	4.26E+01
2013	4,207	93.6	4.47E+01	4.42E+01	4.52E+01	4.38E+01	4.61E+01	4.50E+01
2014	4,154	92.0	4.50E+01	4.46E+01	4.54E+01	4.40E+01	4.63E+01	4.52E+01
2015	4,133	91.0	4.53E+01	4.50E+01	4.57E+01	4.43E+01	4.66E+01	4.54E+01
2016	4,148	91.0	4.57E+01	4.54E+01	4.59E+01	4.44E+01	4.68E+01	4.56E+01
2017	4,097	90.0	4.60E+01	4.57E+01	4.62E+01	4.44E+01	4.67E+01	4.55E+01
2018	4,107	89.7	4.63E+01	4.60E+01	4.66E+01	4.46E+01	4.70E+01	4.58E+01
2019	4,102	88.0	4.66E+01	4.63E+01	4.69E+01	4.54E+01	4.78E+01	4.66E+01
2020	4,080	86.2	4.70E+01	4.66E+01	4.73E+01	4.61E+01	4.86E+01	4.73E+01
2021	3,979	84.3	4.73E+01	4.69E+01	4.77E+01	4.60E+01	4.84E+01	4.72E+01
2022	3,999	83.4	4.76E+01	4.71E+01	4.81E+01	4.67E+01	4.92E+01	4.79E+01
Total	108,995	2,330.3	--	--	--	--	--	--

Table 27. Plot data for Figure 12, frequency of FTLR demands (demands per reactor year) trend for EPS and HPCS EDGs.

Year	Demands	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	4,208	96.0	--	--	--	4.27E+01	4.50E+01	4.38E+01
1999	4,169	96.0	--	--	--	4.23E+01	4.46E+01	4.34E+01
2000	4,261	96.3	--	--	--	4.32E+01	4.54E+01	4.43E+01
2001	4,294	96.0	--	--	--	4.36E+01	4.59E+01	4.47E+01
2002	4,058	96.0	--	--	--	4.12E+01	4.34E+01	4.23E+01
2003	4,005	96.0	--	--	--	4.06E+01	4.28E+01	4.17E+01
2004	3,951	96.3	--	--	--	4.00E+01	4.21E+01	4.10E+01
2005	3,903	96.0	--	--	--	3.96E+01	4.17E+01	4.07E+01
2006	3,881	96.0	--	--	--	3.94E+01	4.15E+01	4.04E+01
2007	3,760	96.0	--	--	--	3.81E+01	4.02E+01	3.92E+01
2008	3,858	96.3	--	--	--	3.90E+01	4.12E+01	4.01E+01
2009	3,792	96.0	--	--	--	3.85E+01	4.06E+01	3.95E+01
2010	3,758	96.0	--	--	--	3.81E+01	4.02E+01	3.91E+01
2011	3,796	96.0	--	--	--	3.85E+01	4.06E+01	3.95E+01
2012	3,626	96.3	--	--	--	3.66E+01	3.87E+01	3.77E+01
2013	3,663	93.6	3.92E+01	3.87E+01	3.96E+01	3.81E+01	4.02E+01	3.91E+01
2014	3,662	92.0	3.94E+01	3.90E+01	3.98E+01	3.87E+01	4.09E+01	3.98E+01
2015	3,628	91.0	3.97E+01	3.93E+01	4.00E+01	3.88E+01	4.10E+01	3.99E+01
2016	3,620	91.0	3.99E+01	3.96E+01	4.02E+01	3.87E+01	4.09E+01	3.98E+01
2017	3,576	90.0	4.01E+01	3.99E+01	4.04E+01	3.86E+01	4.08E+01	3.97E+01
2018	3,612	89.7	4.04E+01	4.01E+01	4.06E+01	3.92E+01	4.14E+01	4.02E+01
2019	3,536	88.0	4.06E+01	4.03E+01	4.09E+01	3.91E+01	4.13E+01	4.02E+01
2020	3,532	86.2	4.09E+01	4.05E+01	4.12E+01	3.98E+01	4.21E+01	4.10E+01
2021	3,467	84.3	4.11E+01	4.07E+01	4.15E+01	4.00E+01	4.23E+01	4.11E+01
2022	3,490	83.4	4.14E+01	4.09E+01	4.19E+01	4.07E+01	4.30E+01	4.18E+01
Total	95,103	2,330.3	--	--	--	--	--	--

Table 28. Plot data for Figure 13, frequency of run > 1H hours (hours per reactor year) trend for EPS and HPCS EDG.

Year	Run Hours	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	11,602	96.0	--	--	--	1.19E+02	1.23E+02	1.21E+02
1999	12,153	96.0	--	--	--	1.25E+02	1.28E+02	1.27E+02
2000	13,955	96.3	--	--	--	1.43E+02	1.47E+02	1.45E+02
2001	14,523	96.0	--	--	--	1.49E+02	1.53E+02	1.51E+02
2002	13,583	96.0	--	--	--	1.39E+02	1.43E+02	1.41E+02
2003	12,321	96.0	--	--	--	1.26E+02	1.30E+02	1.28E+02
2004	12,064	96.3	--	--	--	1.23E+02	1.27E+02	1.25E+02
2005	12,669	96.0	--	--	--	1.30E+02	1.34E+02	1.32E+02
2006	11,743	96.0	--	--	--	1.20E+02	1.24E+02	1.22E+02
2007	11,764	96.0	--	--	--	1.21E+02	1.24E+02	1.23E+02
2008	12,067	96.3	--	--	--	1.23E+02	1.27E+02	1.25E+02
2009	12,017	96.0	--	--	--	1.23E+02	1.27E+02	1.25E+02
2010	11,690	96.0	--	--	--	1.20E+02	1.24E+02	1.22E+02
2011	12,756	96.0	--	--	--	1.31E+02	1.35E+02	1.33E+02
2012	7,513	96.3	--	--	--	7.66E+01	7.95E+01	7.80E+01
2013	8,210	93.6	8.47E+01	8.10E+01	8.85E+01	8.62E+01	8.94E+01	8.77E+01
2014	7,421	92.0	8.52E+01	8.20E+01	8.84E+01	7.91E+01	8.22E+01	8.07E+01
2015	8,016	91.0	8.56E+01	8.30E+01	8.83E+01	8.65E+01	8.97E+01	8.81E+01
2016	7,789	91.0	8.61E+01	8.38E+01	8.84E+01	8.40E+01	8.72E+01	8.56E+01
2017	7,584	90.0	8.65E+01	8.45E+01	8.87E+01	8.27E+01	8.59E+01	8.43E+01
2018	8,061	89.7	8.70E+01	8.49E+01	8.92E+01	8.82E+01	9.15E+01	8.98E+01
2019	7,584	88.0	8.75E+01	8.51E+01	8.99E+01	8.46E+01	8.78E+01	8.62E+01
2020	7,608	86.2	8.79E+01	8.52E+01	9.08E+01	8.66E+01	8.99E+01	8.82E+01
2021	7,377	84.3	8.84E+01	8.51E+01	9.19E+01	8.58E+01	8.92E+01	8.75E+01
2022	7,511	83.4	8.89E+01	8.50E+01	9.30E+01	8.83E+01	9.18E+01	9.00E+01
Total	259,580	2,330.3	--	--	--	--	--	--

Table 29. Plot data for Figure 14, frequency of FTS events (events per reactor year) trend for EPS and HPCS EDGs.

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	18	96.0	--	--	--	1.19E-01	2.70E-01	1.83E-01
1999	9	96.0	--	--	--	5.01E-02	1.62E-01	9.41E-02
2000	12	96.3	--	--	--	7.22E-02	1.98E-01	1.23E-01
2001	12	96.0	--	--	--	7.24E-02	1.99E-01	1.24E-01
2002	10	96.0	--	--	--	5.74E-02	1.74E-01	1.04E-01
2003	17	96.0	--	--	--	1.11E-01	2.58E-01	1.73E-01
2004	14	96.3	--	--	--	8.75E-02	2.22E-01	1.43E-01
2005	16	96.0	--	--	--	1.03E-01	2.47E-01	1.63E-01
2006	9	96.0	--	--	--	5.01E-02	1.62E-01	9.41E-02
2007	11	96.0	--	--	--	6.48E-02	1.86E-01	1.14E-01
2008	9	96.3	--	--	--	5.00E-02	1.61E-01	9.38E-02
2009	15	96.0	--	--	--	9.55E-02	2.35E-01	1.54E-01
2010	15	96.0	--	--	--	9.55E-02	2.35E-01	1.54E-01
2011	19	96.0	--	--	--	1.27E-01	2.82E-01	1.93E-01
2012	14	96.3	--	--	--	8.75E-02	2.22E-01	1.43E-01
2013	6	93.6	1.18E-01	6.64E-02	2.10E-01	2.99E-02	1.27E-01	6.60E-02
2014	13	92.0	1.12E-01	6.87E-02	1.82E-01	8.33E-02	2.19E-01	1.39E-01
2015	13	91.0	1.06E-01	7.02E-02	1.59E-01	8.42E-02	2.22E-01	1.41E-01
2016	13	91.0	9.99E-02	7.01E-02	1.42E-01	8.42E-02	2.22E-01	1.41E-01
2017	10	90.0	9.45E-02	6.77E-02	1.32E-01	6.10E-02	1.85E-01	1.11E-01
2018	8	89.7	8.94E-02	6.28E-02	1.27E-01	4.58E-02	1.59E-01	8.97E-02
2019	5	88.0	8.45E-02	5.62E-02	1.27E-01	2.46E-02	1.20E-01	5.92E-02
2020	6	86.2	7.99E-02	4.92E-02	1.30E-01	3.23E-02	1.37E-01	7.13E-02
2021	12	84.3	7.56E-02	4.25E-02	1.34E-01	8.18E-02	2.25E-01	1.40E-01
2022	3	83.4	7.15E-02	3.64E-02	1.40E-01	1.23E-02	9.57E-02	3.96E-02
Total	289	2,330.3	--	--	--	--	--	--

Table 30. Plot data for Figure 15, frequency of FTLR events (events per reactor year) trend for EPS and HPCS EDGs.

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	14	96.0	--	--	--	8.80E-02	2.23E-01	1.44E-01
1999	5	96.0	--	--	--	2.27E-02	1.11E-01	5.46E-02
2000	8	96.3	--	--	--	4.30E-02	1.49E-01	8.42E-02
2001	13	96.0	--	--	--	8.02E-02	2.11E-01	1.34E-01
2002	14	96.0	--	--	--	8.80E-02	2.23E-01	1.44E-01
2003	15	96.0	--	--	--	9.58E-02	2.35E-01	1.54E-01
2004	10	96.3	--	--	--	5.74E-02	1.74E-01	1.04E-01
2005	15	96.0	--	--	--	9.58E-02	2.35E-01	1.54E-01
2006	15	96.0	--	--	--	9.58E-02	2.35E-01	1.54E-01
2007	21	96.0	--	--	--	1.44E-01	3.06E-01	2.14E-01
2008	16	96.3	--	--	--	1.03E-01	2.47E-01	1.63E-01
2009	18	96.0	--	--	--	1.20E-01	2.71E-01	1.84E-01
2010	11	96.0	--	--	--	6.50E-02	1.87E-01	1.14E-01
2011	16	96.0	--	--	--	1.04E-01	2.47E-01	1.64E-01
2012	17	96.3	--	--	--	1.11E-01	2.59E-01	1.73E-01
2013	12	93.6	1.44E-01	1.01E-01	2.06E-01	7.44E-02	2.04E-01	1.27E-01
2014	12	92.0	1.33E-01	9.89E-02	1.79E-01	7.56E-02	2.08E-01	1.29E-01
2015	13	91.0	1.23E-01	9.57E-02	1.58E-01	8.44E-02	2.22E-01	1.41E-01
2016	11	91.0	1.13E-01	9.11E-02	1.41E-01	6.84E-02	1.97E-01	1.20E-01
2017	9	90.0	1.05E-01	8.47E-02	1.29E-01	5.34E-02	1.73E-01	1.00E-01
2018	14	89.7	9.65E-02	7.68E-02	1.21E-01	9.38E-02	2.38E-01	1.54E-01
2019	7	88.0	8.90E-02	6.83E-02	1.16E-01	3.92E-02	1.49E-01	8.09E-02
2020	4	86.2	8.21E-02	5.99E-02	1.13E-01	1.83E-02	1.08E-01	4.95E-02
2021	5	84.3	7.57E-02	5.21E-02	1.10E-01	2.57E-02	1.26E-01	6.18E-02
2022	8	83.4	6.99E-02	4.51E-02	1.08E-01	4.92E-02	1.71E-01	9.65E-02
Total	303	2,330.3	--	--	--	--	--	--

Table 31. Plot data for Figure 16, frequency of FTR>1H events (events per reactor year) trend for EPS and HPCS EDGs.

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	4	96.0	--	--	--	1.66E-02	9.84E-02	4.50E-02
1999	1	96.0	--	--	--	1.76E-03	5.54E-02	1.50E-02
2000	7	96.3	--	--	--	3.62E-02	1.38E-01	7.48E-02
2001	2	96.0	--	--	--	5.73E-03	7.03E-02	2.50E-02
2002	7	96.0	--	--	--	3.63E-02	1.38E-01	7.50E-02
2003	10	96.0	--	--	--	5.80E-02	1.76E-01	1.05E-01
2004	13	96.3	--	--	--	8.06E-02	2.12E-01	1.35E-01
2005	14	96.0	--	--	--	8.85E-02	2.25E-01	1.45E-01
2006	4	96.0	--	--	--	1.66E-02	9.84E-02	4.50E-02
2007	17	96.0	--	--	--	1.12E-01	2.61E-01	1.75E-01
2008	20	96.3	--	--	--	1.36E-01	2.96E-01	2.04E-01
2009	8	96.0	--	--	--	4.34E-02	1.51E-01	8.50E-02
2010	13	96.0	--	--	--	8.08E-02	2.13E-01	1.35E-01
2011	21	96.0	--	--	--	1.45E-01	3.08E-01	2.15E-01
2012	11	96.3	--	--	--	6.53E-02	1.88E-01	1.15E-01
2013	17	93.6	1.97E-01	1.36E-01	2.84E-01	1.15E-01	2.67E-01	1.79E-01
2014	17	92.0	1.73E-01	1.27E-01	2.35E-01	1.17E-01	2.72E-01	1.82E-01
2015	12	91.0	1.53E-01	1.18E-01	1.98E-01	7.69E-02	2.11E-01	1.32E-01
2016	10	91.0	1.34E-01	1.07E-01	1.69E-01	6.10E-02	1.85E-01	1.11E-01
2017	22	90.0	1.18E-01	9.40E-02	1.49E-01	1.63E-01	3.40E-01	2.39E-01
2018	10	89.7	1.04E-01	8.05E-02	1.35E-01	6.18E-02	1.88E-01	1.12E-01
2019	8	88.0	9.19E-02	6.76E-02	1.25E-01	4.71E-02	1.64E-01	9.24E-02
2020	6	86.2	8.10E-02	5.61E-02	1.17E-01	3.27E-02	1.39E-01	7.20E-02
2021	4	84.3	7.14E-02	4.62E-02	1.10E-01	1.88E-02	1.11E-01	5.10E-02
2022	5	83.4	6.29E-02	3.79E-02	1.04E-01	2.62E-02	1.28E-01	6.29E-02
Total	263	2,330.3	--	--	--	--	--	--

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