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Enhanced Component Performance Study: Emergency Diesel Generators 1998–2016

John A. Schroeder

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John A. Schroeder

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Idaho National Laboratory
Risk Assessment and Management Services Department
Idaho Falls, Idaho 83415

http://www.inl.gov

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ABSTRACT

This report presents an enhanced performance evaluation of 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) Consolidated Events Database (ICES) data from 1998 through 2016 and (2) maintenance unavailability (UA) performance data from Mitigating Systems Performance Index (MSPI) Basis Document data from 2002 through 2016. 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. 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 are: sub-component, failure cause, detection method, recovery, manufacturer, and EDG rating. Four trends with varying degrees of statistical significance were identified in the data.

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ACRONYMS

CNID	constrained non-informative prior distribution
CY	calendar year
EDG	emergency diesel generator
EPIX	Equipment Performance and Information Exchange
EPS	emergency power supply
ESF	engineered safety feature
FTLR	failure to load and run
FTR>1H	failure to run > 1 hour
FTS	failure to start
FY	fiscal year
HPCS	high-pressure core spray
ICES	INPO Consolidated Events Database
INL	Idaho National laboratory
INPO	Institute of Nuclear Power Operations
MSPI	Mitigating Systems Performance Index
NPRDS	Nuclear Plant Reliability Data System
OLS	ordinary least squares
PRA	probabilistic risk assessment
UA	unavailability

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1. INTRODUCTION

This report presents a performance evaluation of emergency diesel generators (EDGs) at U.S. commercial nuclear power plants from 1998 through 2016. 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 has three changes from previous year's updates: 1) this year's results are based on calendar year (CY) instead of fiscal year (FY); 2) the failure events included in this update are now all considered "hard" failures, which is to say the p-values indicating the likelihood the component would have failed during a 24-hour mission are now all 1.0. Previous updates include lesser p-values indicating a degraded condition that probably would have caused failure during a 24-hour mission. 3) The discussion of EDG repair times, which was previously included in the annual LOOP updates (see http://nrcoe.inl.gov/resultsdb/LOSP), is added to this report.

The data used in this study were based on the operating experience failure reports from the Institute of Nuclear Power Operations' (INPO) and Consolidated Events Database (ICES) Database [1]; formerly the Equipment Performance and Information Exchange Database (EPIX). Maintenance unavailability (UA) performance data comes from Mitigating Systems Performance Index (MSPI) data from 2002 through 2016 [2]. The EDG failure modes considered are failure to start (FTS), failure to load and run (FTLR), and failure to run greater than hour (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. The results are reported separately for emergency power system (EPS) and high pressure core spray (HPCS) EDGs.

Each of the estimates is trended for the most recent 10-year period. Yearly estimates have been provided for the entire study period.

This study is modeled on the web page updates associated with the NUREG-1715 series of reports [3], which were published around 2000. Those studies relied on operating experience obtained from licensee event reports, the Nuclear Plant Reliability Data System (NPRDS), and ICES. The ICES database, which includes the MSPI as a subset, has matured to the point where component availability and reliability can be estimated with a higher degree of accuracy. In addition, the population of data in ICES has been growing and is much larger than the population used in the previous studies.

While this report provides an overview of operational data and evaluate component performance over time, it makes no attempt to estimate values for use in probabilistic risk assessments (PRAs). The 2015 Component Reliability Update [4], is an update to the report: *Industry-Average Performance for Components and Initiating Events at U.S Commercial Nuclear Power Plants* [5] and reports the EDG unreliability estimates for probabilistic risk assessments. Estimates from that report are included herein, for comparison. These estimates are labelled "2015 Update" (or "Update 2015") in the associated tables and figures.

Engineering analyses were also performed with respect to time period and failure modes. In Section 6.1, the same failures used in Section 3 are used to compute estimates of overall failure frequencies per plant reactor year (with EPS and HPCS EDG failures combined). Frequencies of demands per plant reactor year are also provided for each year, 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 "2015 Update." First, the subset of failure events and demands from this report that occurred on unplanned demands (engineered safety feature actuations) is compared for consistency with the 2015 Update data. This evaluation provided a check on the ongoing use of the 2015 Update EDG data (which includes failures from possibly incomplete testing 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: sub-component, failure cause, detection method, and recovery.

Finally, Section 7 provides additional information on the EDG assembly component boundaries and failure modes.

An overview of the trending methods, glossary of terms, and abbreviations can be found in the Overview and Reference document [6] on the Reactor Operational Experience Results and Databases web page (http://nrcoe.inl.gov/resultsdb).

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

2.1.1 Extremely Statistically Significant

- None.

2.1.2 Highly Statistically Significant

- None.

2.1.3 Statistically Significant

- A statistically significant increasing trend was identified in the EDG data for HPCS EDG unreliability (8-hour mission) (see Figure 10).

2.2 Decreasing Trends

2.2.1 Extremely Statistically Significant

- None

2.2.2 Highly Statistically Significant

- EPS and HPCS EDG run hours per reactor year (see Figure 13).

2.2.3 Statistically Significant

- Failure probability estimate trend for EPS EDG fail to load and run (see Figure 2).
- Frequency, events per year, of fail to load-run for EPS and HPCS EDGs (see Figure 15).

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 shows the results of a consistency check between industry failure rate estimates and failure counts collected from EDG performance on ESF demands. The consistency checks using ESF demand data indicate that the FTS, FTLR and FTR failure counts are consistent with predictions made using the industry-average estimates from the 2015 Update (Table 2).

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 rest

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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 that 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).

of the manufacturer's 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 ICES includes EDGs in the systems listed in Table 1. Table 2 shows failure probability and failure rate estimates for the EPS EDG from Reference [4], or the 2015 Update. Table 3 shows the failure probability and failure rate estimates for the HPCS EDG. The HPCS EDG failure probability was not fully analyzed in [4] and is presented here based on the current ICES data that has been reviewed at Idaho National Laboratory (INL).

Table 1. EDG systems.

System	Description	EDG Count
EPS	Emergency power supply	232
HPCS	High pressure core spray	8
	Total	**240**

The EDGs do not operate all the time. They are standby-components required to operate when called upon, 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) for EPS EDGs, from the 2015 Update.

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTS	1.45E-3	2.73E-3	2.83E-3	4.59E-3	Beta	8.59	3.02E+03
FTLR	1.18E-3	3.38E-3	3.73E-3	7.42E-3	Gamma	3.61	9.70E+02
FTR>1H	3.78E-4	1.35E-3	1.54E-3	3.34E-3	Gamma	2.68	1.74E+03

Table 3. Industry-wide distributions of p (failure probability) and λ (hourly rate) for HPCS EDGs.

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTS	2.19E-4	8.33E-4	9.56E-4	2.12E-3	Beta	2.50	2.61E+03
FTR	4.25E-4	1.07E-3	1.15E-3	2.16E-3	Gamma	4.50	3.91E+03

3.2 EDG Failure Probability and Failure Rate Trends

Trends in failure probabilities and failure rates are shown in Figures 1–6. The data for the trend plots are contained in Tables 16–21, respectively.

The failure probability and failure rate estimates in the plots 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 tends to be larger than the interval for years when there are one or more failures. The larger interval reflects the uncertainty that comes from having little information in that year's data. Such uncertainty intervals are determined by the prior distribution. In each plot, a relatively "flat" constrained non-informed prior distribution (CNID) is used, which has large bounds. For failure probabilities, the posterior means for each year are calculated from

$$mean = \frac{failures + 0.5}{demands + 1} \tag{1}$$

For failure rates, the posterior means for each year are calculated from

$$mean = \frac{failures + 0.5}{operting\ hours} \tag{2}$$

The horizontal curves plotted around the regression lines in the graphs show 90 percent simultaneous confidence bands for the fitted lines. The simultaneous confidence band bounds are larger than ordinary confidence bands for the trended values because they form a band that has a 90% probability of containing 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 on whether the slope of the regression line might be zero. Low p-values indicate that the slopes are not likely to be zero, and that trends exist. P-values of less than or equal to 0.05 indicate that we are 95% confident 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 minimizes the square of the vertical distance between the annual data points and the regression line. The p-values assume normal distributions for the data in each year, with a constant variance across the years. In the case where the data involve failure counts, the method of iterative reweighing accounts 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). Further information on the trending methods is provided in Section 2 of the Overview and Reference document [6].

A final feature of the trend graphs is that the 2015 Update baseline industry values from Table 2 are shown for comparison.

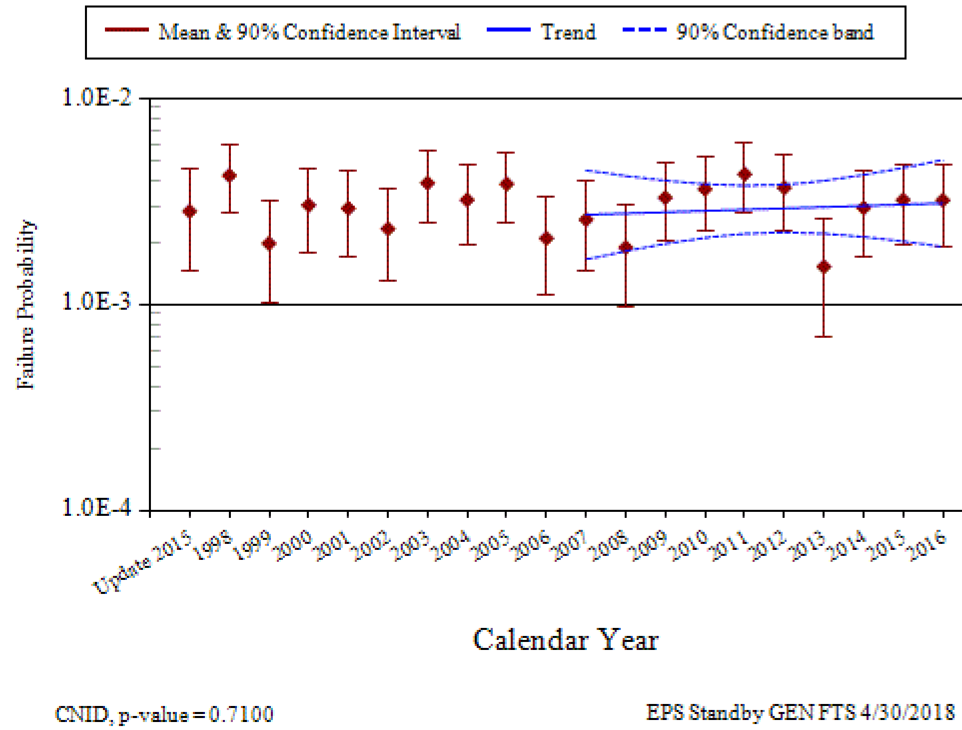

Figure 1. Failure probability estimate trend for EPS EDG FTS.

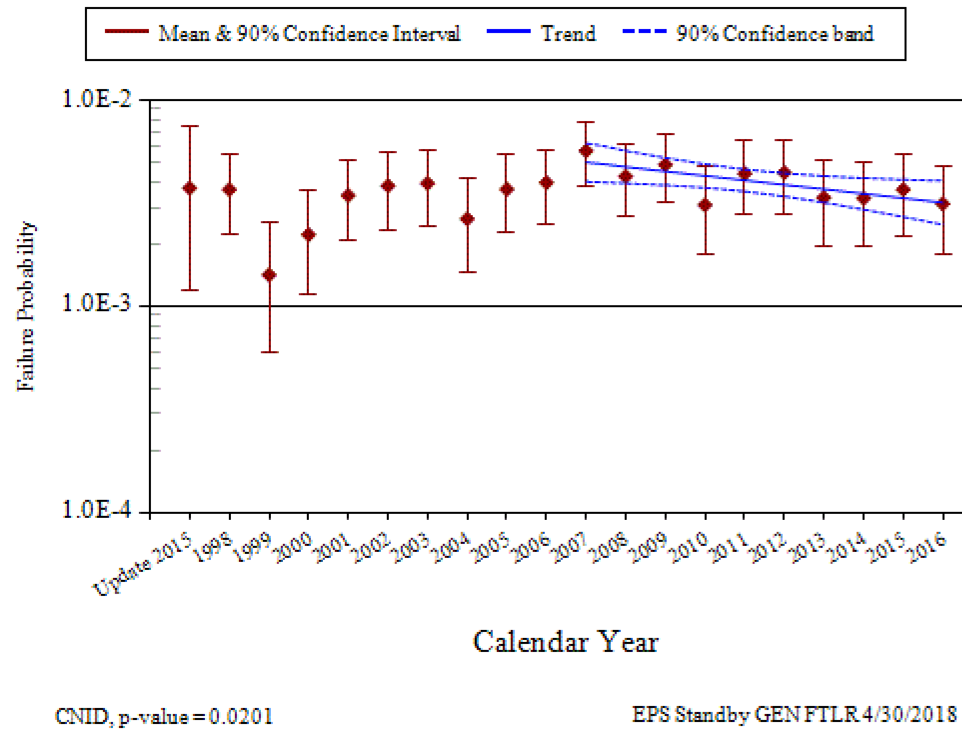

Figure 2. Failure probability estimate trend for EPS EDG FTLR.

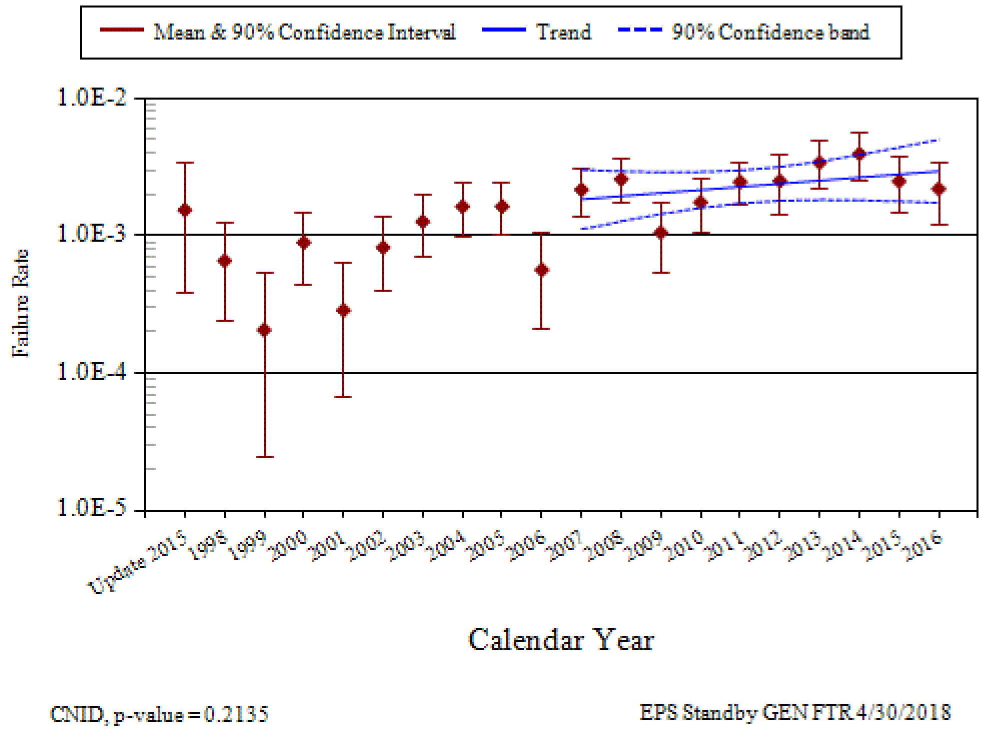

Figure 3. Failure rate estimate trend for EPS EDG FTR>1H.

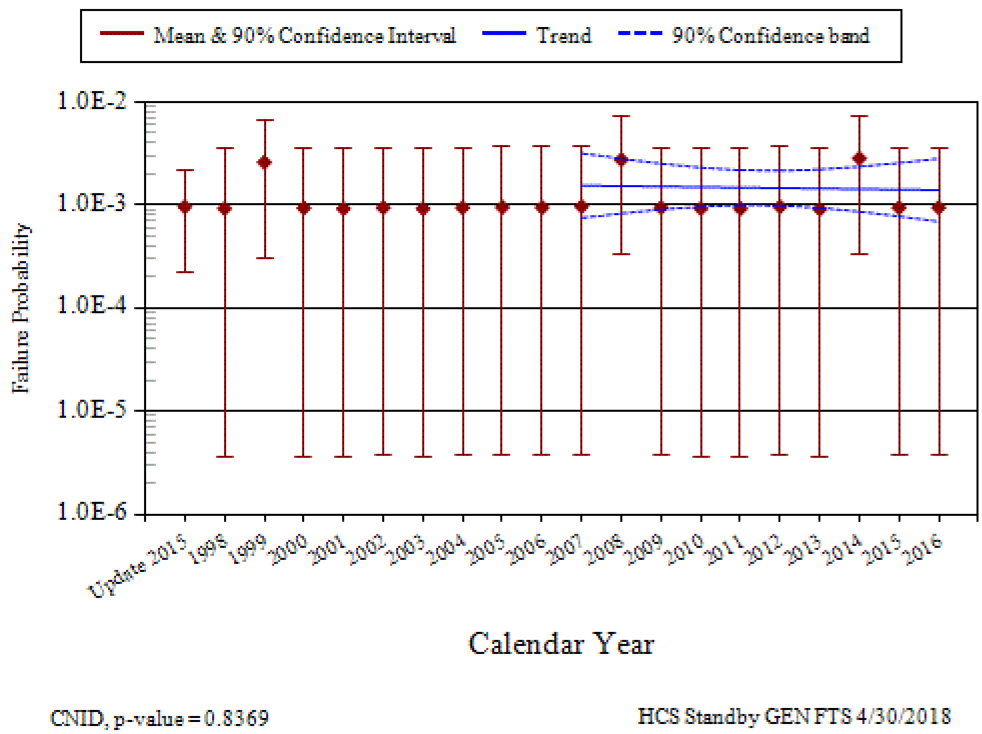

Figure 4. Failure probability estimate trend for HPCS EDG FTS.

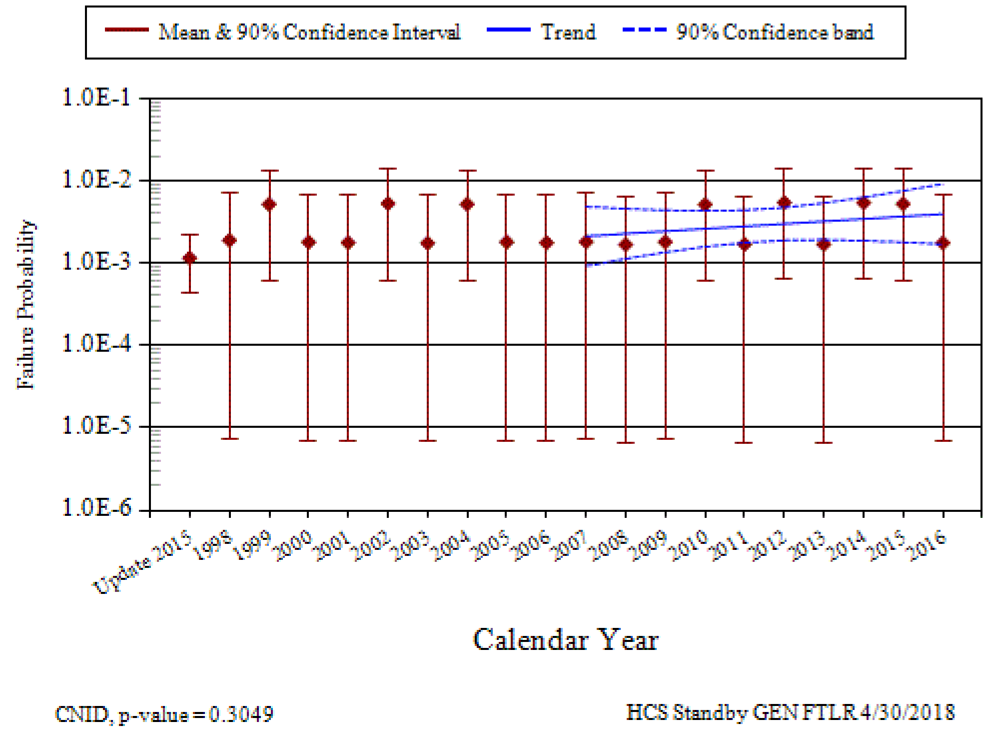

Figure 5. Failure probability estimate trend for HPCS EDG FTLR.

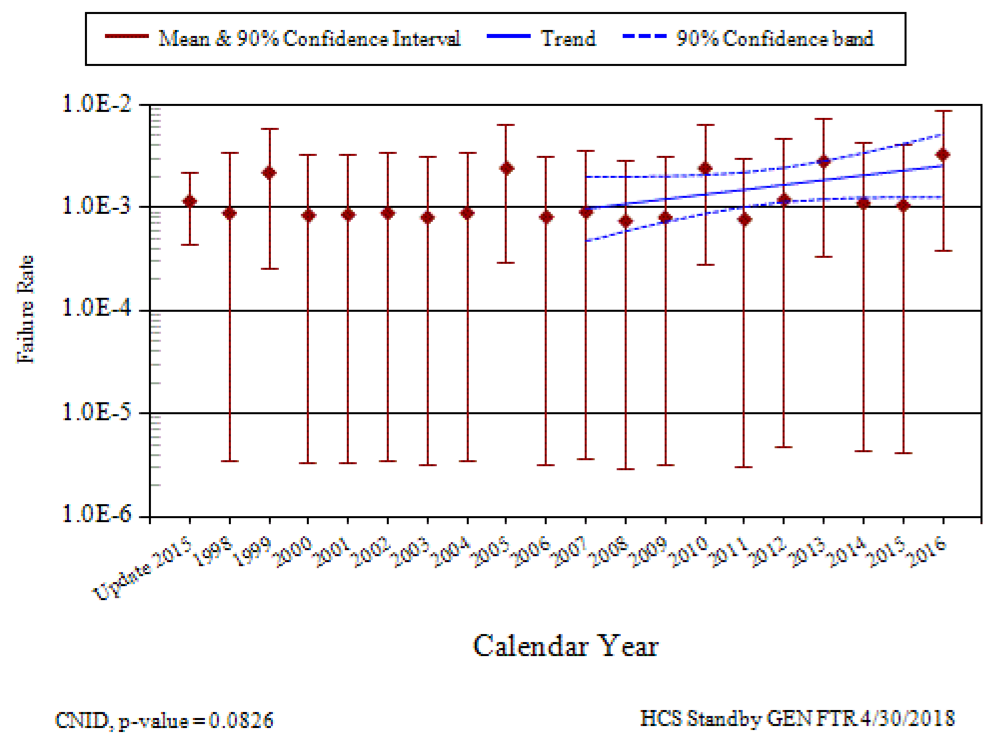

Figure 6. Failure rate estimate trend for HPCS EDG FTR>1H.

4. UNAVAILABILITY

4.1 Overview

The industry-wide test or maintenance UA of EDG trains has been calculated from the 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 [4] based on UA data from MSPI Basis Documents, covering 2002 to 2015. In the calculations, planned and unplanned unavailable hours for a train are combined.

Table 4. Industry-average unavailability estimates for EPS EDGs.

Description	Distribution	Mean	α	β
Emergency diesel generator test or maintenance unavailability (EPS)	Normal	1.48E-2	0.0148	0.0063
Emergency diesel generator test or maintenance unavailability (HPCS)	Normal	1.17E-2	0.0117	0.0025

4.2 EDG Unavailability Trends

The graphs that follow provide overall maintenance unavailability data for the 1998–2016 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 Table 22 and Table 23, respectively. The EDGs in systems EPS and HPCS are trended. The yearly unavailability and reactor critical hour data were obtained from the Reactor Oversight Program (1998 to 2001) and MSPI EPS indicator (2002 to 2016). 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 Program data (1998–2001) did not include EDG overhaul outages while plants were in critical operation, while the MSPI (2002–2016) 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 unavailability's for that year. The vertical bar spans the calculated 5th to 95th percentiles of the beta distribution with matching means.

Further information on the trending methods is provided in Section 3 of the Overview and Reference document [6]. In the lower left hand corner of each trend figure, the p-value is reported.

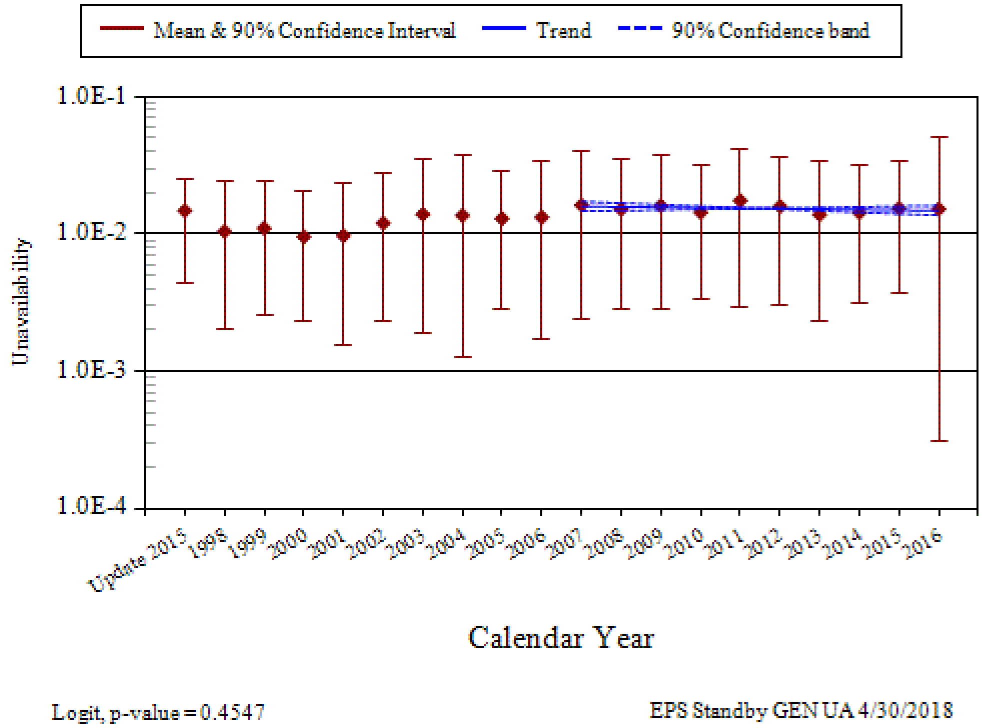

Figure 7. EPS EDG UA trend.

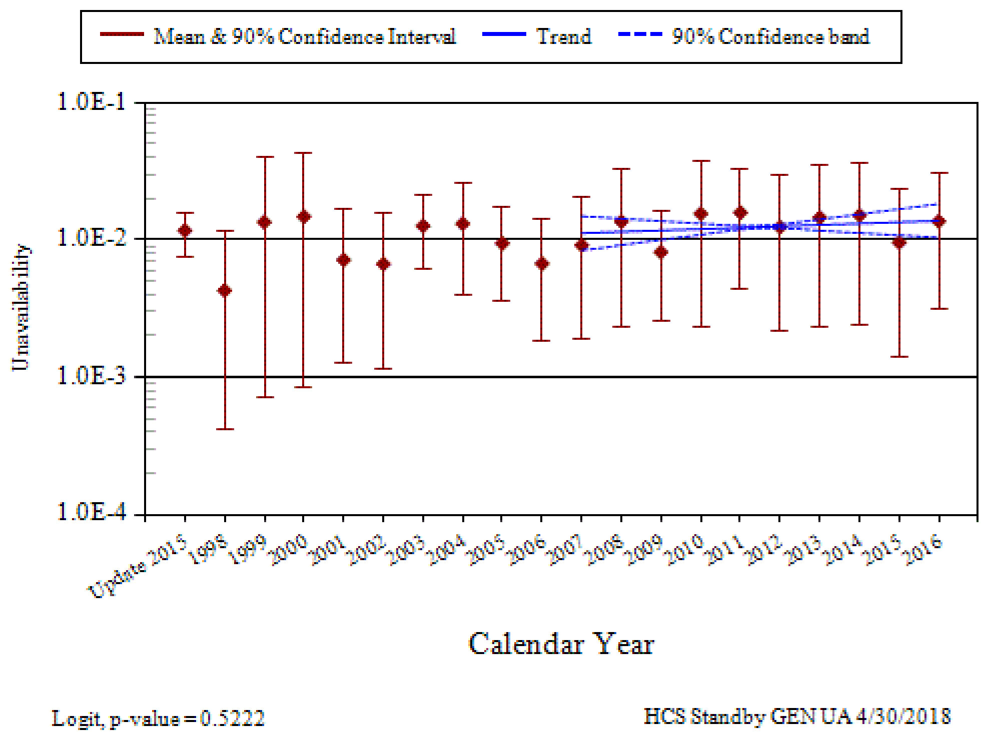

Figure 8. HPCS EDG UA trend.

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 how many hours of unplanned unavailability have been reported for each EDG from 2007 to 2016. The hourly unplanned unavailability is reported to the U.S. Nuclear Regulatory Commission (NRC) in the Mitigating Systems Performance Index (MSPI) data. The MSPI data were not reported prior to 2006.

A Weibull distribution was fit to the unplanned unavailability durations. The Weibull fit parameters are provided in Table 5. The probability an EDG 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 times but not as good at very long repair times (well beyond typical PRA missions), such as where the outage spans hundreds of hours. 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	Value
Mean	30.3
Median	13.5
Weibull(α)	0.679
Weibull(β)	23.3

Table 6. Probability of exceeding selected EDG repair times (2007 – 2016).

Recovery Time (hr)	Weibull Model Probability
0.5	0.929
1	0.889
1.5	0.856
2	0.828
3	0.780
4	0.739
5	0.703
6	0.671
7	0.643
8	0.616
9	0.592
10	0.569
11	0.548
12	0.528
13	0.510
14	0.492
15	0.476
16	0.460
17	0.446
18	0.432
19	0.418
20	0.406
21	0.393
22	0.382
23	0.371
24	0.360

5. EDG UNRELIABILITY TRENDS

Trends in total component unreliability are shown in Figure 9 and Figure 10. Plot data for these figures are in Table 24 and Table 25, respectively. 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. The trends are shown at the system-specific level across the industry. The trending method is described in more detail in Section 4 of the Overview and Reference document [6]. In the lower left hand corner of the trend figures, the regression method is reported.

No "2015 Update" data for use in risk assessments are cited for EDG unreliability because these data are not published. The risk assessment models compute unreliability as an output rather than an input.

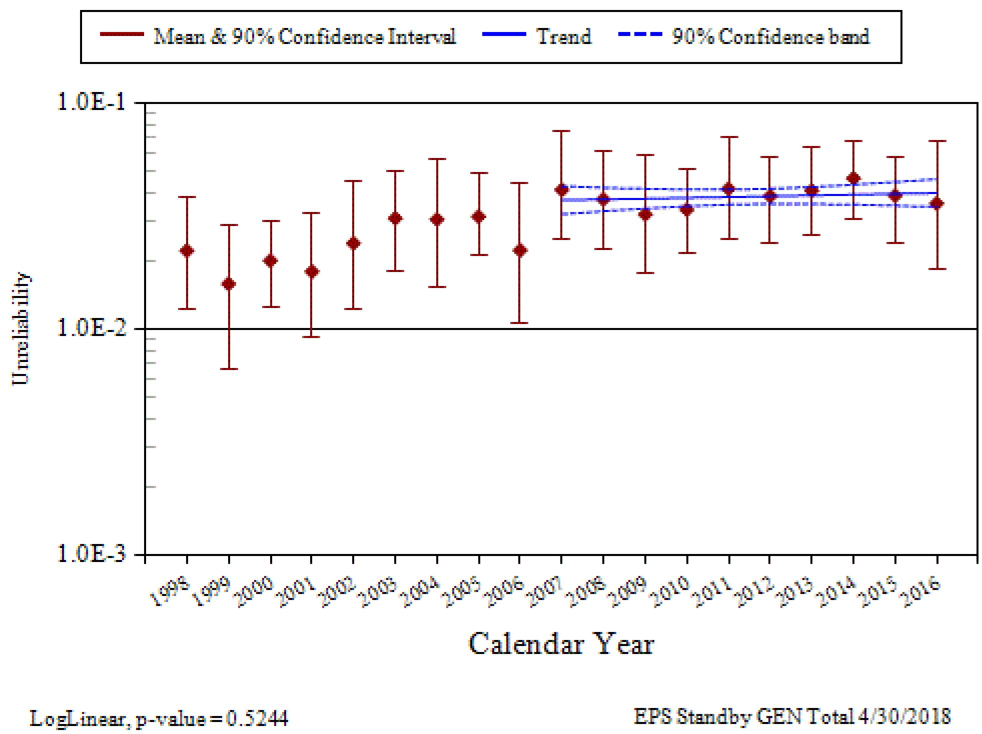

Figure 9. EPS EDG unreliability trend (8-hour mission).

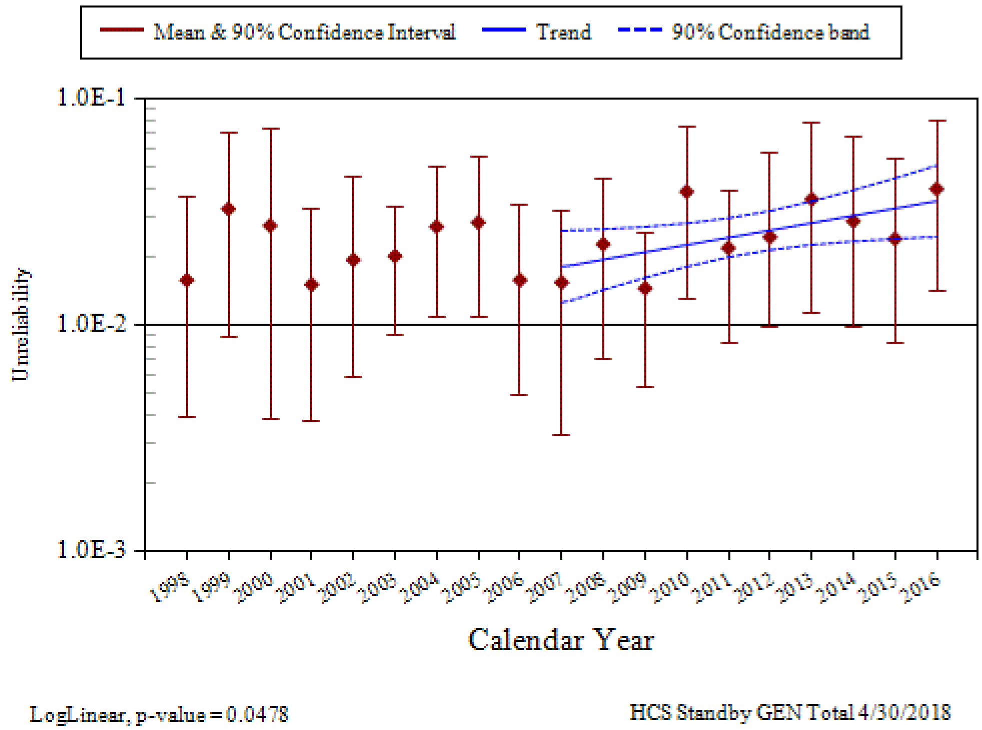

Figure 10. HPCS EDG unreliability trend (8-hour mission).

6. ENGINEERING ANALYSIS

The engineering analysis section presents an analysis of factors that could influence the system and 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 failure mode factors analyzed were: sub-component, 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 shows the trend for EPS and HPCS EDG demands. Figure 12 shows the trend for EPS and HPCS EDG load and run demands. Figure 13 shows the trend for the EPS and HPCS EDG run hours. Tables 26–28 provide the plot data, respectively.

Figure 14 shows the trend for EPS and HPCS EDG FTS events. Figure 15 shows the trend EPS and HPCS EDG FTLR events and Figure 16 shows the trend for the EPS and HPCS EDG FTR>1H events. Tables 29–31 provide the plot data, respectively.

Table 7–Table 9 provide a summary of the total failure event count for each of the years for which 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–Table 9 show failure events resulting from FTLR and FTR>1H occur in roughly equal numbers, while FTS failures occur somewhat less frequently than FTLR and FTR>1H failures. Furthermore, HPCS EDGs are about 3percent of the EDG population, but account for only 1 to 2 percent of the failure counts throughout the period being trended.

The systems from Table 1 are trended together for each figure. The rate methods described in Section 2 of the Overview and Reference document are used [6].

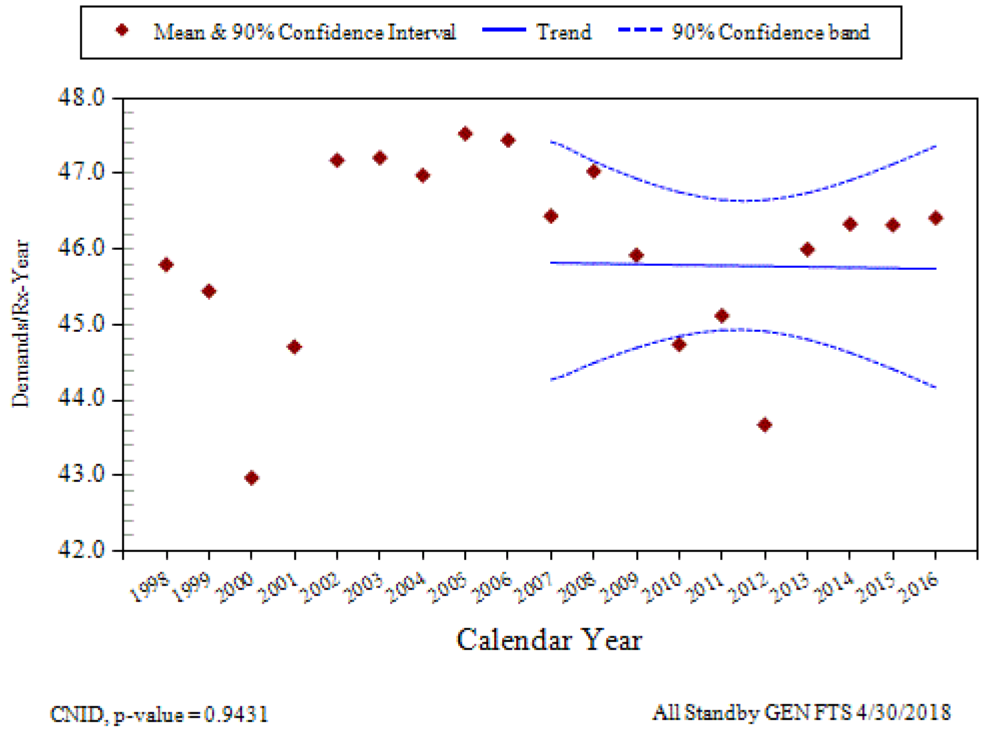

Figure 11. Frequency (events per reactor year) of start demands, EPS and HPCS EDGs.

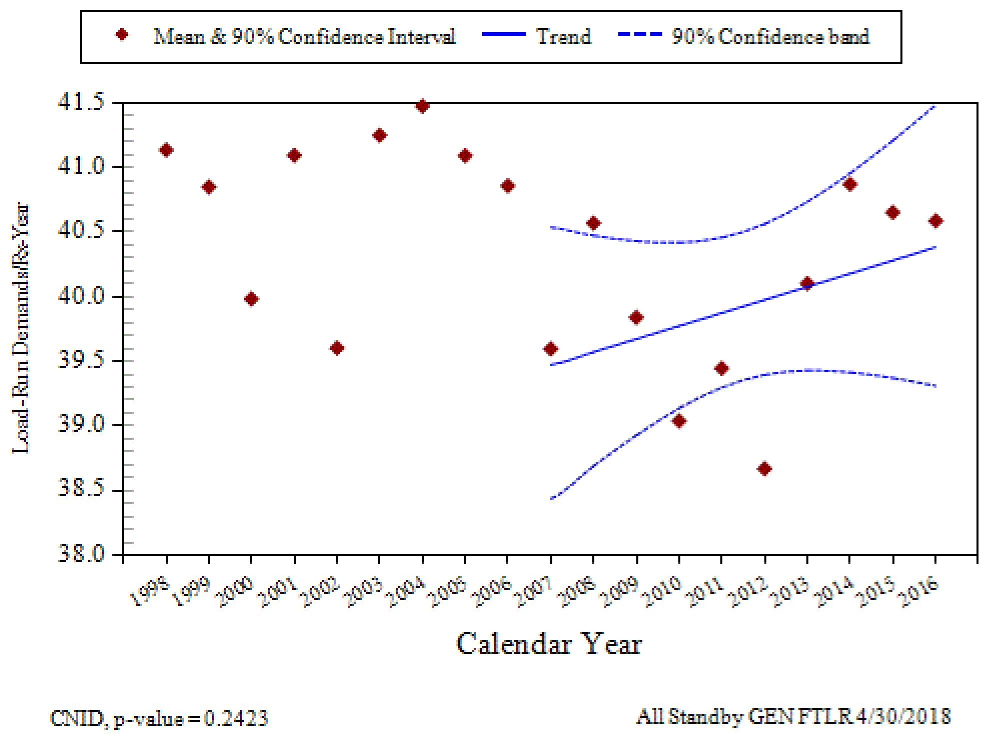

Figure 12. Frequency (events per reactor year) of load and run ≤ 1 hour demands, EPS and HPCS EDGs.

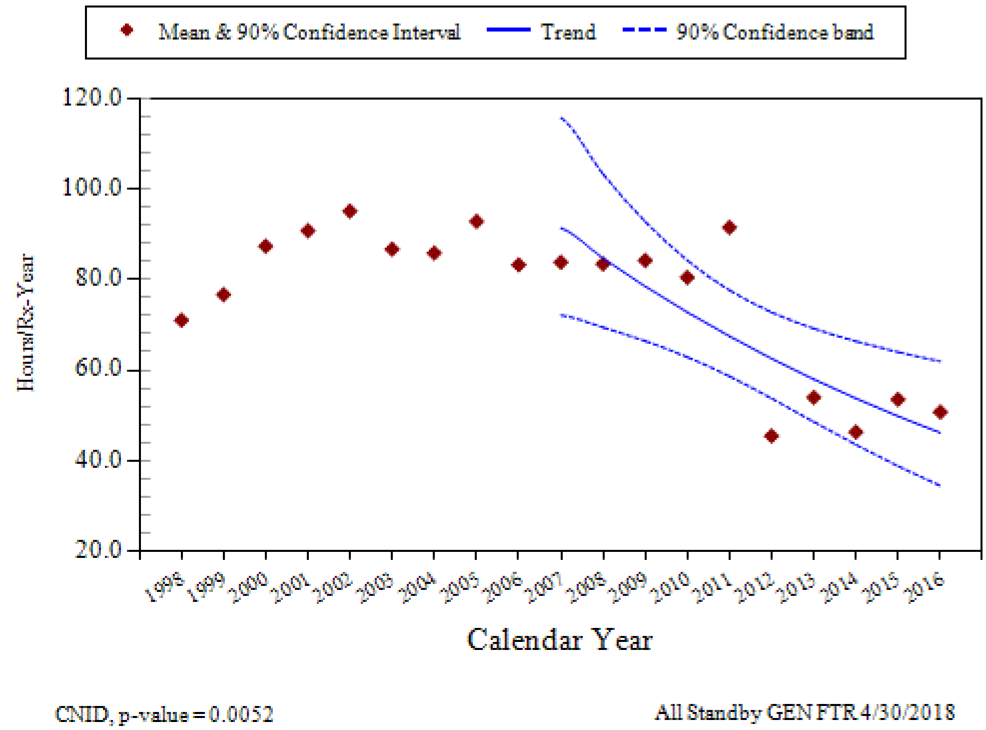

Figure 13. EPS and HPCS EDG run hours per reactor year.

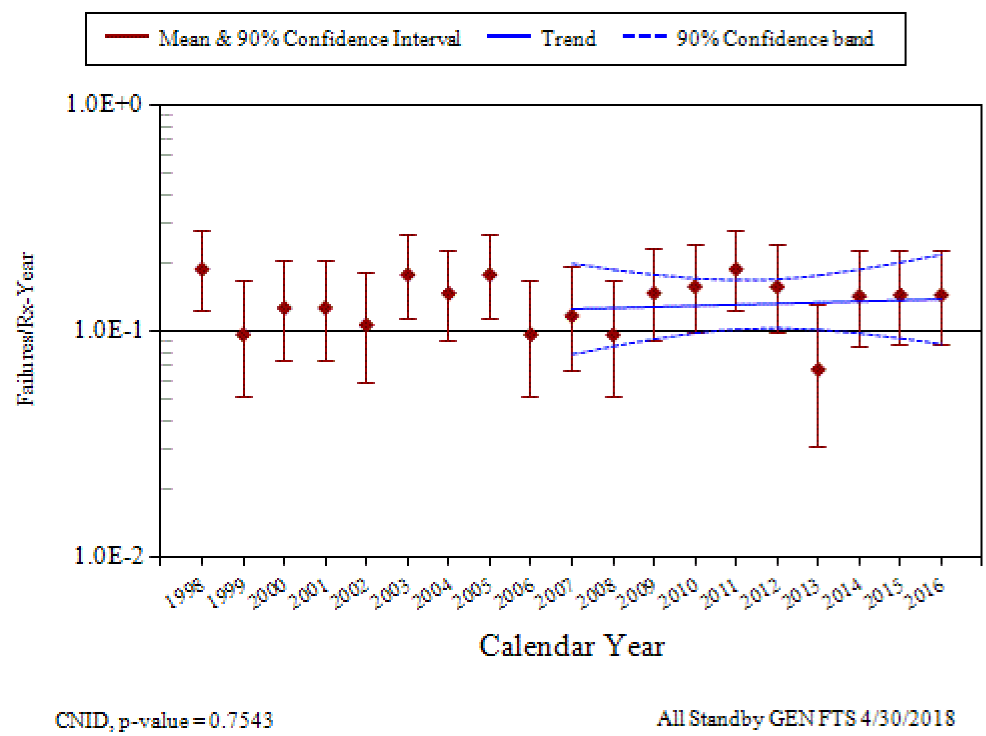

Figure 14. Frequency (events per reactor year) of FTS events, EPS and HPCS EDGs.

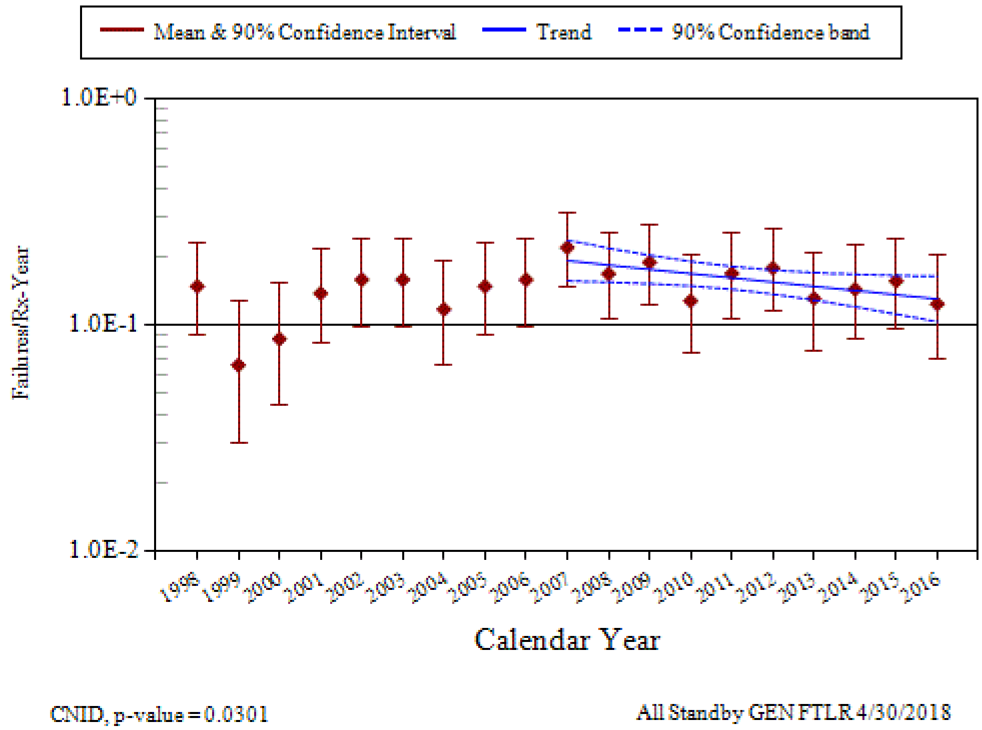

Figure 15. Frequency (events per reactor year) of FTLR events, EPS and HPCS EDGs.

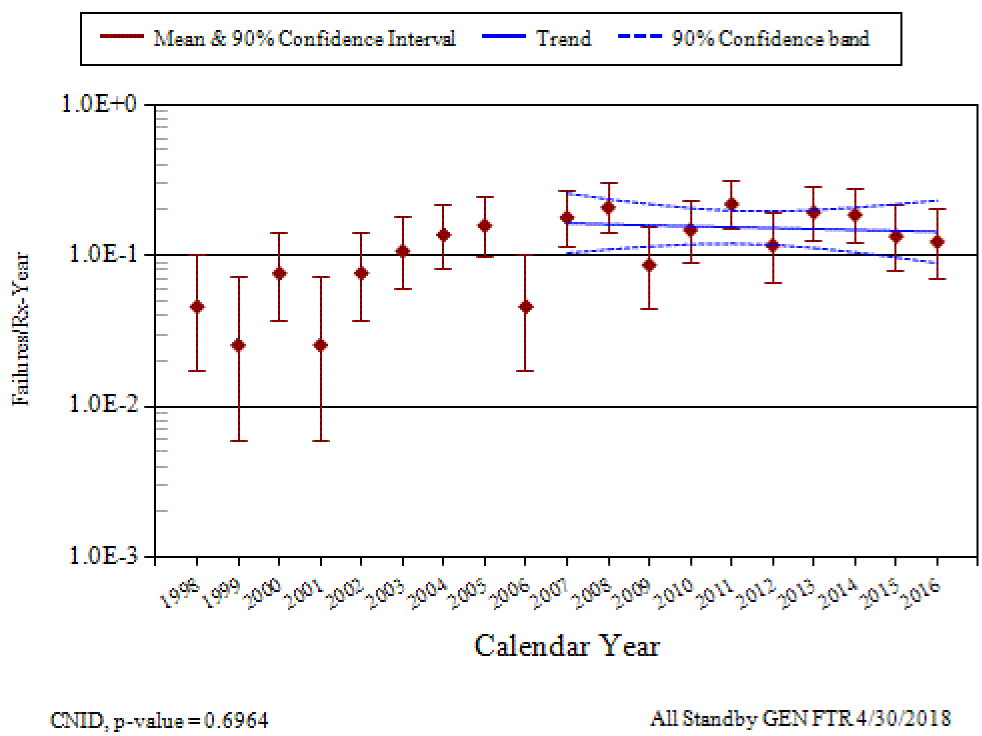

Figure 16. Frequency (events per reactor year) of FTR>1H events, EPS and HPCS EDGs.

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

System Code	EDG Count	EDG Percent	Year 07	08	09	10	11	12	13	14	15	16	Total	Percent of Failures
EPS	232	96.7%	11	8	14	15	18	15	6	12	13	13	125	98.4%
HPCS	8	3.3%		1						1			2	1.6%
Total	240	100%	11	9	14	15	18	15	6	13	13	13	127	100%

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

System Code	EDG Count	EDG Percent	Year 07	08	09	10	11	12	13	14	15	16	Total	Percent of Failures
EPS	232	96.7%	21	16	18	11	16	16	12	12	13	11	146	97.3 %
HPCS	8	3.3%				1		1		1	1		4	2.7 %
Total	240	100%	21	16	18	12	16	17	12	13	14	11	150	100%

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

System Code	EDG Count	EDG Percent	Year 07	08	09	10	11	12	13	14	15	16	Total	Percent of Failures
EPS	232	96.7%	17	20	8	13	21	11	17	17	12	10	146	**98.0%**
HPCS	8	3.3%				1			1			1	3	2.0%
Total	240	100%	17	20	8	14	21	11	18	17	12	11	149	100%

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

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

To answer this question, ICES 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 those 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 – 2016 are summarized in Table 10. Consistency between the unplanned demand data and industry-average performance (from Table 2) was evaluated using the predictive distribution approach outlined in the Handbook of Parameter Estimation for Probabilistic Risk Assessment, NUREG/CR-6823, Sections 6.2.3.5 and 6.3.3.4 [7].

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 1000 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 ICES data analysis is considered to be consistent with the observed unplanned demand performance.

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

Failure Modes	Plants	Demands or Hours	Observed Failures	Expected Failures	Probability of ≥ Failures	Consistent with Industry-Average Performance?
FTS	95	519	0	1.5	1.00	Yes[a]
FTLR	95	304	1	1.1	0.79	Yes
FTR>1H	95	3497	4	5.4	0.62	Yes

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

The consistency checks using unplanned demand data indicate that the FTS, FTLR, and FTR failure observations lie within their industry-average estimate distributions from Table 2.

6.3 EPS EDG Performance by Manufacturer

Table 11 presents the results of summarizing EPS EDG performance by manufacturer. ICES contains information on EPS EDG manufacturers, but it appears that over the years some manufacturers have changed names or have been acquired by other manufacturers. Therefore, in order to identify the original manufacturer, the ICES 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	64	71.5	0.61	Yes
Cooper Bessemer	CB	37	70	110.2	0.89	Yes
Electro Motive/General Motors	EM/ GM	69	180	199.0	0.59	Yes
Fairbanks Morse/Colt	FM/C	67	227	198.8	0.29	Yes
Nordberg	NB	8	35	28.3	0.24	Yes
SAC/Compair Luchard/ Jeumont Schndr	SC/JS	3	19	7.7	0.01	No
TransAmerica DeLaval	TD	20	74	62.2	0.26	Yes
Worthington Corp	WC	4	35	10.1	0.00	No

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	6	8.6	0.76	Yes
1,000–4,999 KW	170	519	505.8	0.42	Yes
5,000–99,999 KW	58	177	170.3	0.41	Yes
100,000-499,999 KW	2	2	3.9	0.86	Yes

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 EPS EDG failure sub-components, causes, detection methods, and recovery are presented in this section (There are too few HPCS EDGs to perform similar analyses on them). The events are also categorized by the failure mode determined after ICES data review by the staff. See Section 7 for more description of failure modes.

EPS EDG sub-component contributions to the three failure modes are presented in Figure 17. The sub-component contributions are similar to those used in the CCF database. For FTS, instrumentation and control and the generator piece parts have the highest percentage contributions to failures. FTLR high contributors include the breaker and instrumentation and control and the breaker. Finally, FTR high contributors include the cooling, engine, fuel oil, and instrumentation and control.

EPS EDG 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 cause is grouped as Internal. Internal means that the cause was related to something within the EPS EDG component such as a worn out part or the normal internal environment. The second largest cause group is Human. The human cause group includes human actions, procedures, and maintenance.

EPS EDG detection methods for the three failure modes are presented in Figure 19. The most likely detection method is testing, which is the prevalent detection method for most standby components. The inspection failure detection method is 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 to not be recoverable. The overall non-recovery to recovery ratio is approximately 13.5:1.

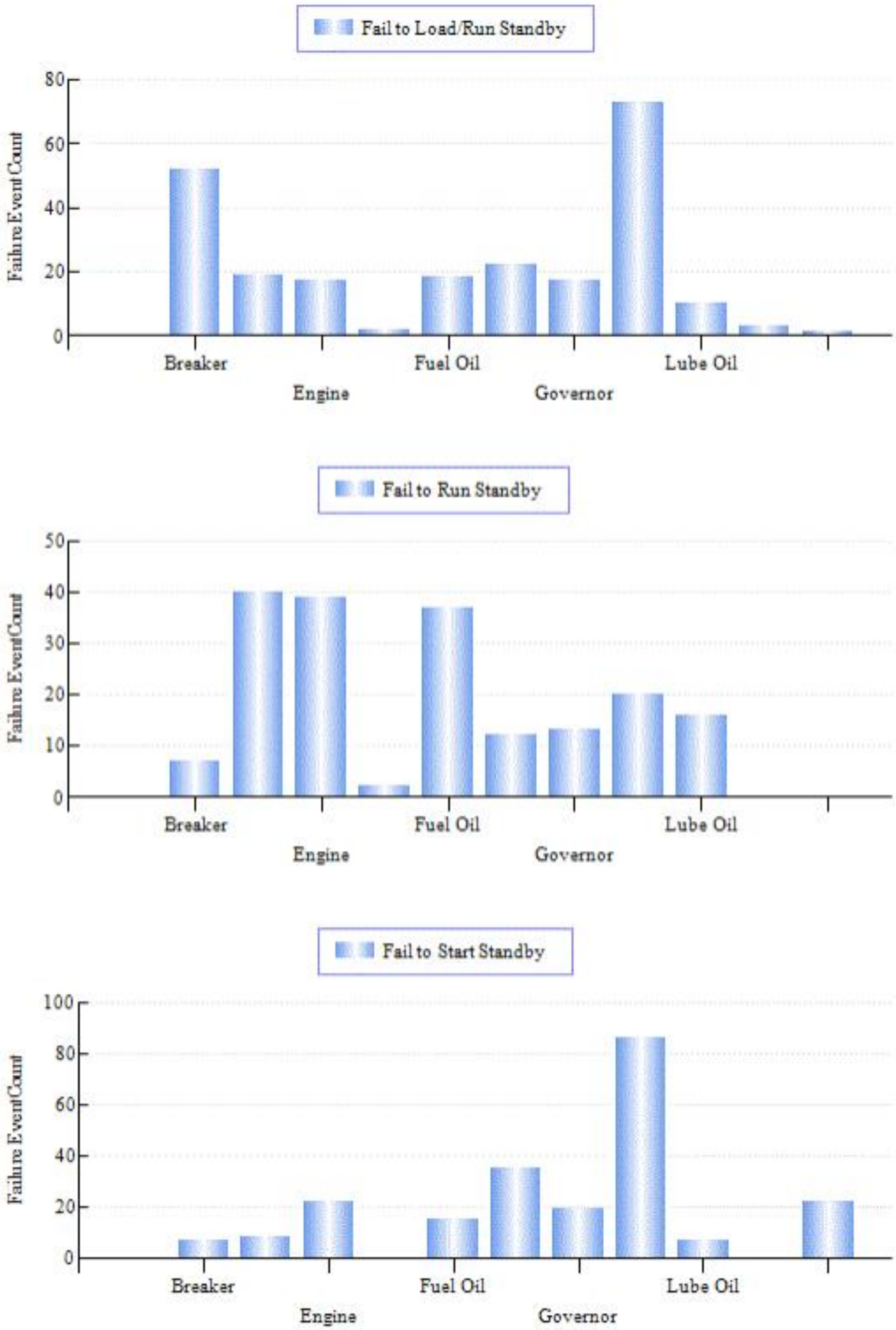

Figure 17. EPS EDG failure breakdown by sub component and failure mode

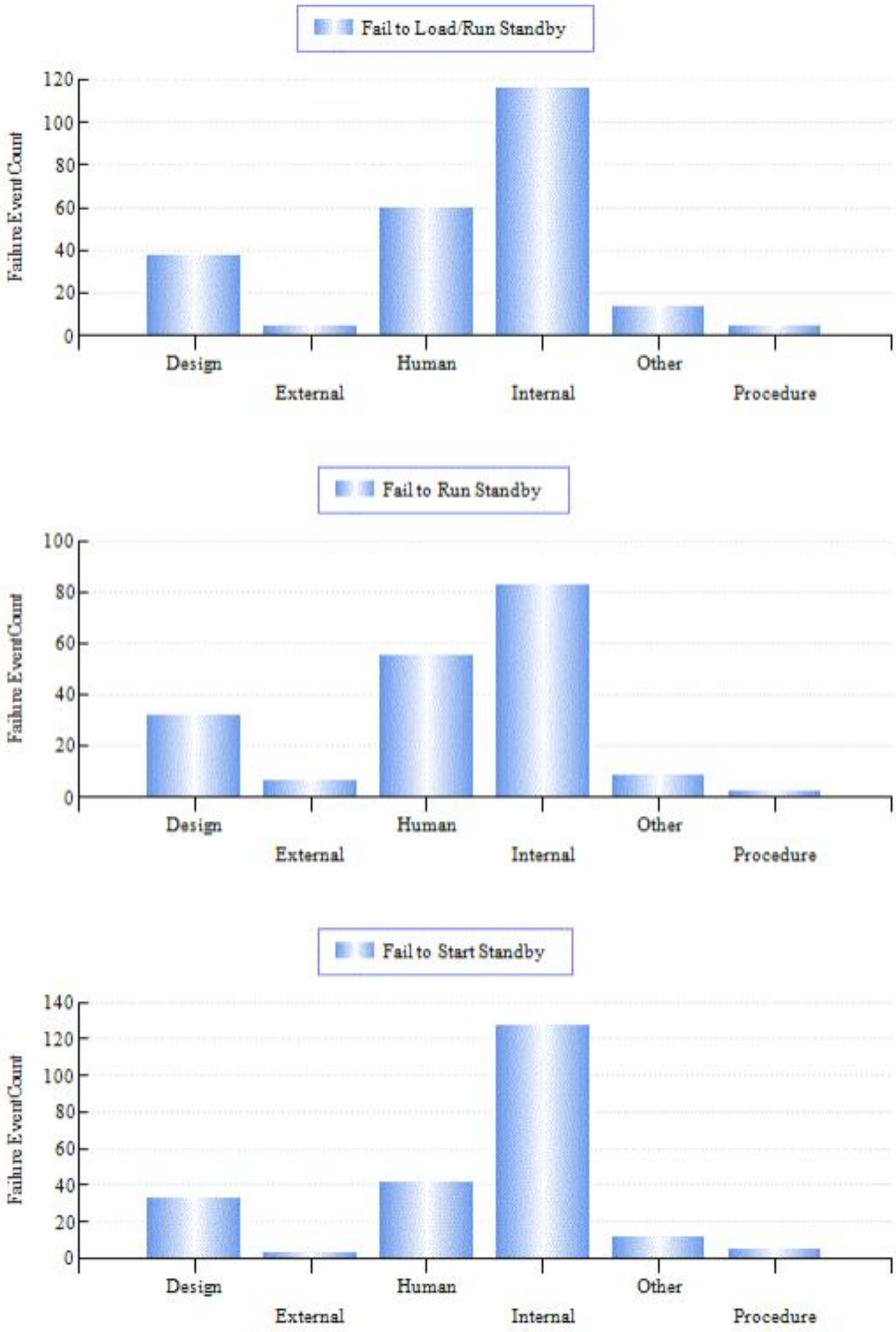

Figure 18. EPS EDG breakdown by cause group and failure mode

Table 13. Component failure cause groups.

Group	Specific Cause	Description
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 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.
External	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 no fuel in the fuel storage tanks.
	Ambient environmental stress	Used when the cause of a failure is the result of an environmental condition from the location of the component.
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.
Internal	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.
	Internal environment	The internal environment led to the failure. Debris/Foreign material as well as an operating medium chemistry issue.
	Setpoint drift	Used when the cause of a failure is the result of setpoint drift or adjustment.
	Age/Wear	Used when the cause of the failure is a non-specific aging or wear issue.
Other	Unknown	Used when the cause of the failure is not known.
	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.
Procedure	Inadequate procedure	Used when the cause of a failure is the result of an inadequate procedure operating or maintenance.

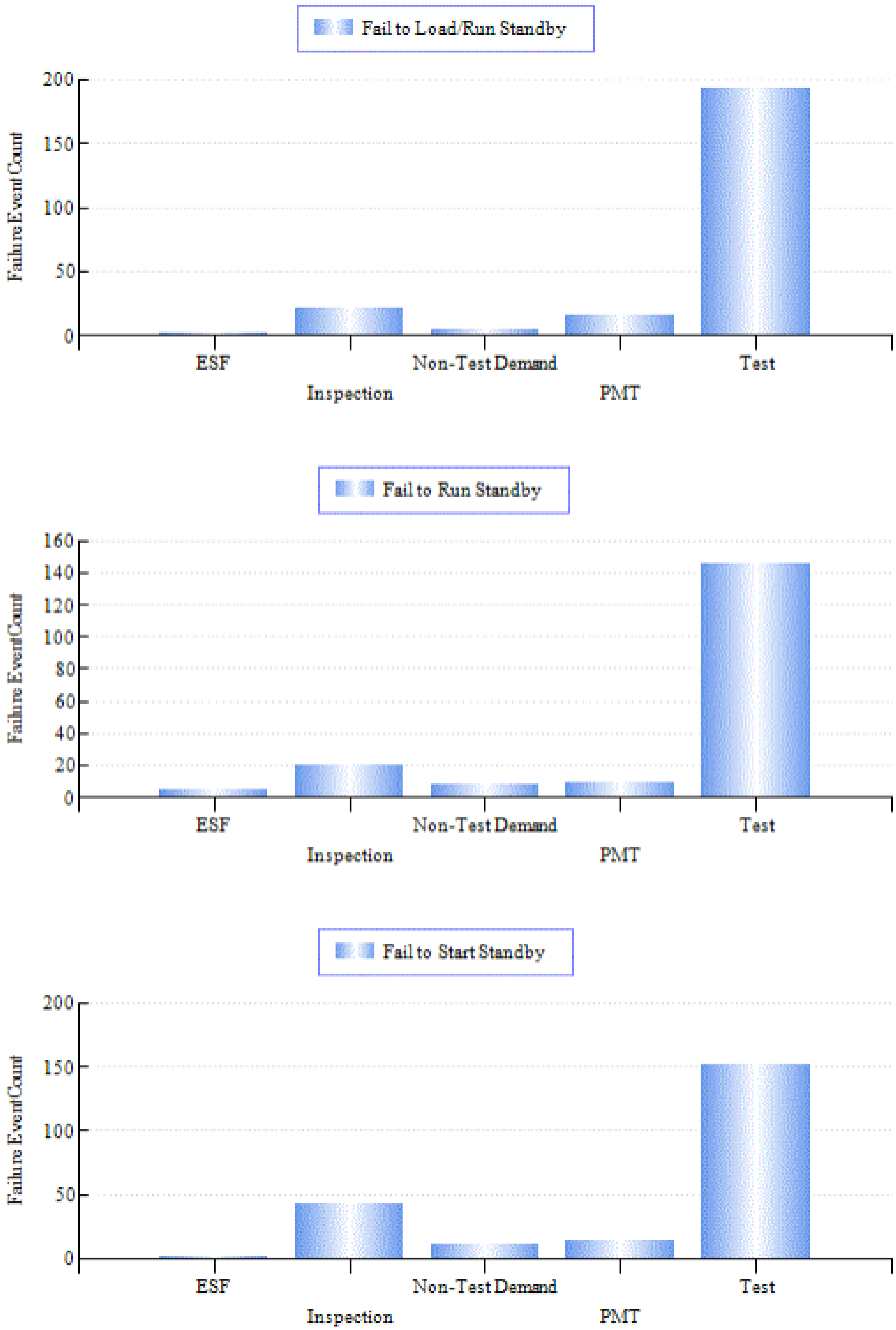

Figure 19. EPS EDG component failure distribution failure mode and method of detection

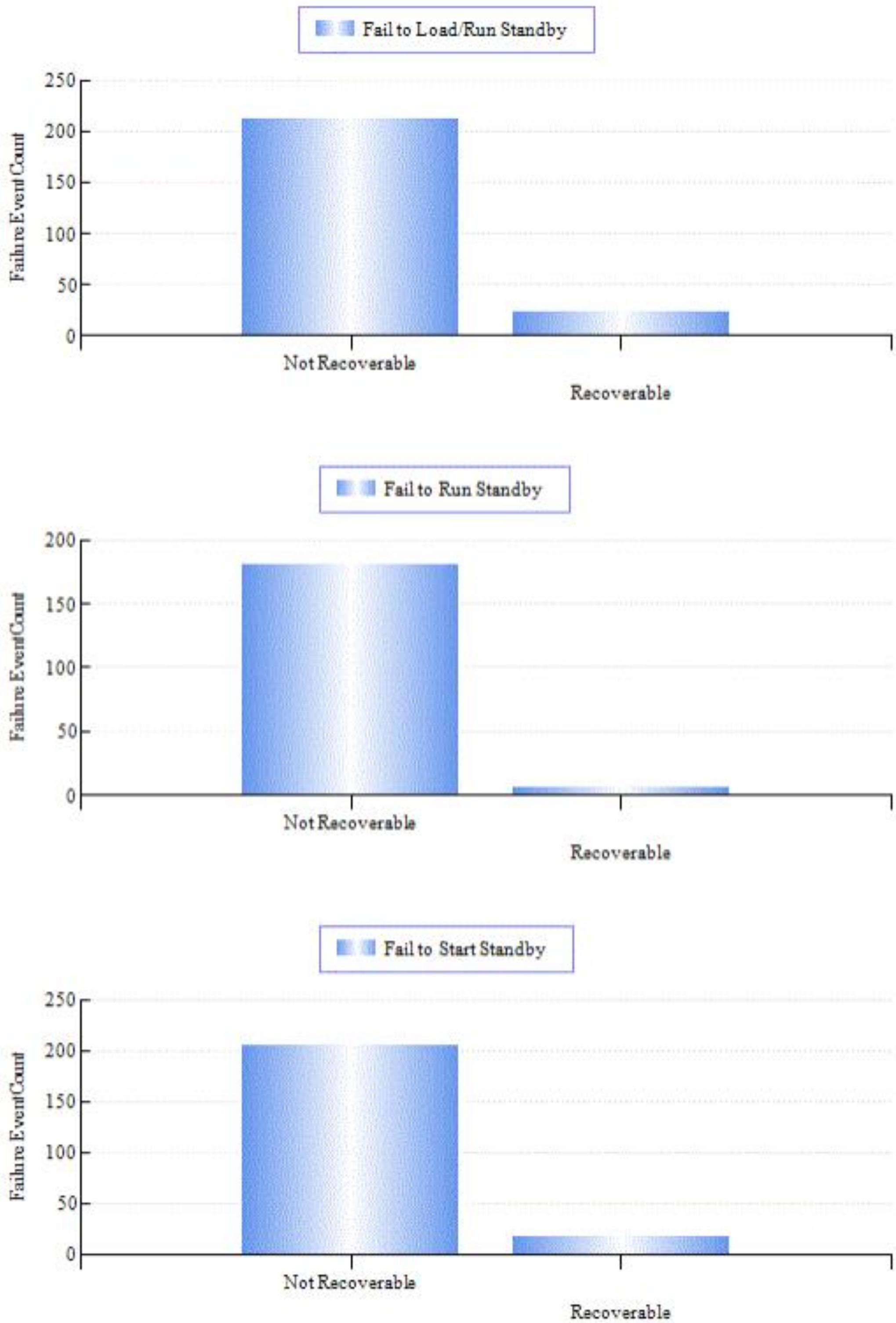

Figure 20. EPS EDG component failure distribution by failure mode and recovery determination

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

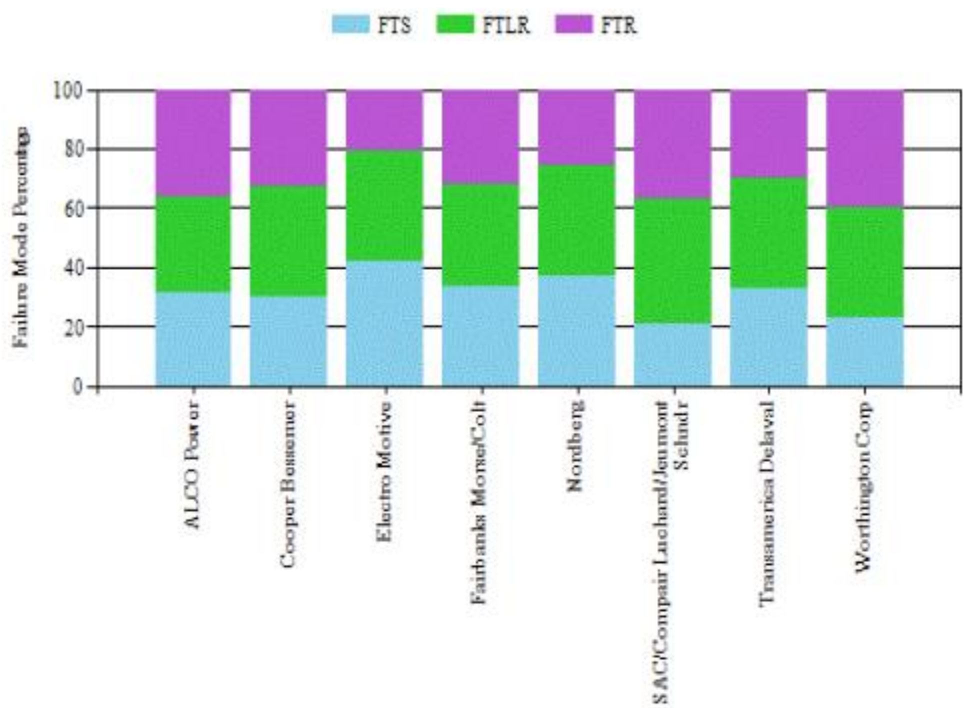

Figure 21. EPS EDG failure distribution by manufacturer

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

Manufacturer	Code	EPS EDGs	Total Failure Count
ALCO Power	AP	24	64
Cooper Bessemer	CB	37	70
Electro Motive	EM/GM	69	180
Fairbanks Morse/Colt	FM/C	67	227
Nordberg	NB	8	35
SAC/Compair Luchard/Jeumont Schndr	SC/JS	3	19
Transamerica Delaval	TD	20	74
Worthington Corp	WC	4	35
Totals		232	704

Figure 22 shows the percentage of failure events for the three failure modes segregated by EPS EDG rating as indicated in the ICES database. Table 15 shows the distribution of the various rated EPS EDGs in the ICES 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.

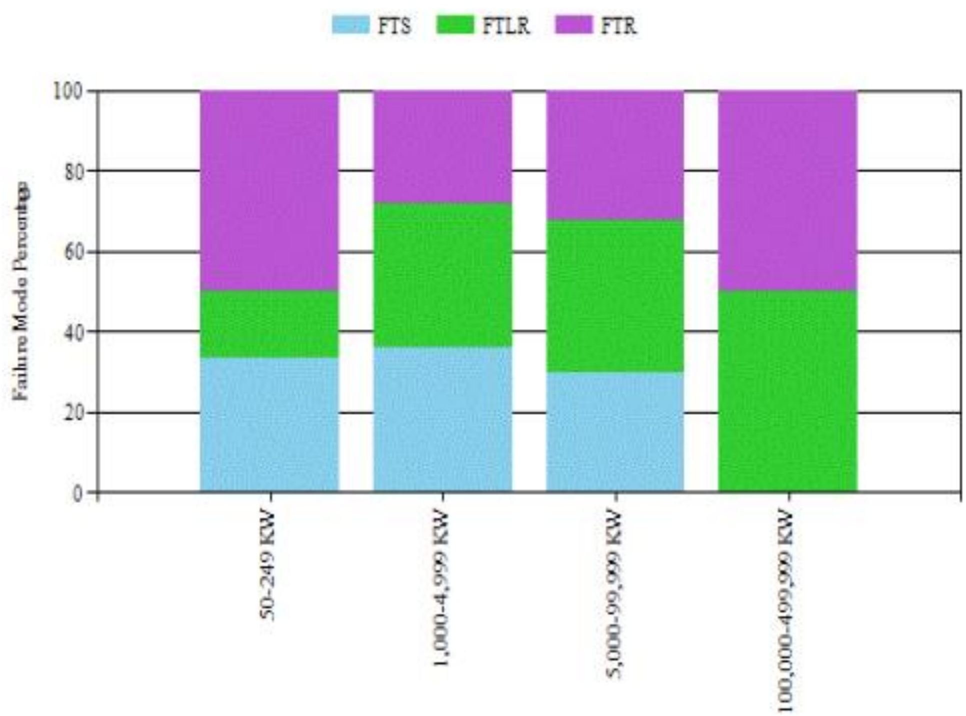

Figure 22. EPS EDG component failure modes by EPS EDG rating

Table 15. EPS EDG population by rating.

EPS EDG Rating	Device Count	Total Failure Count
50-249 KW	2	6
1,000-4,999 KW	170	519
5,000-99,999 KW	58	177
100,000-499,999 KW	2	2
Total	232	704

7. EPS 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; should they start as soon as the EDG starts 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 ICES. 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 ICES 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. Also, 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. Also, 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 EDG 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 of the EDG events within ICES 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

Table 16. Plot data for Figure 1, EPS EDG FTS industry trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Failures**	**Demands**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
2015 Update						1.45E-03	4.59E-03	2.83E-03
1998	18	4,200.5				2.76E-03	6.25E-03	4.24E-03
1999	8	4,131.9				1.01E-03	3.51E-03	1.98E-03
2000	12	3,948.5				1.78E-03	4.87E-03	3.04E-03
2001	12	4,095.4				1.72E-03	4.70E-03	2.93E-03
2002	10	4,341.8				1.29E-03	3.90E-03	2.33E-03
2003	17	4,333.2				2.50E-03	5.80E-03	3.89E-03
2004	14	4,335.8				1.97E-03	4.99E-03	3.22E-03
2005	17	4,382.2				2.47E-03	5.73E-03	3.85E-03
2006	9	4,371.0				1.12E-03	3.60E-03	2.09E-03
2007	11	4,286.0	2.72E-03	1.66E-03	4.47E-03	1.47E-03	4.23E-03	2.58E-03
2008	8	4,328.7	2.76E-03	1.81E-03	4.20E-03	9.65E-04	3.35E-03	1.89E-03
2009	14	4,224.4	2.80E-03	1.97E-03	3.99E-03	2.02E-03	5.12E-03	3.30E-03
2010	15	4,099.0	2.84E-03	2.10E-03	3.84E-03	2.26E-03	5.55E-03	3.64E-03
2011	18	4,134.1	2.88E-03	2.20E-03	3.77E-03	2.80E-03	6.34E-03	4.30E-03
2012	15	4,032.8	2.92E-03	2.24E-03	3.82E-03	2.30E-03	5.64E-03	3.69E-03
2013	6	4,100.2	2.97E-03	2.21E-03	3.99E-03	6.90E-04	2.93E-03	1.52E-03
2014	12	4,080.7	3.01E-03	2.13E-03	4.25E-03	1.72E-03	4.72E-03	2.94E-03
2015	13	4,029.1	3.05E-03	2.02E-03	4.60E-03	1.93E-03	5.07E-03	3.22E-03
2016	13	4,039.3	3.09E-03	1.90E-03	5.03E-03	1.92E-03	5.06E-03	3.21E-03
Total	242	79,494.3						

Table 17. Plot data for Figure 2, EPS EDG FTLR industry trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Failures**	**Demands**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
2015 Update						1.18E-03	7.42E-03	3.73E-03
1998	14	3,802.4				2.26E-03	5.72E-03	3.69E-03
1999	5	3,750.6				5.90E-04	2.88E-03	1.42E-03
2000	8	3,688.1				1.14E-03	3.95E-03	2.23E-03
2001	13	3,779.2				2.07E-03	5.45E-03	3.46E-03
2002	14	3,638.1				2.36E-03	5.97E-03	3.86E-03
2003	15	3,790.2				2.46E-03	6.05E-03	3.96E-03
2004	10	3,821.6				1.47E-03	4.45E-03	2.66E-03
2005	14	3,784.4				2.27E-03	5.75E-03	3.71E-03
2006	15	3,757.2				2.49E-03	6.10E-03	3.99E-03
2007	21	3,644.0	4.97E-03	4.01E-03	6.15E-03	3.85E-03	8.18E-03	5.71E-03
2008	16	3,725.2	4.72E-03	3.94E-03	5.66E-03	2.71E-03	6.46E-03	4.29E-03
2009	18	3,666.5	4.49E-03	3.86E-03	5.23E-03	3.18E-03	7.19E-03	4.88E-03
2010	11	3,576.6	4.28E-03	3.75E-03	4.88E-03	1.77E-03	5.08E-03	3.11E-03
2011	16	3,610.2	4.07E-03	3.60E-03	4.60E-03	2.80E-03	6.66E-03	4.42E-03
2012	16	3,566.7	3.87E-03	3.40E-03	4.40E-03	2.83E-03	6.74E-03	4.47E-03
2013	12	3,575.0	3.68E-03	3.18E-03	4.27E-03	1.98E-03	5.42E-03	3.38E-03
2014	12	3,601.2	3.50E-03	2.94E-03	4.17E-03	1.96E-03	5.38E-03	3.36E-03
2015	13	3,531.7	3.33E-03	2.70E-03	4.10E-03	2.21E-03	5.82E-03	3.69E-03
2016	11	3,526.7	3.17E-03	2.48E-03	4.05E-03	1.79E-03	5.15E-03	3.15E-03
Total	254	69,835.4						

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

Year	Failures	Run Time (hr)	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						3.78E-04	3.34E-03	1.54E-03
1998	4	6,539.3				2.46E-04	1.46E-03	6.67E-04
1999	1	6,959.7				2.45E-05	7.72E-04	2.09E-04
2000	7	8,088.9				4.38E-04	1.66E-03	9.04E-04
2001	2	8,401.1				6.65E-05	8.17E-04	2.90E-04
2002	7	8,829.1				4.02E-04	1.53E-03	8.30E-04
2003	10	7,972.8				7.08E-04	2.15E-03	1.28E-03
2004	13	7,971.7				9.87E-04	2.60E-03	1.65E-03
2005	14	8,559.1				1.01E-03	2.57E-03	1.65E-03
2006	4	7,653.2				2.11E-04	1.25E-03	5.72E-04
2007	17	7,768.9	1.84E-03	1.12E-03	3.02E-03	1.41E-03	3.27E-03	2.19E-03
2008	20	7,632.7	1.94E-03	1.28E-03	2.95E-03	1.74E-03	3.78E-03	2.61E-03
2009	8	7,736.6	2.05E-03	1.44E-03	2.91E-03	5.46E-04	1.90E-03	1.07E-03
2010	13	7,382.8	2.15E-03	1.60E-03	2.91E-03	1.06E-03	2.80E-03	1.78E-03
2011	21	8,403.5	2.27E-03	1.72E-03	2.99E-03	1.68E-03	3.58E-03	2.50E-03
2012	11	4,270.7	2.39E-03	1.80E-03	3.17E-03	1.46E-03	4.20E-03	2.57E-03
2013	17	4,821.4	2.52E-03	1.83E-03	3.47E-03	2.23E-03	5.19E-03	3.48E-03
2014	17	4,121.4	2.65E-03	1.82E-03	3.88E-03	2.59E-03	6.03E-03	4.04E-03
2015	12	4,700.9	2.80E-03	1.78E-03	4.39E-03	1.49E-03	4.08E-03	2.55E-03
2016	10	4,468.0	2.95E-03	1.73E-03	5.01E-03	1.24E-03	3.76E-03	2.24E-03
Total	208	132,281.8						

Table 19. Plot data for Figure 4, HPCS EDG FTS industry trend

Year	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						2.19E-04	2.12E-03	9.56E-04
1998	0	150.1				4.40E-06	8.99E-03	1.15E-03
1999	1	185.4				3.75E-04	1.18E-02	3.20E-03
2000	0	144.8				4.45E-06	9.10E-03	1.16E-03
2001	0	151.6				4.38E-06	8.96E-03	1.15E-03
2002	0	140.2				4.50E-06	9.20E-03	1.18E-03
2003	0	152.1				4.38E-06	8.95E-03	1.15E-03
2004	0	139.4				4.51E-06	9.22E-03	1.18E-03
2005	0	133.4				4.57E-06	9.35E-03	1.20E-03
2006	0	136.5				4.54E-06	9.28E-03	1.19E-03
2007	0	125.7	1.54E-03	7.49E-04	3.16E-03	4.66E-06	9.53E-03	1.22E-03
2008	1	151.7	1.52E-03	8.25E-04	2.81E-03	4.04E-04	1.27E-02	3.45E-03
2009	0	138.1	1.50E-03	8.99E-04	2.52E-03	4.52E-06	9.25E-03	1.18E-03
2010	0	151.1	1.49E-03	9.60E-04	2.31E-03	4.39E-06	8.97E-03	1.15E-03
2011	0	152.1	1.47E-03	9.93E-04	2.18E-03	4.38E-06	8.95E-03	1.15E-03
2012	0	127.8	1.45E-03	9.85E-04	2.15E-03	4.64E-06	9.48E-03	1.21E-03
2013	0	157.8	1.44E-03	9.34E-04	2.21E-03	4.32E-06	8.84E-03	1.13E-03
2014	1	135.8	1.42E-03	8.58E-04	2.35E-03	4.19E-04	1.32E-02	3.58E-03
2015	0	139.8	1.41E-03	7.71E-04	2.56E-03	4.50E-06	9.21E-03	1.18E-03
2016	0	137.8	1.39E-03	6.85E-04	2.82E-03	4.53E-06	9.26E-03	1.18E-03
Total	3	2,750.9						

Table 20. Plot data for Figure 5, HPCS EDG FTLR industry trend

Year	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						4.25E-04	2.16E-03	1.15E-03
1998	0	105.5				7.49E-06	1.58E-02	2.02E-03
1999	1	130.1				6.46E-04	2.03E-02	5.54E-03
2000	0	120.7				7.05E-06	1.49E-02	1.90E-03
2001	0	124.7				6.94E-06	1.46E-02	1.87E-03
2002	1	124.2				6.61E-04	2.08E-02	5.66E-03
2003	0	128.5				6.85E-06	1.44E-02	1.84E-03
2004	1	129.3				6.48E-04	2.04E-02	5.56E-03
2005	0	119.3				7.09E-06	1.50E-02	1.91E-03
2006	0	124.3				6.95E-06	1.47E-02	1.87E-03
2007	0	117.5	2.12E-03	9.25E-04	4.85E-03	7.14E-06	1.51E-02	1.92E-03
2008	0	139.4	2.27E-03	1.12E-03	4.58E-03	6.58E-06	1.39E-02	1.77E-03
2009	0	118.2	2.43E-03	1.35E-03	4.39E-03	7.12E-06	1.50E-02	1.92E-03
2010	1	132.1	2.61E-03	1.57E-03	4.32E-03	6.42E-04	2.02E-02	5.50E-03
2011	0	137.1	2.79E-03	1.77E-03	4.41E-03	6.64E-06	1.40E-02	1.79E-03
2012	1	117.0	2.99E-03	1.88E-03	4.75E-03	6.79E-04	2.14E-02	5.82E-03
2013	0	137.1	3.21E-03	1.91E-03	5.38E-03	6.64E-06	1.40E-02	1.79E-03
2014	1	118.0	3.44E-03	1.87E-03	6.31E-03	6.77E-04	2.13E-02	5.80E-03
2015	1	127.0	3.68E-03	1.79E-03	7.57E-03	6.54E-04	2.06E-02	5.60E-03
2016	0	126.0	3.94E-03	1.68E-03	9.21E-03	6.91E-06	1.46E-02	1.86E-03
Total	7	2,376.1						

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

Year	Failures	Run Time (hr)	Regression Curve Data Points Mean	Regression Curve Data Points Lower (5%)	Regression Curve Data Points Upper (95%)	Plot Trend Error Bar Points Lower (5%)	Plot Trend Error Bar Points Upper (95%)	Plot Trend Error Bar Points Mean
2015 Update						4.25E-04	2.16E-03	1.15E-03
1998	0	204.7				4.21E-06	8.36E-03	1.07E-03
1999	1	322.7				3.00E-04	9.45E-03	2.56E-03
2000	0	231.6				3.98E-06	7.90E-03	1.01E-03
2001	0	222.6				4.05E-06	8.05E-03	1.03E-03
2002	0	203.5				4.22E-06	8.38E-03	1.07E-03
2003	0	261.9				3.75E-06	7.45E-03	9.53E-04
2004	0	202.6				4.22E-06	8.40E-03	1.07E-03
2005	1	257.9				3.38E-04	1.06E-02	2.88E-03
2006	0	254.4				3.80E-06	7.55E-03	9.67E-04
2007	0	189.3	9.76E-04	4.76E-04	2.00E-03	4.35E-06	8.64E-03	1.11E-03
2008	0	312.9	1.09E-03	5.91E-04	2.00E-03	3.42E-06	6.79E-03	8.69E-04
2009	0	262.6	1.21E-03	7.25E-04	2.01E-03	3.74E-06	7.44E-03	9.52E-04
2010	1	259.7	1.34E-03	8.72E-04	2.07E-03	3.37E-04	1.06E-02	2.87E-03
2011	0	287.5	1.49E-03	1.02E-03	2.20E-03	3.57E-06	7.10E-03	9.09E-04
2012	0	55.9	1.66E-03	1.13E-03	2.44E-03	6.17E-06	1.23E-02	1.57E-03
2013	1	171.6	1.85E-03	1.21E-03	2.83E-03	4.05E-04	1.27E-02	3.45E-03
2014	0	91.2	2.06E-03	1.25E-03	3.39E-03	5.55E-06	1.10E-02	1.41E-03
2015	0	114.4	2.29E-03	1.26E-03	4.15E-03	5.21E-06	1.04E-02	1.33E-03
2016	1	94.6	2.54E-03	1.26E-03	5.15E-03	4.92E-04	1.55E-02	4.20E-03
Total	5	4,001.7						

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

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**UA Hours**	**Critical Hours**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
2015 Update						4.44E-03	2.52E-02	1.48E-02
1998	21,235	1,874,166				2.21E-03	2.42E-02	1.07E-02
1999	22,769	2,005,223				2.67E-03	2.42E-02	1.11E-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	2,104,023	1.59E-02	1.44E-02	1.75E-02	2.41E-03	3.99E-02	1.62E-02
2008	31,755	2,089,978	1.58E-02	1.45E-02	1.72E-02	2.87E-03	3.53E-02	1.52E-02
2009	33,204	2,059,429	1.57E-02	1.46E-02	1.68E-02	2.86E-03	3.79E-02	1.61E-02
2010	30,037	2,081,690	1.56E-02	1.47E-02	1.65E-02	3.32E-03	3.16E-02	1.44E-02
2011	36,401	2,023,478	1.55E-02	1.47E-02	1.63E-02	2.95E-03	4.18E-02	1.75E-02
2012	32,470	1,977,596	1.53E-02	1.46E-02	1.62E-02	3.17E-03	3.68E-02	1.60E-02
2013	30,642	2,007,371	1.52E-02	1.44E-02	1.62E-02	2.53E-03	3.34E-02	1.42E-02
2014	28,297	2,027,147	1.51E-02	1.41E-02	1.62E-02	3.15E-03	3.19E-02	1.43E-02
2015	30,721	2,008,809	1.50E-02	1.38E-02	1.63E-02	3.66E-03	3.36E-02	1.54E-02
2016	30,011	2,025,233	1.49E-02	1.35E-02	1.64E-02	3.07E-04	5.06E-02	1.52E-02
Total	537,562	38,795,002						

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
2015 Update						7.59E-03	1.58E-02	1.17E-02
1998	255	42,029				8.49E-04	1.16E-02	4.88E-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	1.12E-02	7.84E-03	1.60E-02	1.92E-03	2.07E-02	9.14E-03
2008	861	65,262	1.15E-02	8.47E-03	1.55E-02	2.31E-03	3.24E-02	1.36E-02
2009	519	63,966	1.17E-02	9.10E-03	1.51E-02	2.54E-03	1.63E-02	8.13E-03
2010	1,050	67,158	1.20E-02	9.67E-03	1.49E-02	2.34E-03	3.80E-02	1.55E-02
2011	991	62,329	1.23E-02	1.01E-02	1.49E-02	4.37E-03	3.29E-02	1.58E-02
2012	815	64,557	1.26E-02	1.03E-02	1.52E-02	2.20E-03	2.92E-02	1.24E-02
2013	952	64,142	1.29E-02	1.04E-02	1.59E-02	2.33E-03	3.51E-02	1.45E-02
2014	1,012	66,677	1.32E-02	1.02E-02	1.69E-02	2.39E-03	3.66E-02	1.51E-02
2015	627	65,277	1.35E-02	9.96E-03	1.82E-02	1.40E-03	2.37E-02	9.56E-03
2016	884	62,704	1.38E-02	9.66E-03	1.96E-02	3.09E-03	3.03E-02	1.37E-02
Total	13,924	1,202,267						

Table 24. Plot data for Figure 9, EPS EDG unreliability trend

	Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998				1.22E-02	3.86E-02	2.22E-02
1999				6.59E-03	2.90E-02	1.58E-02
2000				1.25E-02	2.99E-02	2.01E-02
2001				9.23E-03	3.27E-02	1.79E-02
2002				1.22E-02	4.49E-02	2.39E-02
2003				1.81E-02	4.99E-02	3.09E-02
2004				1.53E-02	5.64E-02	3.05E-02
2005				2.14E-02	4.85E-02	3.14E-02
2006				1.07E-02	4.40E-02	2.23E-02
2007	3.71E-02	3.22E-02	4.27E-02	2.51E-02	7.52E-02	4.13E-02
2008	3.74E-02	3.32E-02	4.21E-02	2.25E-02	6.05E-02	3.74E-02
2009	3.77E-02	3.41E-02	4.17E-02	1.78E-02	5.87E-02	3.21E-02
2010	3.80E-02	3.49E-02	4.14E-02	2.17E-02	5.08E-02	3.37E-02
2011	3.83E-02	3.55E-02	4.14E-02	2.48E-02	6.97E-02	4.17E-02
2012	3.86E-02	3.58E-02	4.17E-02	2.40E-02	5.79E-02	3.87E-02
2013	3.90E-02	3.58E-02	4.24E-02	2.57E-02	6.32E-02	4.09E-02
2014	3.93E-02	3.55E-02	4.34E-02	3.08E-02	6.71E-02	4.63E-02
2015	3.96E-02	3.51E-02	4.46E-02	2.41E-02	5.78E-02	3.89E-02
2016	3.99E-02	3.47E-02	4.60E-02	1.83E-02	6.71E-02	3.59E-02

Table 25. Plot data for Figure 10, HPCS EDG unreliability trend

Year	Regression Curve Data Points			Plot Trend Error Bar Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998				3.92E-03	3.65E-02	1.58E-02
1999				8.75E-03	7.09E-02	3.25E-02
2000				3.84E-03	7.28E-02	2.75E-02
2001				3.74E-03	3.25E-02	1.51E-02
2002				5.89E-03	4.46E-02	1.94E-02
2003				9.02E-03	3.34E-02	2.01E-02
2004				1.08E-02	4.96E-02	2.72E-02
2005				1.08E-02	5.55E-02	2.83E-02
2006				4.90E-03	3.40E-02	1.58E-02
2007	1.81E-02	1.26E-02	2.60E-02	3.29E-03	3.20E-02	1.54E-02
2008	1.95E-02	1.43E-02	2.65E-02	7.03E-03	4.38E-02	2.27E-02
2009	2.10E-02	1.62E-02	2.72E-02	5.29E-03	2.56E-02	1.45E-02
2010	2.26E-02	1.81E-02	2.81E-02	1.30E-02	7.44E-02	3.87E-02
2011	2.43E-02	1.99E-02	2.96E-02	8.24E-03	3.90E-02	2.19E-02
2012	2.62E-02	2.15E-02	3.19E-02	9.80E-03	5.79E-02	2.44E-02
2013	2.82E-02	2.26E-02	3.51E-02	1.14E-02	7.75E-02	3.59E-02
2014	3.03E-02	2.34E-02	3.93E-02	9.68E-03	6.75E-02	2.87E-02
2015	3.27E-02	2.40E-02	4.45E-02	8.32E-03	5.43E-02	2.40E-02
2016	3.52E-02	2.45E-02	5.06E-02	1.42E-02	8.03E-02	3.98E-02

Table 26. Plot data for Figure 11, EPS and HPCS EDG start demands trend

Year	Demands	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	4,351	95.0				4.47E+01	4.70E+01	4.58E+01
1999	4,317	95.0				4.43E+01	4.66E+01	4.54E+01
2000	4,093	95.3				4.19E+01	4.41E+01	4.30E+01
2001	4,247	95.0				4.36E+01	4.59E+01	4.47E+01
2002	4,482	95.0				4.60E+01	4.84E+01	4.72E+01
2003	4,485	95.0				4.61E+01	4.84E+01	4.72E+01
2004	4,475	95.3				4.58E+01	4.81E+01	4.70E+01
2005	4,516	95.0				4.64E+01	4.87E+01	4.75E+01
2006	4,507	95.0				4.63E+01	4.86E+01	4.74E+01
2007	4,412	95.0	4.58E+01	4.43E+01	4.74E+01	4.53E+01	4.76E+01	4.64E+01
2008	4,480	95.3	4.58E+01	4.45E+01	4.72E+01	4.59E+01	4.82E+01	4.70E+01
2009	4,362	95.0	4.58E+01	4.47E+01	4.69E+01	4.48E+01	4.71E+01	4.59E+01
2010	4,250	95.0	4.58E+01	4.48E+01	4.68E+01	4.36E+01	4.59E+01	4.47E+01
2011	4,286	95.0	4.58E+01	4.49E+01	4.67E+01	4.40E+01	4.63E+01	4.51E+01
2012	4,161	95.3	4.58E+01	4.49E+01	4.67E+01	4.26E+01	4.48E+01	4.37E+01
2013	4,258	92.6	4.58E+01	4.48E+01	4.67E+01	4.48E+01	4.72E+01	4.60E+01
2014	4,216	91.0	4.58E+01	4.46E+01	4.69E+01	4.52E+01	4.75E+01	4.63E+01
2015	4,169	90.0	4.57E+01	4.44E+01	4.71E+01	4.51E+01	4.75E+01	4.63E+01
2016	4,177	90.0	4.57E+01	4.42E+01	4.74E+01	4.52E+01	4.76E+01	4.64E+01
Total	82,245	1,789.6						

Table 27. Plot data for Figure 12, EPS and HPCS EDG load and run ≤1-hour demands trend

Year	Demands	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	3,908	95.0				4.01E+01	4.22E+01	4.11E+01
1999	3,881	95.0				3.98E+01	4.19E+01	4.08E+01
2000	3,809	95.3				3.89E+01	4.11E+01	4.00E+01
2001	3,904	95.0				4.00E+01	4.22E+01	4.11E+01
2002	3,762	95.0				3.85E+01	4.07E+01	3.96E+01
2003	3,919	95.0				4.02E+01	4.23E+01	4.12E+01
2004	3,951	95.3				4.04E+01	4.26E+01	4.15E+01
2005	3,904	95.0				4.00E+01	4.22E+01	4.11E+01
2006	3,882	95.0				3.98E+01	4.20E+01	4.09E+01
2007	3,761	95.0	3.95E+01	3.84E+01	4.05E+01	3.85E+01	4.07E+01	3.96E+01
2008	3,865	95.3	3.96E+01	3.87E+01	4.05E+01	3.95E+01	4.17E+01	4.06E+01
2009	3,785	95.0	3.97E+01	3.89E+01	4.04E+01	3.88E+01	4.09E+01	3.98E+01
2010	3,709	95.0	3.98E+01	3.91E+01	4.04E+01	3.80E+01	4.01E+01	3.90E+01
2011	3,747	95.0	3.99E+01	3.93E+01	4.05E+01	3.84E+01	4.05E+01	3.94E+01
2012	3,684	95.3	4.00E+01	3.94E+01	4.06E+01	3.76E+01	3.97E+01	3.87E+01
2013	3,712	92.6	4.01E+01	3.94E+01	4.07E+01	3.90E+01	4.12E+01	4.01E+01
2014	3,719	91.0	4.02E+01	3.94E+01	4.10E+01	3.98E+01	4.20E+01	4.09E+01
2015	3,659	90.0	4.03E+01	3.94E+01	4.12E+01	3.96E+01	4.18E+01	4.07E+01
2016	3,653	90.0	4.04E+01	3.93E+01	4.15E+01	3.95E+01	4.17E+01	4.06E+01
Total	72,212	1,789.6						

Table 28. Plot data for Figure 13, EPS and HPCS EDG run hours (greater than 1H) trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Run Hours**	**Reactor Years**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998	6,744	95.0				6.96E+01	7.24E+01	7.10E+01
1999	7,282	95.0				7.52E+01	7.82E+01	7.67E+01
2000	8,321	95.3				8.58E+01	8.89E+01	8.73E+01
2001	8,624	95.0				8.92E+01	9.24E+01	9.08E+01
2002	9,033	95.0				9.34E+01	9.67E+01	9.51E+01
2003	8,235	95.0				8.51E+01	8.83E+01	8.67E+01
2004	8,174	95.3				8.43E+01	8.74E+01	8.58E+01
2005	8,817	95.0				9.12E+01	9.45E+01	9.28E+01
2006	7,908	95.0				8.17E+01	8.48E+01	8.32E+01
2007	7,958	95.0	9.13E+01	7.21E+01	1.16E+02	8.22E+01	8.53E+01	8.38E+01
2008	7,946	95.3	8.47E+01	6.94E+01	1.03E+02	8.19E+01	8.50E+01	8.34E+01
2009	7,999	95.0	7.85E+01	6.64E+01	9.28E+01	8.27E+01	8.58E+01	8.42E+01
2010	7,643	95.0	7.28E+01	6.29E+01	8.42E+01	7.89E+01	8.20E+01	8.04E+01
2011	8,691	95.0	6.74E+01	5.86E+01	7.76E+01	8.99E+01	9.31E+01	9.15E+01
2012	4,327	95.3	6.25E+01	5.37E+01	7.28E+01	4.43E+01	4.66E+01	4.54E+01
2013	4,993	92.6	5.79E+01	4.86E+01	6.92E+01	5.27E+01	5.52E+01	5.39E+01
2014	4,213	91.0	5.37E+01	4.35E+01	6.63E+01	4.51E+01	4.75E+01	4.63E+01
2015	4,815	90.0	4.98E+01	3.88E+01	6.40E+01	5.22E+01	5.48E+01	5.35E+01
2016	4,563	90.0	4.62E+01	3.44E+01	6.19E+01	4.95E+01	5.20E+01	5.07E+01
Total	136,283	1,789.6						

Table 29. Plot data for Figure 14, EPS and HPCS EDG FTS events trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	18	95.0				1.22E-01	2.77E-01	1.88E-01
1999	9	95.0				5.13E-02	1.66E-01	9.63E-02
2000	12	95.3				7.39E-02	2.03E-01	1.26E-01
2001	12	95.0				7.40E-02	2.03E-01	1.27E-01
2002	10	95.0				5.87E-02	1.78E-01	1.06E-01
2003	17	95.0				1.14E-01	2.64E-01	1.77E-01
2004	14	95.3				8.95E-02	2.27E-01	1.47E-01
2005	17	95.0				1.14E-01	2.64E-01	1.77E-01
2006	9	95.0				5.13E-02	1.66E-01	9.63E-02
2007	11	95.0	1.25E-01	7.89E-02	1.98E-01	6.63E-02	1.91E-01	1.17E-01
2008	9	95.3	1.26E-01	8.56E-02	1.87E-01	5.11E-02	1.65E-01	9.60E-02
2009	14	95.0	1.28E-01	9.21E-02	1.77E-01	8.97E-02	2.28E-01	1.47E-01
2010	15	95.0	1.29E-01	9.78E-02	1.71E-01	9.77E-02	2.40E-01	1.57E-01
2011	18	95.0	1.31E-01	1.02E-01	1.68E-01	1.22E-01	2.77E-01	1.88E-01
2012	15	95.3	1.32E-01	1.03E-01	1.69E-01	9.74E-02	2.40E-01	1.57E-01
2013	6	92.6	1.34E-01	1.01E-01	1.76E-01	3.06E-02	1.30E-01	6.75E-02
2014	13	91.0	1.35E-01	9.77E-02	1.87E-01	8.53E-02	2.25E-01	1.43E-01
2015	13	90.0	1.37E-01	9.29E-02	2.01E-01	8.62E-02	2.27E-01	1.44E-01
2016	13	90.0	1.38E-01	8.76E-02	2.18E-01	8.62E-02	2.27E-01	1.44E-01
Total	245	1,789.6						

Table 30. Plot data for Figure 15, EPS EDG FTLR events trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Failures**	**Reactor Years**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998	14	95.0				9.02E-02	2.29E-01	1.48E-01
1999	5	95.0				2.33E-02	1.14E-01	5.60E-02
2000	8	95.3				4.40E-02	1.53E-01	8.63E-02
2001	13	95.0				8.22E-02	2.17E-01	1.37E-01
2002	14	95.0				9.02E-02	2.29E-01	1.48E-01
2003	15	95.0				9.82E-02	2.41E-01	1.58E-01
2004	10	95.3				5.89E-02	1.79E-01	1.07E-01
2005	14	95.0				9.02E-02	2.29E-01	1.48E-01
2006	15	95.0				9.82E-02	2.41E-01	1.58E-01
2007	21	95.0	1.90E-01	1.53E-01	2.36E-01	1.47E-01	3.14E-01	2.19E-01
2008	16	95.3	1.81E-01	1.51E-01	2.17E-01	1.06E-01	2.53E-01	1.68E-01
2009	18	95.0	1.72E-01	1.48E-01	2.01E-01	1.23E-01	2.78E-01	1.88E-01
2010	11	95.0	1.64E-01	1.44E-01	1.88E-01	6.67E-02	1.92E-01	1.17E-01
2011	16	95.0	1.57E-01	1.38E-01	1.78E-01	1.06E-01	2.54E-01	1.68E-01
2012	16	95.3	1.49E-01	1.31E-01	1.70E-01	1.06E-01	2.53E-01	1.68E-01
2013	12	92.6	1.42E-01	1.22E-01	1.66E-01	7.63E-02	2.09E-01	1.31E-01
2014	12	91.0	1.36E-01	1.14E-01	1.62E-01	7.76E-02	2.13E-01	1.33E-01
2015	13	90.0	1.29E-01	1.05E-01	1.60E-01	8.67E-02	2.28E-01	1.45E-01
2016	11	90.0	1.23E-01	9.61E-02	1.58E-01	7.02E-02	2.02E-01	1.23E-01
Total	254	1,789.6						

Table 31. Plot data for Figure 16, EPS EDG FTR>1H events trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Failures**	**Reactor Years**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998	4	95.0				1.69E-02	1.00E-01	4.58E-02
1999	1	95.0				1.79E-03	5.64E-02	1.53E-02
2000	7	95.3				3.69E-02	1.40E-01	7.62E-02
2001	2	95.0				5.83E-03	7.16E-02	2.55E-02
2002	7	95.0				3.70E-02	1.40E-01	7.64E-02
2003	10	95.0				5.90E-02	1.79E-01	1.07E-01
2004	13	95.3				8.20E-02	2.16E-01	1.37E-01
2005	14	95.0				9.02E-02	2.29E-01	1.48E-01
2006	4	95.0				1.69E-02	1.00E-01	4.58E-02
2007	17	95.0	1.63E-01	1.03E-01	2.58E-01	1.14E-01	2.66E-01	1.78E-01
2008	20	95.3	1.60E-01	1.09E-01	2.36E-01	1.39E-01	3.01E-01	2.08E-01
2009	8	95.0	1.57E-01	1.14E-01	2.18E-01	4.42E-02	1.53E-01	8.66E-02
2010	13	95.0	1.54E-01	1.17E-01	2.04E-01	8.22E-02	2.17E-01	1.37E-01
2011	21	95.0	1.51E-01	1.17E-01	1.95E-01	1.47E-01	3.14E-01	2.19E-01
2012	11	95.3	1.49E-01	1.15E-01	1.93E-01	6.65E-02	1.91E-01	1.17E-01
2013	17	92.6	1.46E-01	1.09E-01	1.96E-01	1.17E-01	2.73E-01	1.83E-01
2014	17	91.0	1.43E-01	1.01E-01	2.03E-01	1.19E-01	2.77E-01	1.86E-01
2015	12	90.0	1.41E-01	9.29E-02	2.12E-01	7.84E-02	2.15E-01	1.34E-01
2016	10	90.0	1.38E-01	8.48E-02	2.24E-01	6.22E-02	1.89E-01	1.13E-01
Total	208	1,789.6						

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