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Enhanced Component Performance Study: Emergency Diesel Generators 1998–2014

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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 2014 and (2) maintenance unavailability (UA) performance data from Mitigating Systems Performance Index (MSPI) Basis Document data from 2002 through 2014. 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. Six trends with varying degrees of statistical significance were identified in the data.

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ACRONYMS

CNID	constrained noninformative prior distribution
EDG	emergency diesel generator
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
GLM	generalized linear model
HPCS	high-pressure core spray
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
MSPI	Mitigating Systems Performance Index
PRA	probabilistic risk assessment
UA	unavailability

Enhanced Component Performance Study: Emergency Diesel Generators 1998–2014

1. INTRODUCTION

This report presents a performance evaluation of emergency diesel generators (EDGs) at U.S. commercial nuclear power plants from fiscal year (FY) 1998 through FY-2014. 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.

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 2014 [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, similar to the NRC's Industry Trend Program [3]. Yearly estimates have been provided for the entire active period.

This study is modeled on the web page updates associated with the NUREG/CR-1715 series of reports [4], 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 Mitigating Systems Performance Index (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.

This report provides an overview of operational data and makes no attempt to estimate values for use in probabilistic risk assessments. The 2010 Component Reliability Update [5], is an update to the report: *Industry-Average Performance for Components and Initiating Events at U.S Commercial Nuclear Power Plants* [6] and reports the current EDG unreliability estimates for probabilistic risk assessments (PRA). Estimates from that report are included herein, for comparison. These estimates are labelled "2010 Update" in the associated tables and figures.

Engineering analyses were also performed, first with respect to time period. 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 FY, for each of the three 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 “2010 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 2010 Update data. This evaluation provided a check on the ongoing use of the 2010 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.

An overview of the trending methods, glossary of terms, and abbreviations can be found in the Overview and Reference document on the Reactor Operational Experience Results and Databases web page [7].

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

- A highly statistically significant increasing trend was identified in the EDG data for the failure rate estimate for EPS EDG fail-to-run for greater than one hour (FTR>1H) (see Figure 3). Independent analysis using a generalized linear regression model indicates this could be considered extremely statistically significant (p-value < 0.0001).
- A highly statistically significant increasing trends was identified in the EDG data for EPS EDG unreliability (8-hour mission) (see Figure 9). Independent analysis using a generalized linear regression model indicates this could be considered extremely statistically significant (p-value = 0.0002).The increasing trend in the EPS EDG unreliability is primarily due to the increasing trend in the greater than 1 hour failure to run events (reflected in Figure 3).

2.1.3 Statistically Significant

- High-pressure core spray EDG unreliability (see Figure 10 and Figure 8) was independently re-evaluated using a normal generalized linear regression instead of the iteratively re-weighted least squares routine currently built into the annual update software and was found to be statistically significant. The figures show the results produced by the annual update software, which were not estimated to be significant.

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). Independent analysis using a generalized linear regression model indicates this should be considered Extremely Statistically Significant (p-value = 0.0001).

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).

2.2.3 Statistically Significant

- Frequency (events per reactor year) of start demands, EPS and HPCS EDGs. (see Figure 11) Independent analysis using a generalized linear regression model indicates this should be considered Extremely Statistically Significant (p-value < 0.0001).
- Frequency (events per reactor year) of load and run ≤ 1 hour demands, EPS and HPCS EDGs (see Figure 12). Independent analysis using a generalized linear regression model indicates this should be considered Highly Statistically Significant (p-value = 0.003).

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 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 lower 5% of the uncertainty range of the industry-average estimate, however, these manufacturer's have very few EPS EDGs, and so the data are limited. The rest 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 [6]. Table 3 shows the failure probability and failure rate estimates for the HPCS EDG. The HPCS EDG failure probability was not fully analyzed in [5] and is presented here based on the current ICES data that has been reviewed at the INL.

Table 1. EDG systems.

System	Description	EDG Count
EPS	Emergency power supply	223
HPCS	High pressure core spray	8
	Total	**231**

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. The number of EDGs in operation is assumed to be constant throughout the study period. 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 2010 Update.

Failure Mode	5%	Median	Mean	95%	Distribution Type	α	β
FTS	1.45E−03	2.77E−03	2.89E−03	4.73E−03	Beta	8.11	2.798E+03
FTLR	9.61E−04	3.34E−03	3.78E−03	8.10E−03	Beta	2.77	7.311E+02
FTR>1H	4.04E−04	1.02E−03	1.10E−03	2.06E−03	Gamma	4.49	4.093E+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	2.86E−03	3.18E−02	4.32E−02	1.23E−01	Beta	1.09	2.423E+01
FTR	1.52E−04	1.02E−03	1.30E−03	3.38E−03	Gamma	1.50	1.155E+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 14–19, respectively.

In the plots, the means of the posterior distributions from the Bayesian update process were trended across the years. The posterior distributions were also used for the vertical bounds for each year. The 5th and 95th percentiles of these distributions give an indication of the relative variation from year to year in the data. 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. The mean of such a prior distribution is the number of failures plus 0.5 divided by the number of demands plus 1.0 (for probabilities) or reactor hours (for rates).

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 intervals 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.

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 [7].

"Generalized linear model" (GLM) regression is a trending method that accounts for the expected variance of the count data. The method is based on maximizing the likelihood of the observed data. It uses the actual data—counts and demands or time; no transformation of the input data are needed. It can also be applied to ordinary data that might be normally-distributed, in which case it gives the same result if the sample is large enough. In this study, the GLM method was applied using the R [8] and SAS [9] statistical packages for those cases where the p-value was less than or equal to 0.10. Instances have occurred where the p-value from OLS is less than 0.05 but the GLM p-value exceeds 0.05. In these instances, the GLM method is believed to be more reliable because it accounts for more of the features present in the data.

A final feature of the trend graphs is that the 2010 Update baseline industry values from Table 2 are shown for comparison.

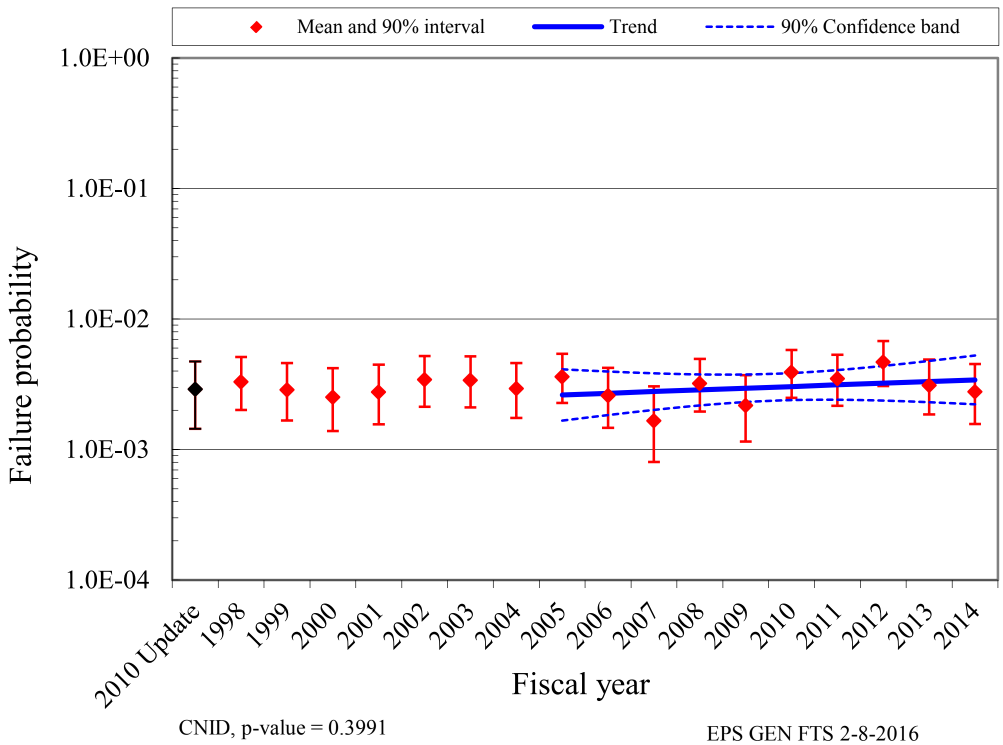

Figure 1. Failure probability estimate trend for EPS EDG FTS.

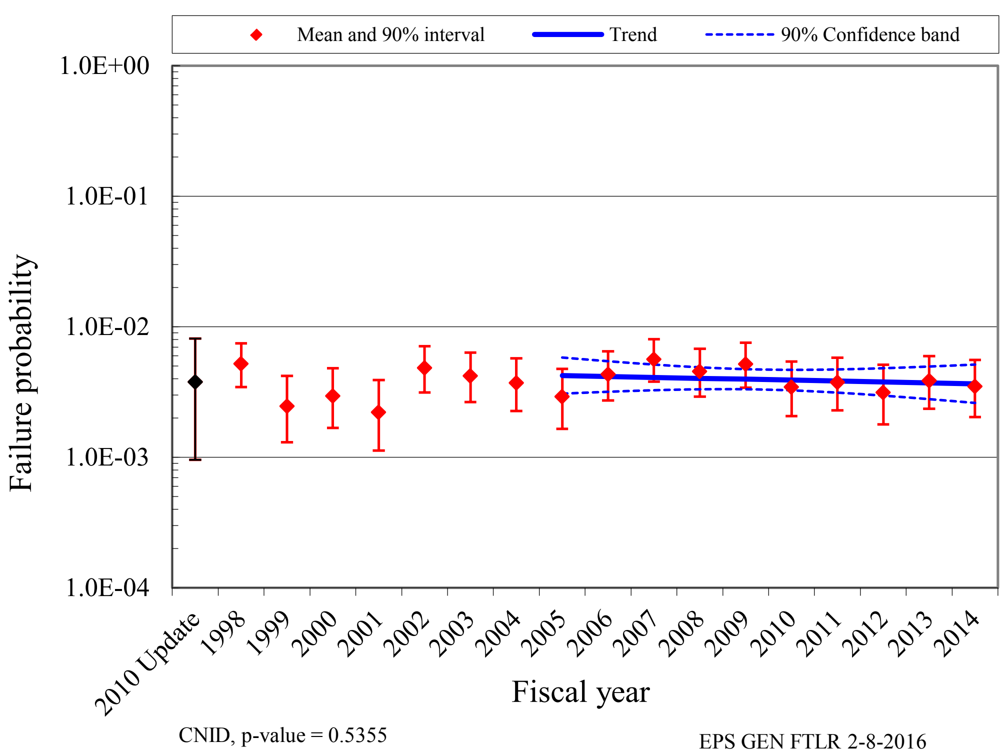

Figure 2. Failure probability estimate trend for EPS EDG FTLR .

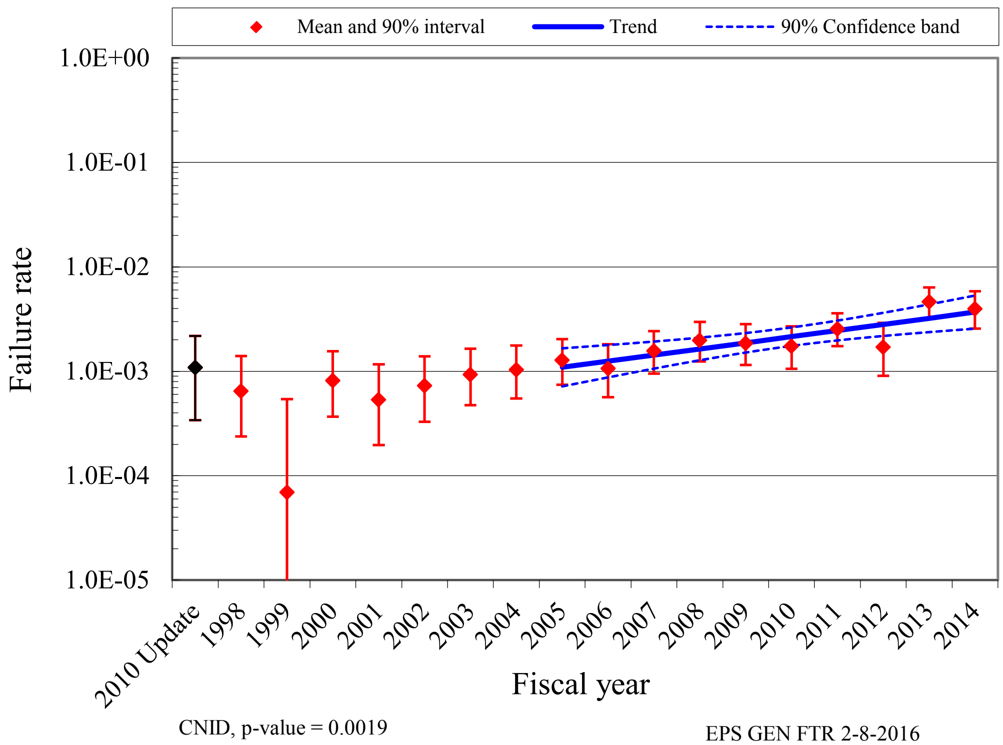

Figure 3. Failure rate estimate trend for EPS EDG FTR>1H.

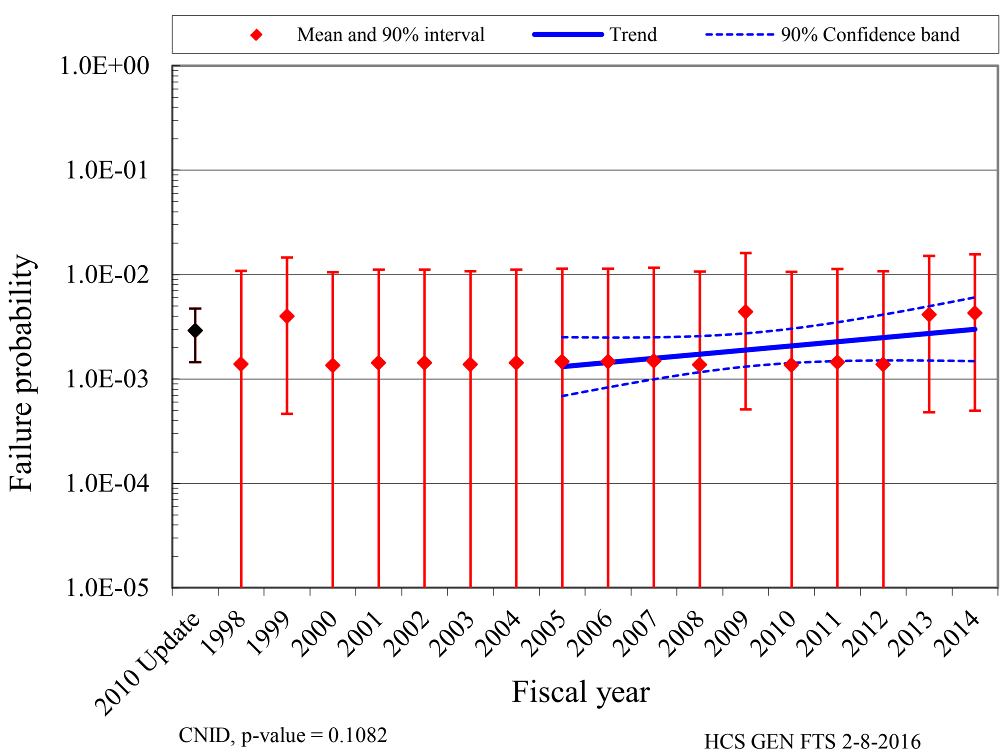

Figure 4. Failure probability estimate trend for HPCS EDG FTS.

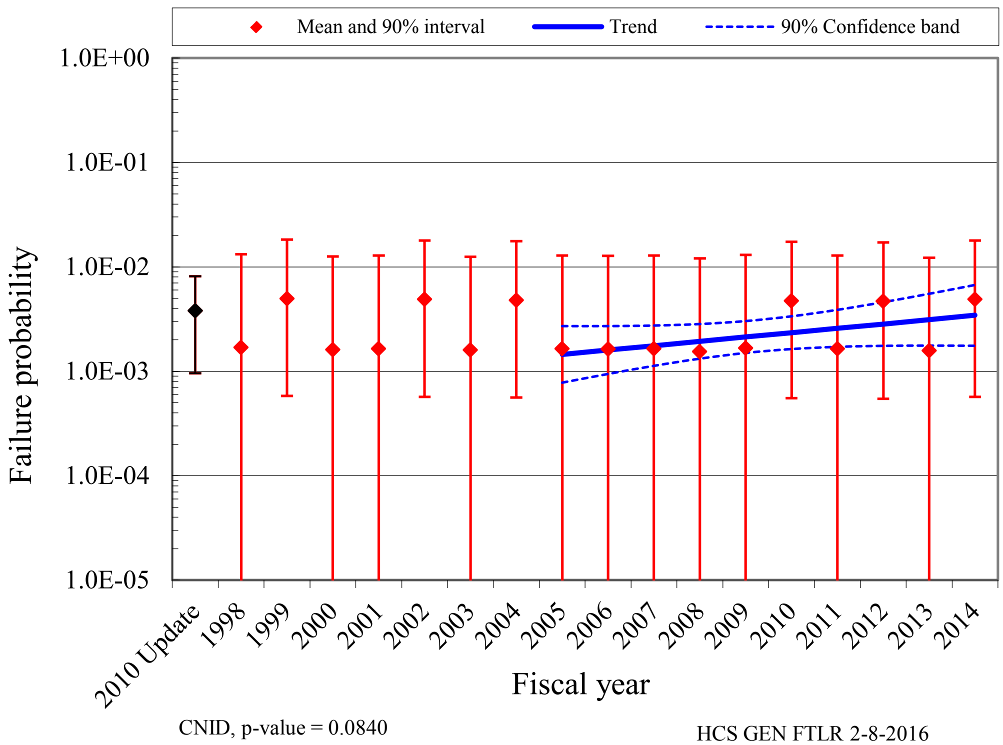

Figure 5. Failure probability estimate trend for HPCS EDG FTLR.

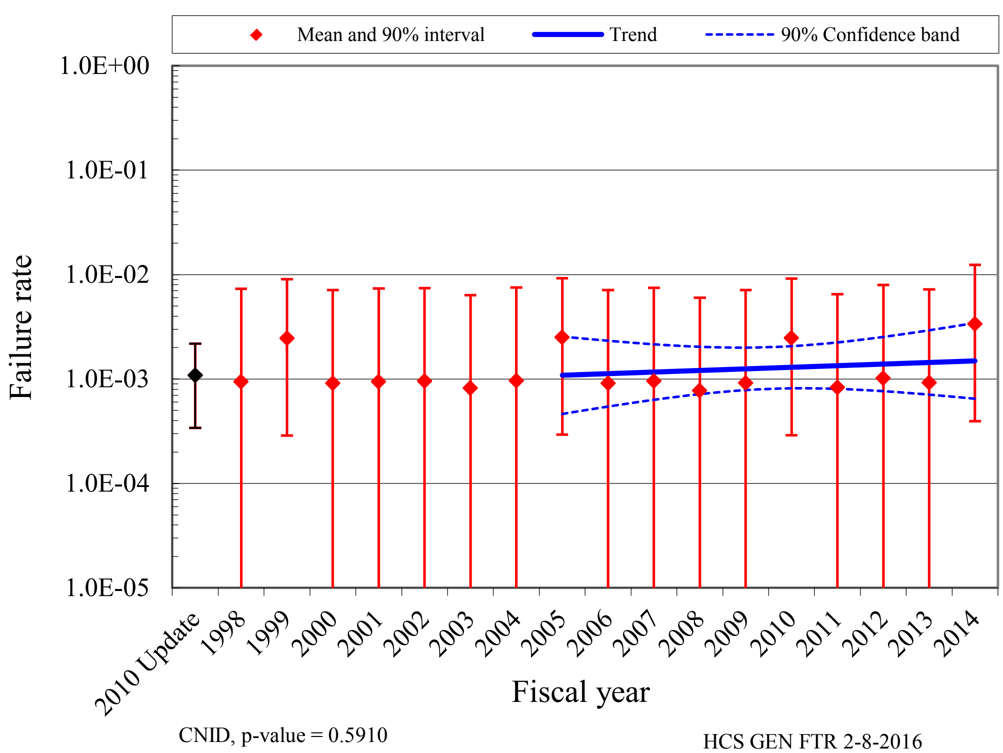

Figure 6. Failure rate estimate trend for HPCS EDG FTR>1H.

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 [5] based on UA data from MSPI Basis Documents, covering 2002 to 2010. In the calculations, planned and unplanned unavailable hours for a train are combined.

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

Description	Mean	Distribution	α	β
Emergency diesel generator test or maintenance unavailability (EPS)	1.44E−02	Beta	3.71	254.7
Emergency diesel generator test or maintenance unavailability (HPCS)	1.06E−02	Beta	42.88	4021.4

4.2 EDG Unavailability Trends

The graphs that follow provide overall maintenance unavailability data for the 1998–2014 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 20 and Table 21, 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 2014). 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 (2002–2014) requires plants to report such outages. The difference in the annual means of these two groups is not statistically significant, indicating that there is insufficient evidence that they differ.

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 [7]. In the lower left hand corner of each trend figure, the p-value is reported.

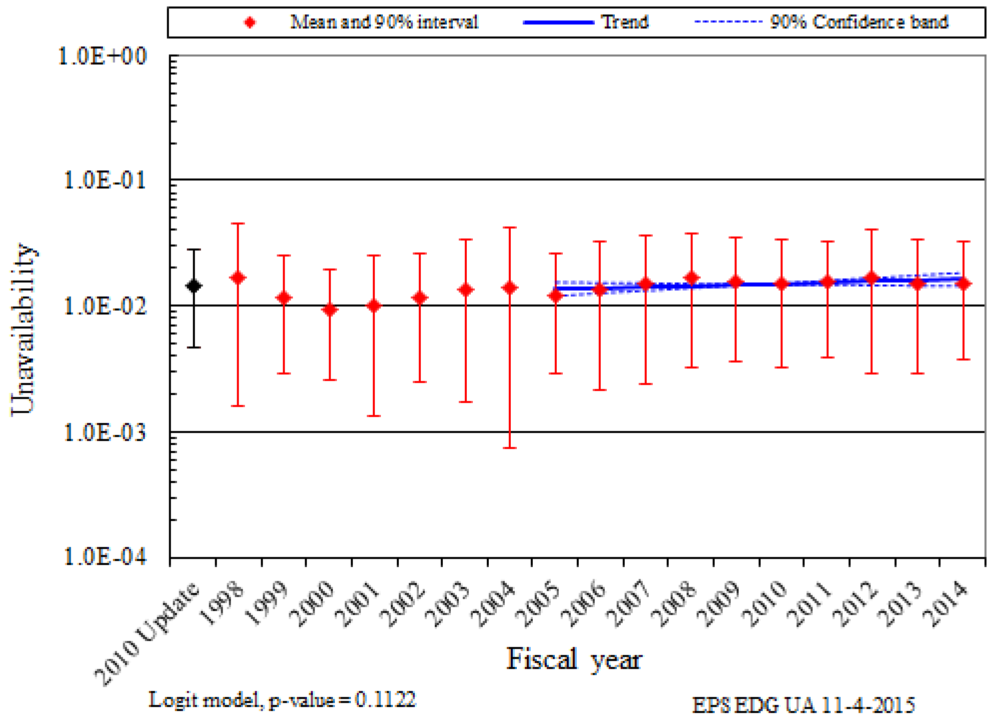

Figure 7. EPS EDG UA trend.

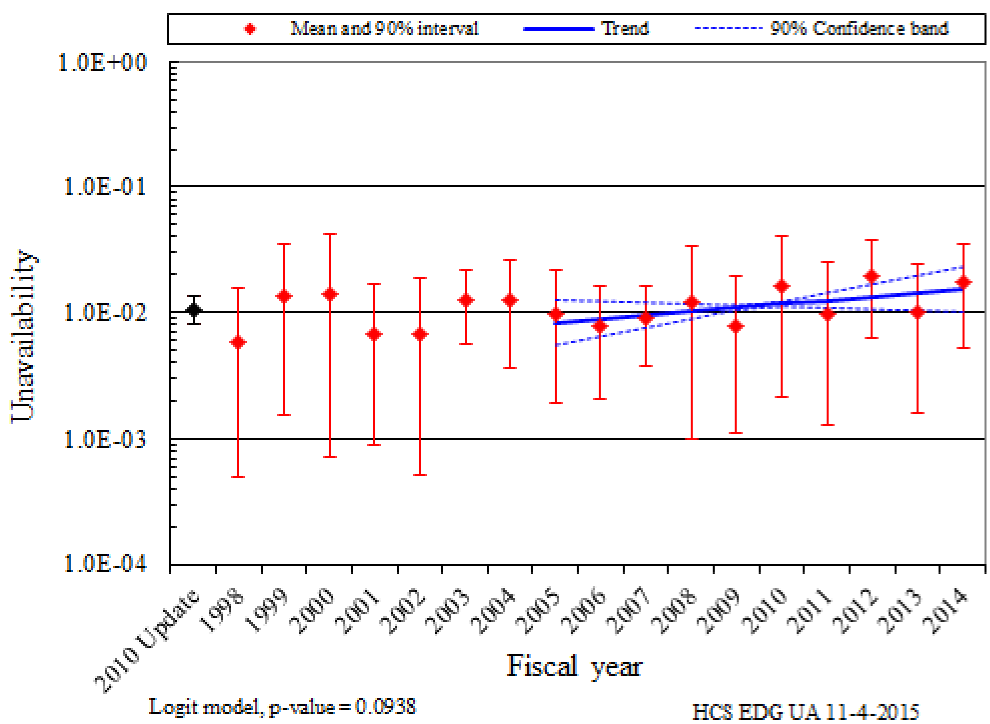

Figure 8. HPCS EDG UA trend.

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 22 and Table 23, 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 [7]. In the lower left hand corner of the trend figures, the regression method is reported.

No “2010 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.

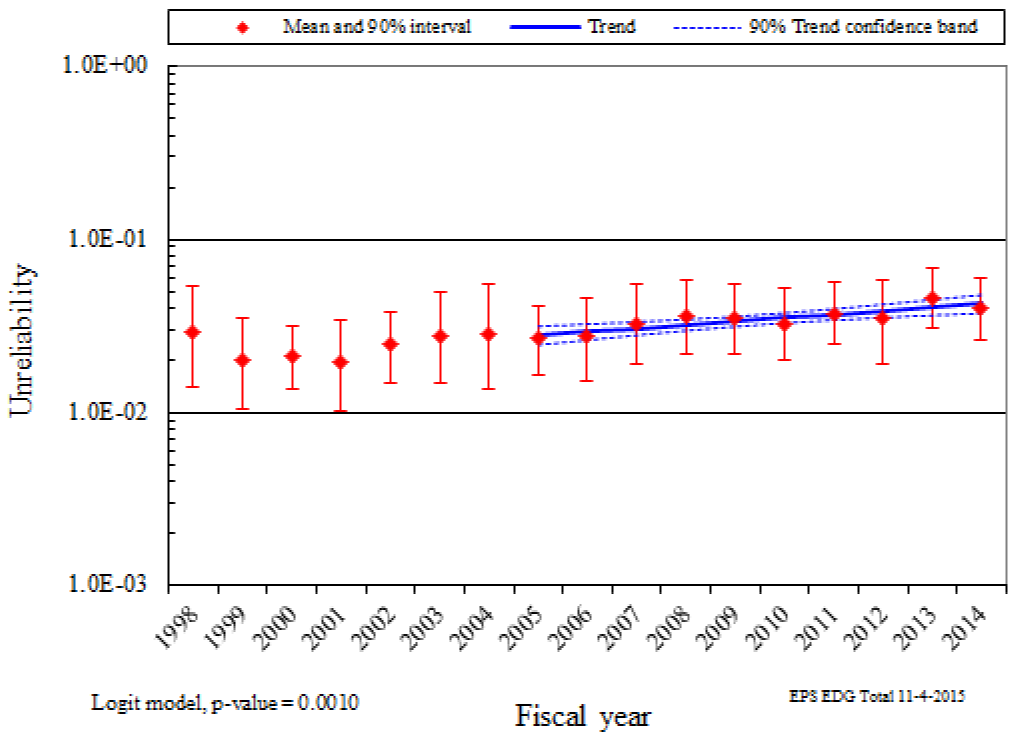

Figure 9. EPS EDG unreliability trend (8-hour mission).

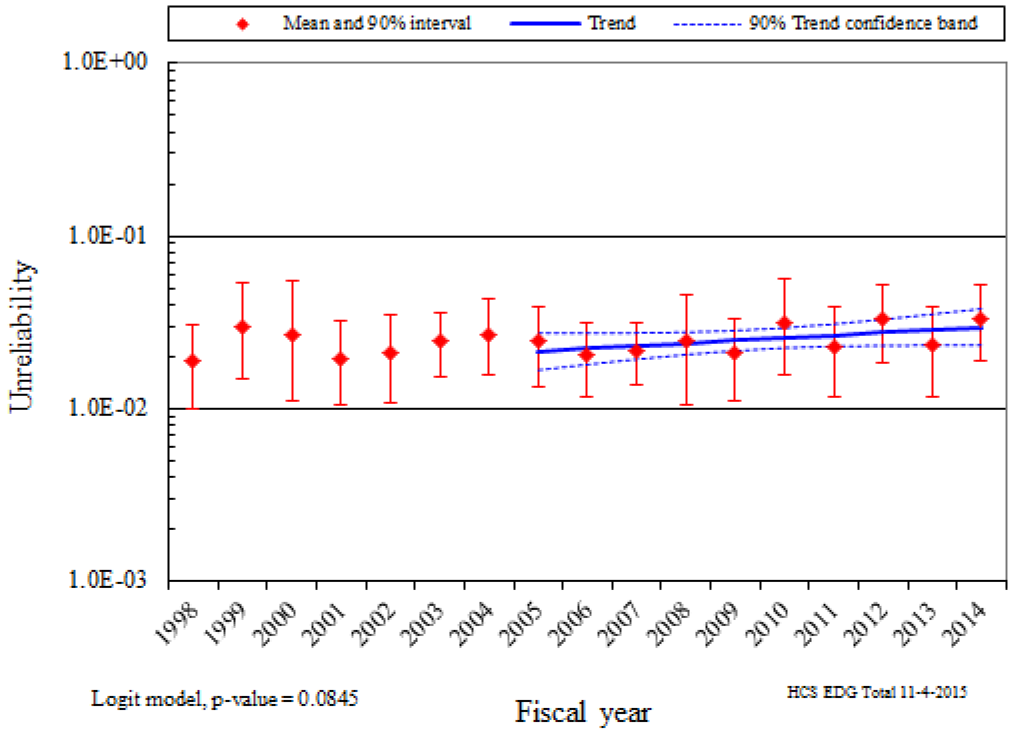

Figure 10. HPCS EDG unreliability trend (8-hour mission).

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 just provide an overview of the demand counts and failure counts per reactor year 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 24–26 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 27–29 provide the plot data, respectively.

Table 5–Table 7 provide a summary of the total failure event count for each of the years for which a trend line is plotted. Table 5 summarizes the failures by system and year for the FTS failure mode. Table 6 summarizes the failures by system and year for the FTLR failure mode. Table 7 summarizes the failures by system and year for the FTR>1H failure mode. The data in Table 5–Table 7 show failure events resulting from FTLR and FTR>1H occur in roughly equal numbers, while FTS failures occur somewhat less frequently. Furthermore, HCS 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 [7].

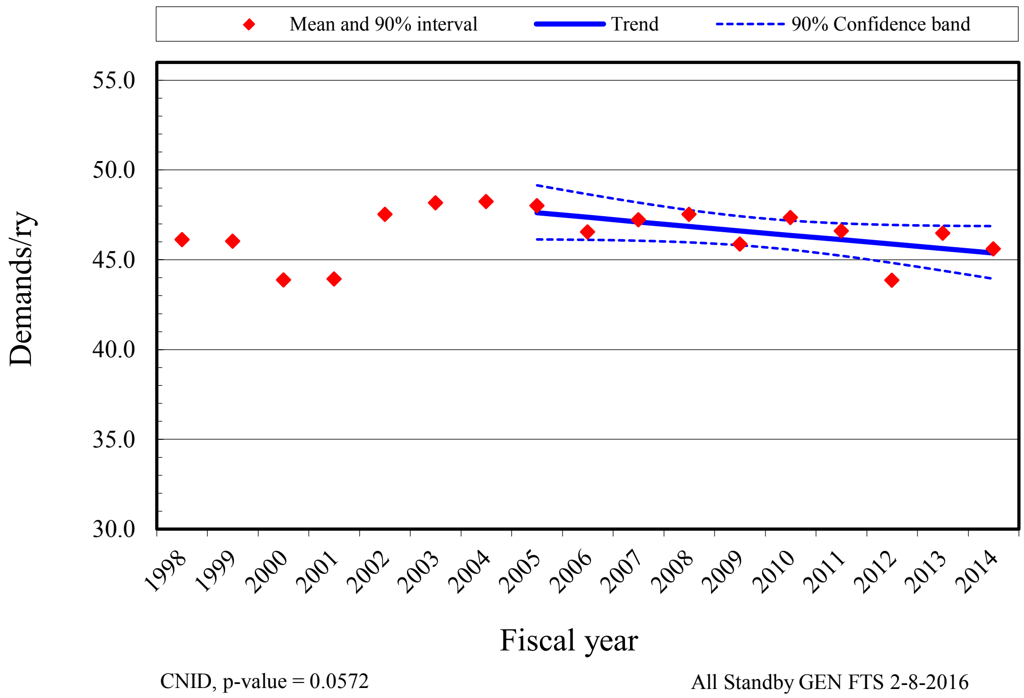

Figure 11. Frequency (events per reactor year) of start demands, EPS and HPCS EDGs.

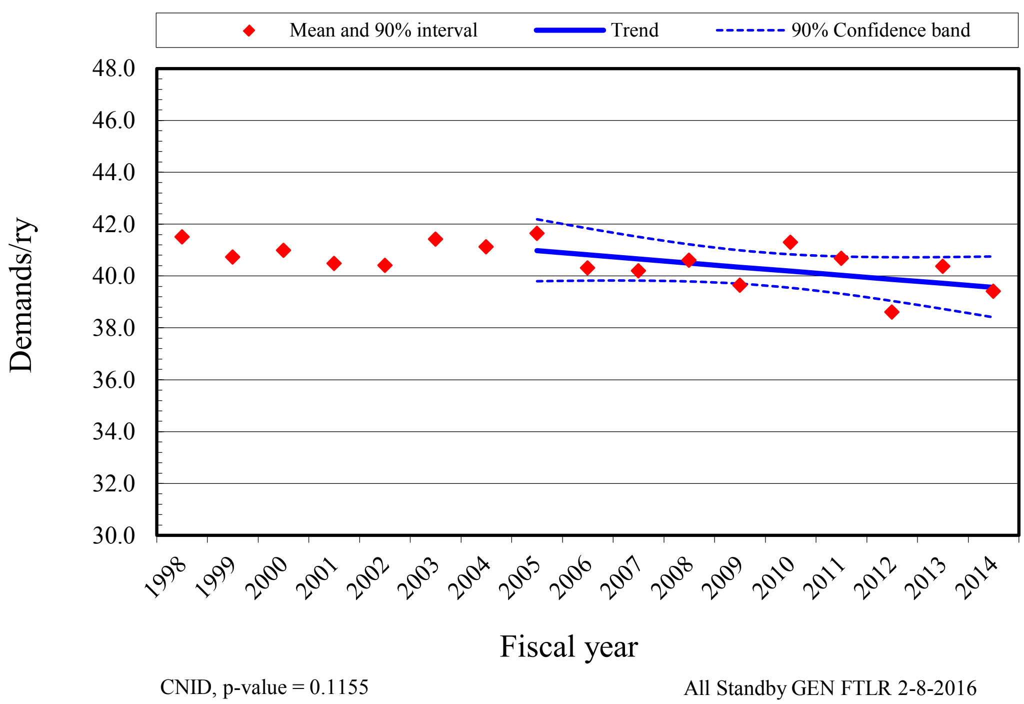

Figure 12. Frequency (events per reactor year) of load and run ≤ 1 hour demands, EPS and HPCS EDGs.

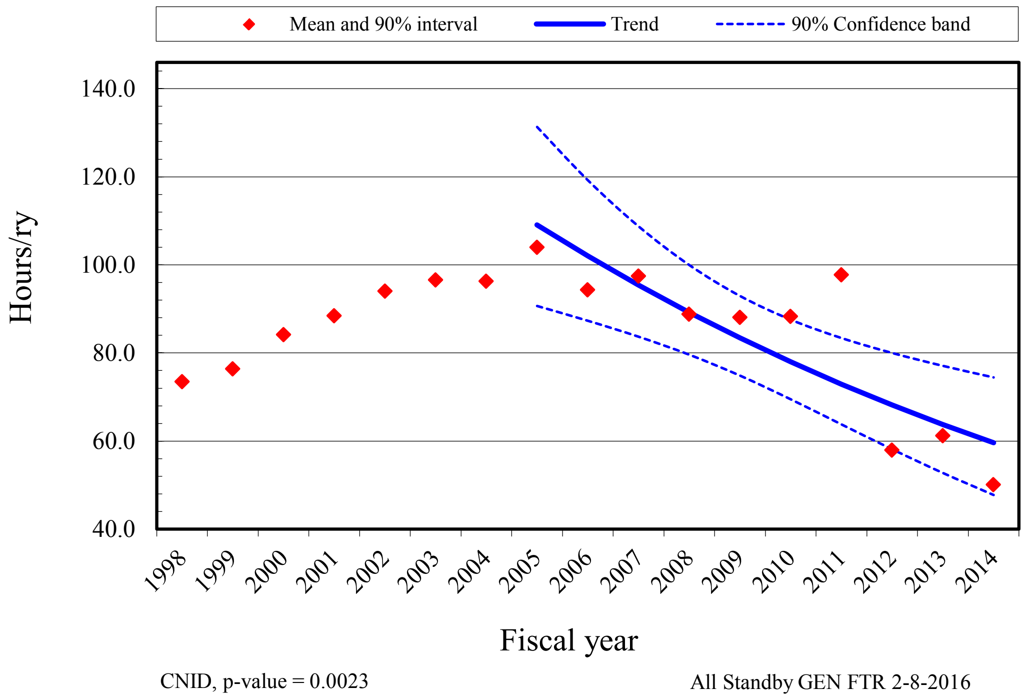

Figure 13. EPS and HPCS EDG run hours per reactor year.

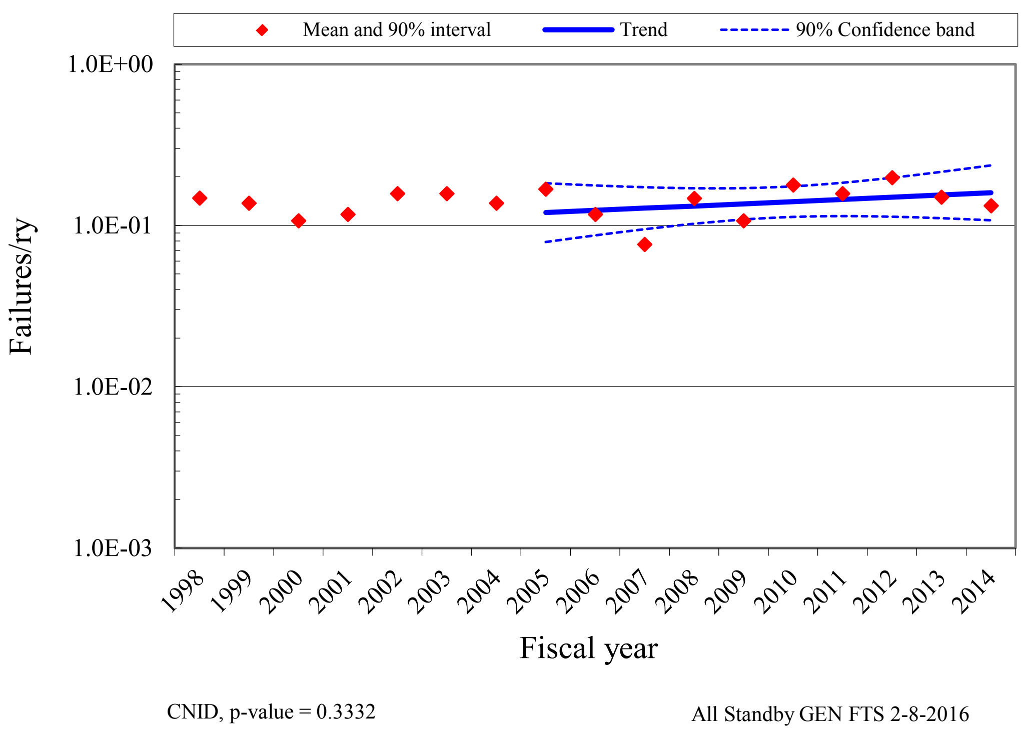

Figure 14. Frequency (events per reactor year) of FTS events, EPS and HPCS EDGs.

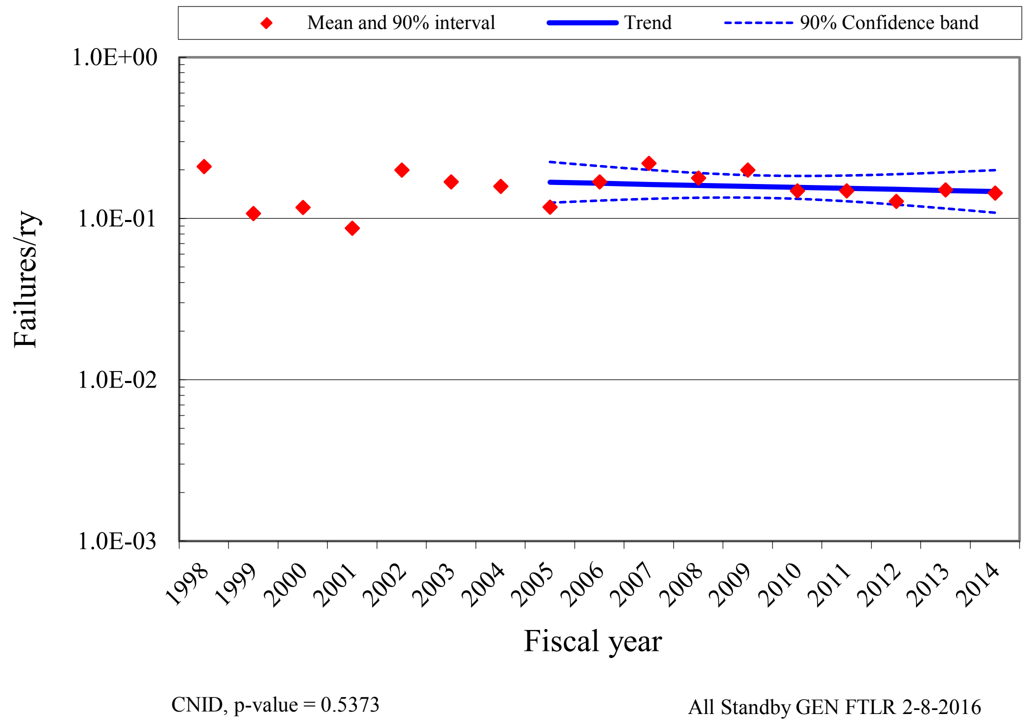

Figure 15. Frequency (events per reactor year) of FTLR events, EPS and HPCS EDGs.

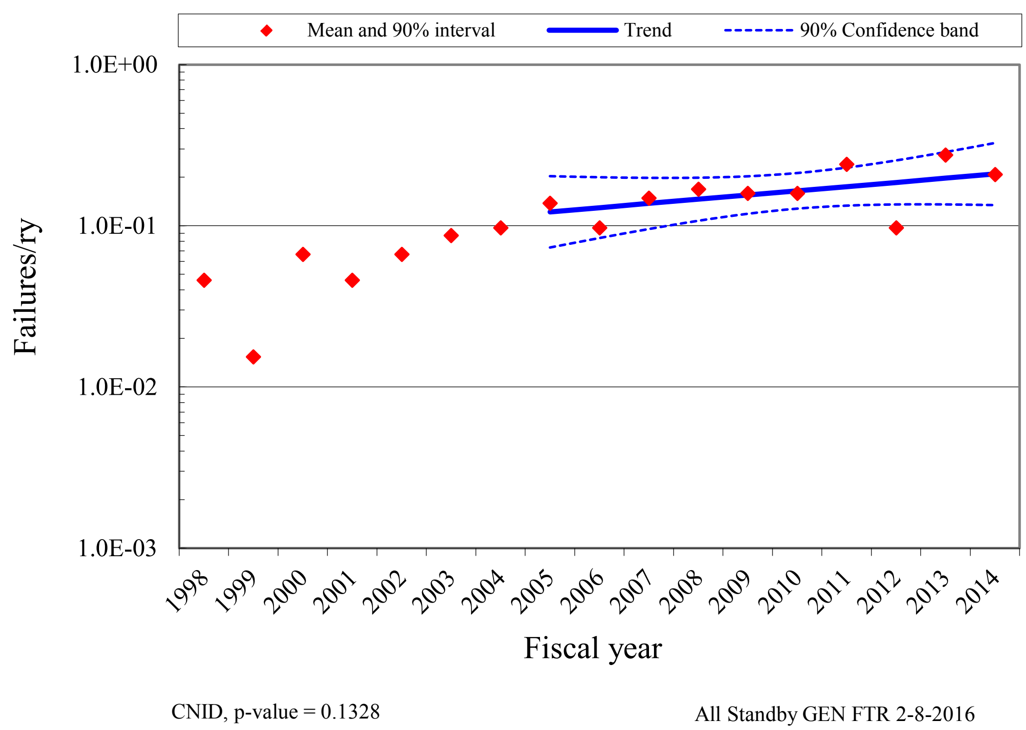

Figure 16. Frequency (events per reactor year) of FTR>1H events, EPS and HPCS EDGs.

Table 5. Summary of EDG failure counts for the FTS failure mode over time by system.

System Code	EDG Count	EDG Percent	Fiscal Year 05	06	07	08	09	10	11	12	13	14	Total	Percent of Failures
EPS	223	96.5%	16	11	7	14	9	17	15	19	13	11	132	**97.8%**
HCS	8	3.5%					1				1	1	3	2.2%
Total	231	100%	16	11	7	14	10	17	15	19	14	12	135	100%

Table 6. Summary of EDG failure counts for the FTLR failure mode over time by system.

System Code	EDG Count	EDG Percent	Fiscal Year 05	06	07	08	09	10	11	12	13	14	Total	Percent of Failures
EPS	223	96.5%	11	16	21	17	19	13	14	11	14	12	148	**98.0%**
HCS	8	3.5%						1		1		1	3	2.0%
Total	231	100%	11	16	21	17	19	14	14	12	14	13	151	100%

Table 7. Summary of EDG failure counts for the FTR > 1H failure mode over time by system.

System Code	EDG Count	EDG Percent	Fiscal Year 05	06	07	08	09	10	11	12	13	14	Total	Percent of Failures
EPS	223	96.5%	12	9	14	16	15	14	23	9	26	18	156	**98.1%**
HCS	8	3.5%	1					1				1	3	1.9%
Total	231	100%	13	9	14	16	15	15	23	9	26	19	159	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 FY 2003 to present since the ESF demand reporting in ICES is inconsistent prior to FY 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 FY 2003 – 2014 are summarized in Table 8. 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 [10].

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 Table 8) 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 unplanned demand performance was considered to be consistent with the industry-average distribution obtained from the ICES data analysis.

Table 8. EPS EDG unplanned demand performance comparison with industry-average performance from ICES data.

Failure Modes	Plants	Demands or Hours	Failures	Expected Failures	Probability of ≥ Failures	Consistent with Industry-Average Performance?
FTS	96	451	0	1.3	1.00	Yes[a]
FTLR	96	272	1	1.0	0.58	Yes
FTR>1H	96	3296	4	3.6	0.45	Yes

a. In this case P(X=0) = 0.29 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. Note that for the FTR data from 2008 on, the data are near or above the 2010 Update 95th percentile.

6.3 EPS EDG Performance by Manufacturer

Table 9 presents the results of the evaluation of 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 lower 5% of the industry average distribution, however, these two manufacturers involve very few EPS EDGs, and so may not be representative of the manufacturer compared to the other EDGs. The rest of the manufacturers failure observations lie within the 5% to 95% interval and are consistent with the industry-average performance.

Table 9. EPS EDG manufacturer performance consistency 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	63	56.3	0.32	Yes
Cooper Bessemer	CB	33	66	93.4	0.86	Yes
Electro Motive/General Motors	EM/GM	68	169	165.7	0.58	Yes
Fairbanks Morse/Colt	FM/C	69	213	171.0	0.22	Yes
Nordberg	NB	8	32	23.8	0.19	Yes
SAC/Compair Luchard/ Jeumont Schndr	SC/JS	3	16	6.5	0.01	No
TransAmerica DeLaval	TD	20	73	52.2	0.12	Yes
Worthington Corp	WC	4	24	8.7	0.00	No

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

6.4 EPS EDG Performance by Rating

Table 10 presents the results of the evaluation of EPS EDG performance by rating. The results are a consistency check against the industry-average distributions in Table 2. 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 10. EPS EDG rating performance consistency 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	4	6.9	0.86	Yes
1,000–4,999 KW	169	455	422.5	0.35	Yes
5,000–99,999 KW	52	169	148.6	0.29	Yes

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

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. 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 11 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 to 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 11:1.

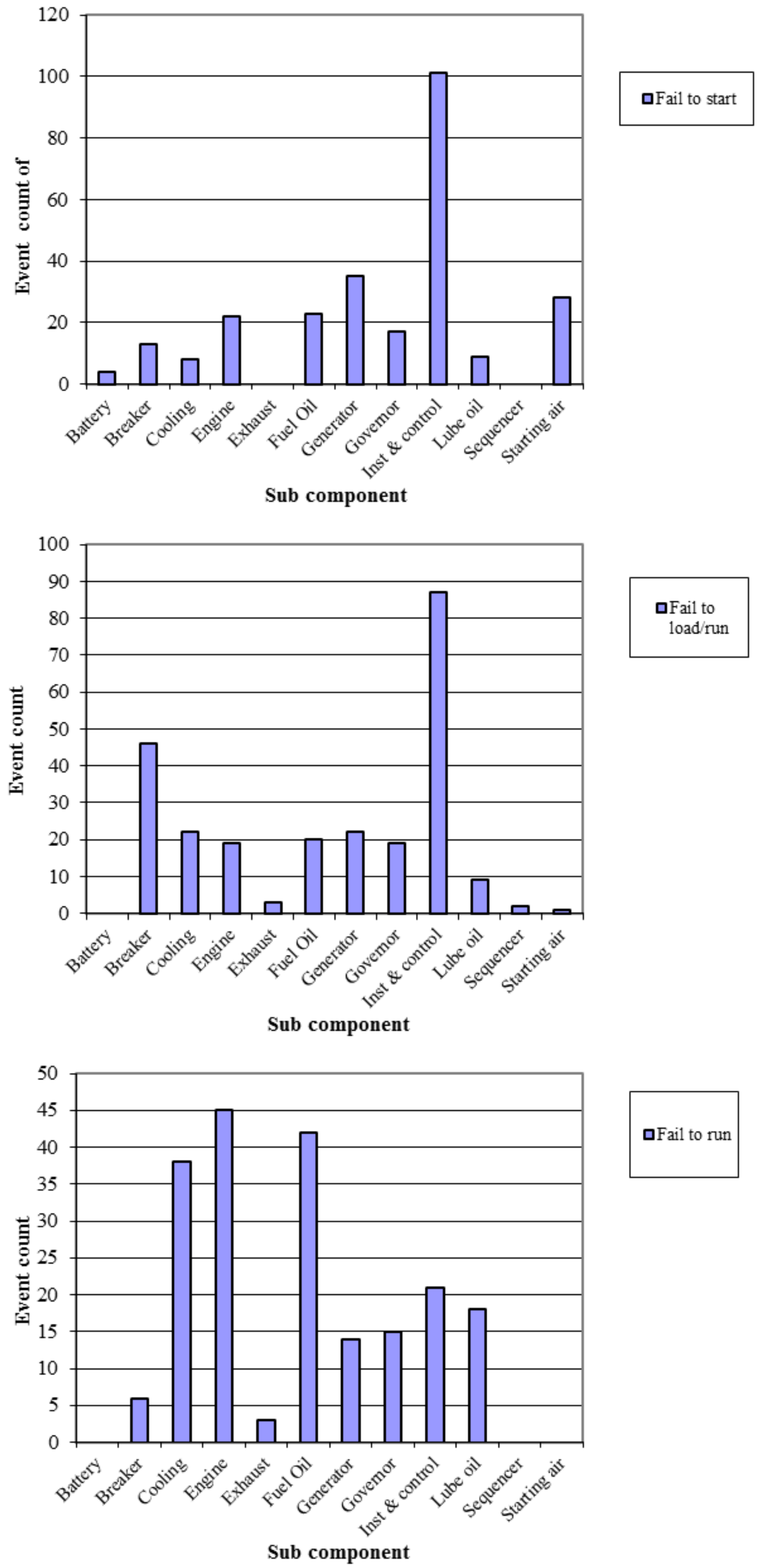

Figure 17. EPS EDG failure breakdown by sub component and failure mode

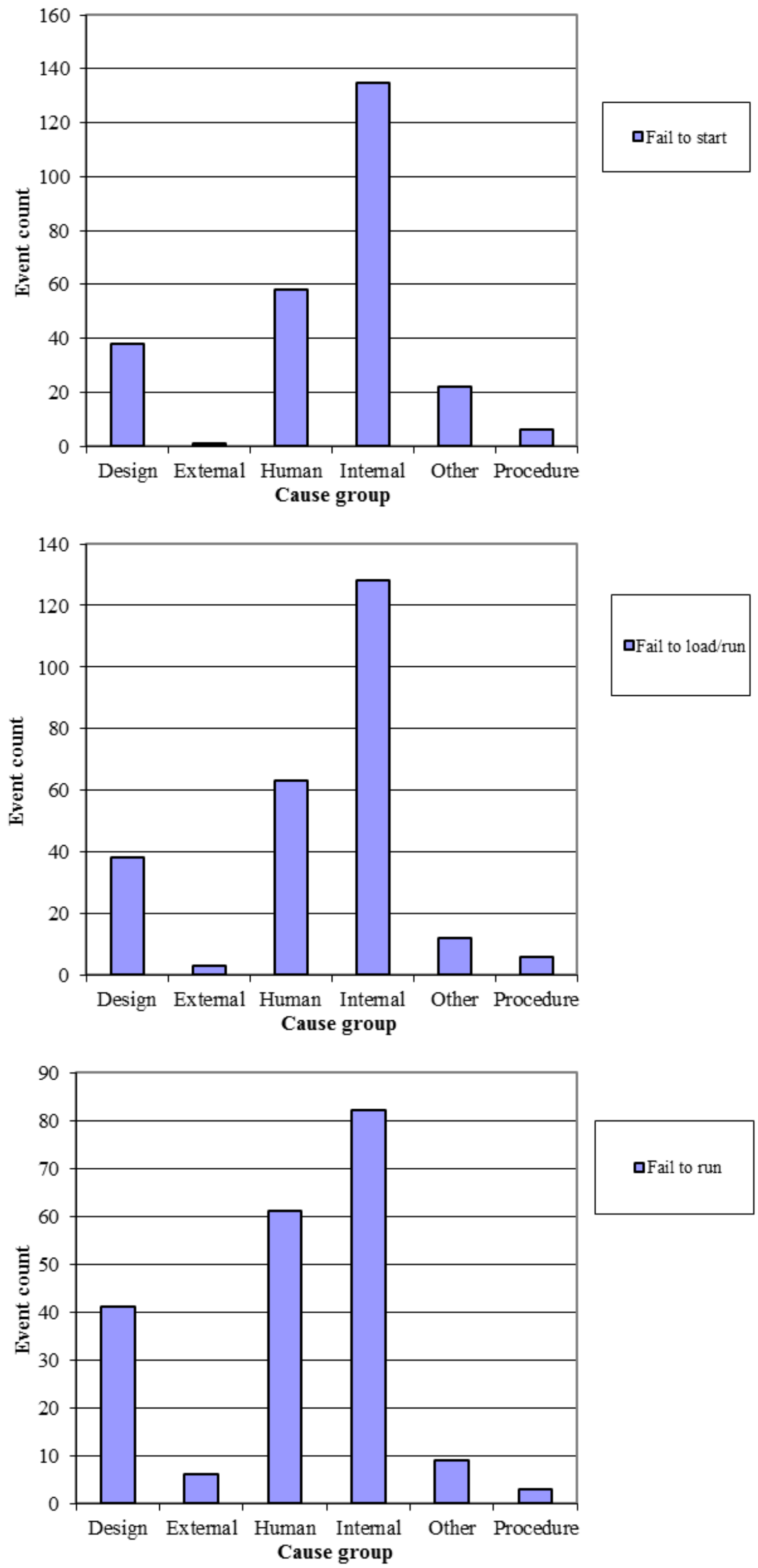

Figure 18. EPS EDG breakdown by cause group and failure mode

Table 11. 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 procedure is not followed or the procedure is incorrect. 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.

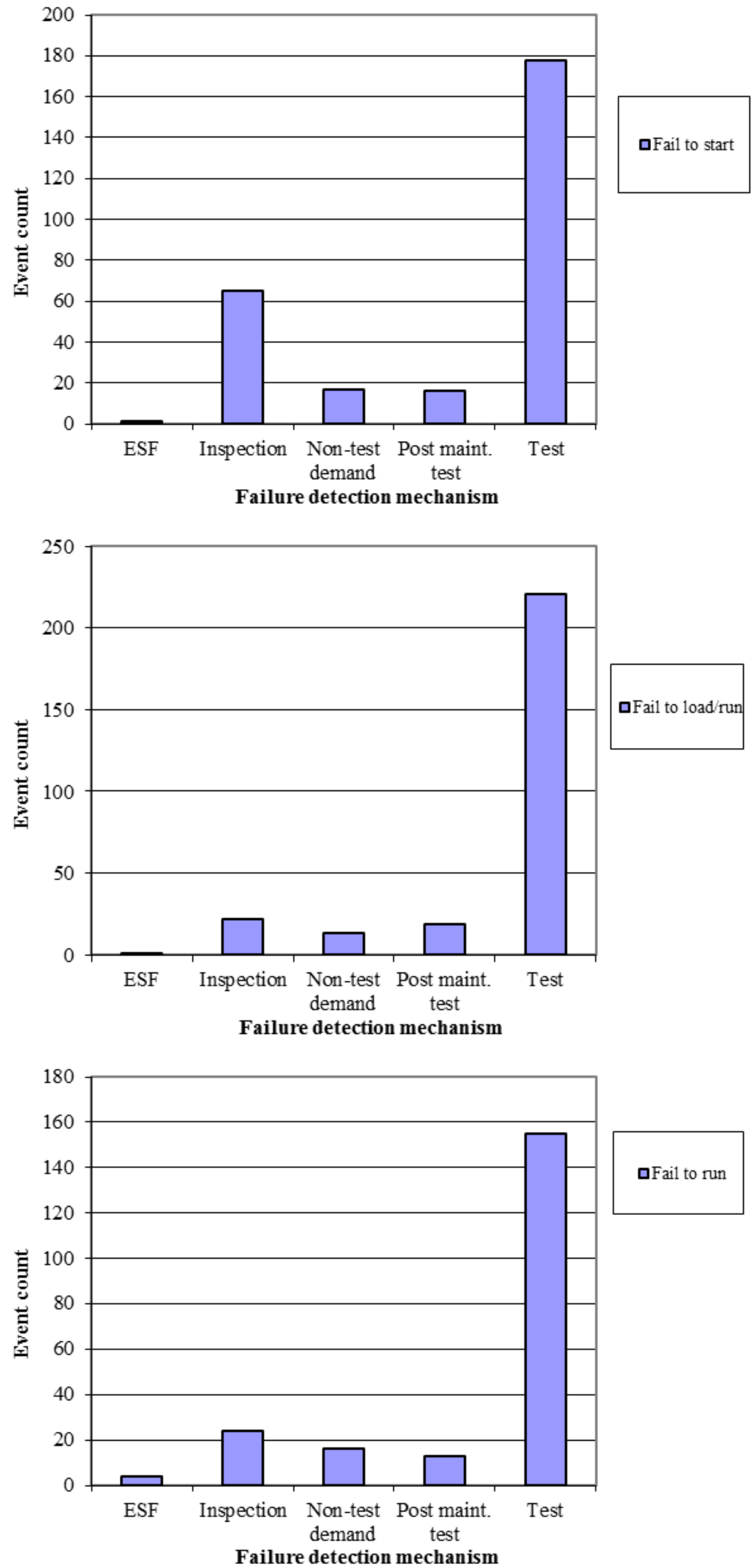

Figure 19. EPS EDG component failure distribution failure mode and method of detection

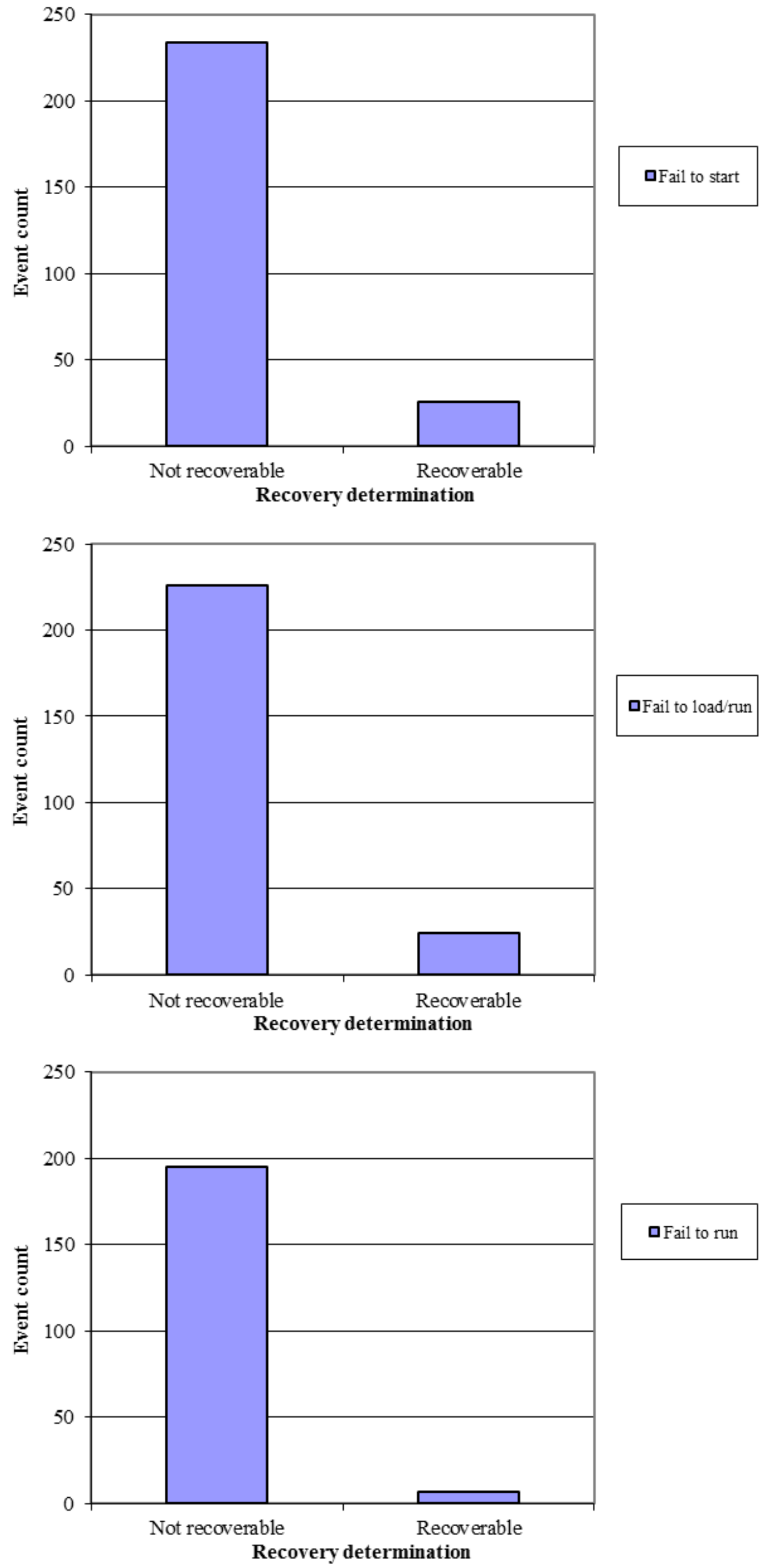

Figure 20. EPS EDG component failure distribution by failure mode and recovery determination

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 12 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.

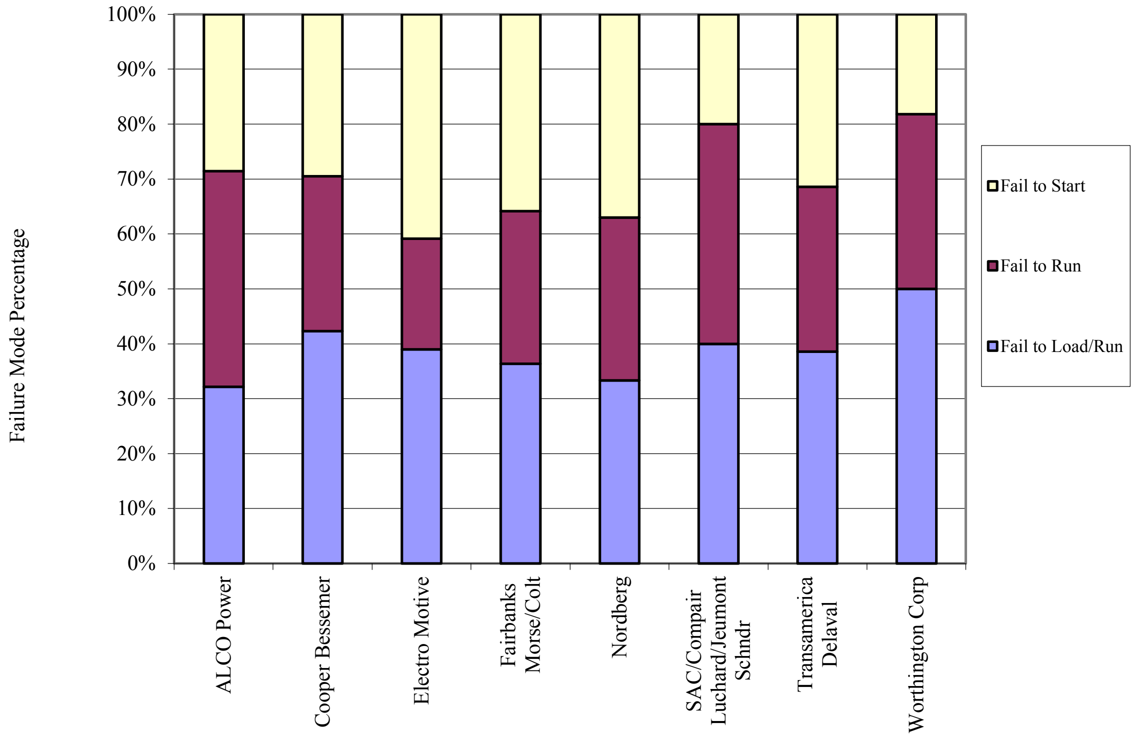

Figure 21. EPS EDG failure distribution by manufacturer

Table 12. EPS EDG manufacturer population and total failure count.

Manufacturer	Code	EPS EDGs	Total Failure Count
ALCO Power	AP	24	56
Cooper Bessemer	CB	31	78
Electro Motive	EM/GM	68	159
Fairbanks Morse/Colt	FM/C	65	187
Nordberg	NB	8	27
SAC/Compair Luchard/Jeumont Schndr	SC/JS	3	15
Transamerica Delaval	TD	20	70
Worthington Corp	WC	4	22
Totals		223	614

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 13 shows the distribution of the various rated EPS EDGs in the ICES database used in this study. The smaller EDGs differ from the others in not yet having any FTS events, but the operational experience for these EDG is much shorter than for the larger EDGs.

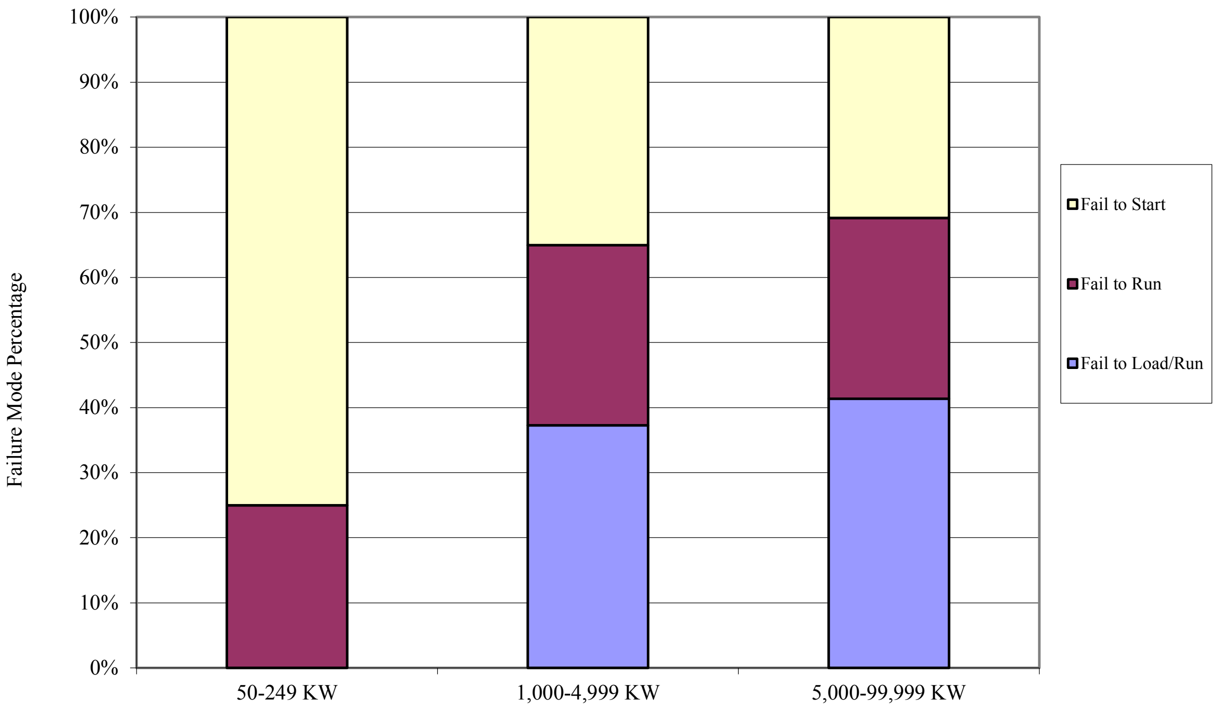

Figure 22. EPS EDG component failure modes by EPS EDG rating

Table 13. EPS EDG population by rating.

EPS EDG Rating	Count	Total Failure Count
50–249 KW	2	4
1,000–4,999 KW	169	448
5,000–99,999 KW	52	162
Total	223	614

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.

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 probabilistic risk assessment (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 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 14. Plot data for Figure 1, EPS EDG FTS industry trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
FY/ Source	**Failures**	**Demands**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
2010 Update						1.45E-03	4.74E-03	2.89E-03
1998	14	4,176.7				2.04E-03	5.18E-03	3.34E-03
1999	12	4,199.8				1.68E-03	4.60E-03	2.87E-03
2000	10	3,986.0				1.40E-03	4.24E-03	2.53E-03
2001	11	4,012.3				1.57E-03	4.51E-03	2.76E-03
2002	15	4,357.8				2.14E-03	5.24E-03	3.43E-03
2003	15	4,314.7				2.16E-03	5.29E-03	3.47E-03
2004	13	4,427.8				1.76E-03	4.64E-03	2.94E-03
2005	16	4,399.5	2.63E-03	1.67E-03	4.15E-03	2.29E-03	5.46E-03	3.62E-03
2006	11	4,291.6	2.72E-03	1.84E-03	4.00E-03	1.47E-03	4.23E-03	2.58E-03
2007	7	4,333.3	2.80E-03	2.02E-03	3.88E-03	8.08E-04	3.07E-03	1.67E-03
2008	14	4,364.7	2.89E-03	2.19E-03	3.81E-03	1.96E-03	4.97E-03	3.21E-03
2009	9	4,173.9	2.98E-03	2.33E-03	3.81E-03	1.17E-03	3.77E-03	2.19E-03
2010	17	4,230.1	3.08E-03	2.42E-03	3.91E-03	2.56E-03	5.94E-03	3.99E-03
2011	15	4,201.3	3.17E-03	2.44E-03	4.13E-03	2.21E-03	5.43E-03	3.56E-03
2012	19	3,958.2	3.27E-03	2.40E-03	4.46E-03	3.12E-03	6.91E-03	4.74E-03
2013	13	4,106.7	3.38E-03	2.34E-03	4.87E-03	1.89E-03	4.98E-03	3.17E-03
2014	11	3,974.8	3.48E-03	2.25E-03	5.37E-03	1.58E-03	4.55E-03	2.78E-03
Total	222	71,509.1						

Table 15. Plot data for Figure 2, EPS EDG FTLR industry trend

FY/ Source	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2010 Update						9.59E-04	8.11E-03	3.78E-03
1998	20	3,807.1				3.48E-03	7.54E-03	5.22E-03
1999	9	3,752.0				1.31E-03	4.21E-03	2.45E-03
2000	11	3,761.5				1.69E-03	4.84E-03	2.96E-03
2001	8	3,710.7				1.13E-03	3.93E-03	2.22E-03
2002	18	3,709.3				3.14E-03	7.11E-03	4.83E-03
2003	16	3,713.7				2.72E-03	6.48E-03	4.30E-03
2004	14	3,781.0				2.27E-03	5.76E-03	3.71E-03
2005	11	3,804.8	4.26E-03	3.10E-03	5.84E-03	1.67E-03	4.79E-03	2.93E-03
2006	16	3,707.4	4.20E-03	3.21E-03	5.48E-03	2.73E-03	6.50E-03	4.31E-03
2007	21	3,682.7	4.14E-03	3.30E-03	5.18E-03	3.81E-03	8.09E-03	5.65E-03
2008	17	3,708.8	4.08E-03	3.36E-03	4.94E-03	2.93E-03	6.80E-03	4.57E-03
2009	19	3,594.6	4.02E-03	3.37E-03	4.79E-03	3.46E-03	7.65E-03	5.25E-03
2010	13	3,697.4	3.96E-03	3.31E-03	4.74E-03	2.12E-03	5.57E-03	3.53E-03
2011	14	3,646.3	3.90E-03	3.18E-03	4.78E-03	2.35E-03	5.96E-03	3.85E-03
2012	11	3,486.5	3.84E-03	3.02E-03	4.89E-03	1.81E-03	5.21E-03	3.19E-03
2013	14	3,570.2	3.79E-03	2.85E-03	5.04E-03	2.40E-03	6.09E-03	3.93E-03
2014	12	3,445.4	3.73E-03	2.67E-03	5.22E-03	2.05E-03	5.62E-03	3.50E-03
Total	244	62,579.3						

Table 16. Plot data for Figure 3, EPS EDG FTR>1H industry trend

FY/ Source	Failures	Run Time (hr)	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2010 Update						3.40E-04	2.18E-03	1.09E-03
1998	4	6,779.0				2.37E-04	1.40E-03	6.41E-04
1999	0	6,928.3				2.74E-07	5.45E-04	6.98E-05
2000	6	7,787.3				3.67E-04	1.56E-03	8.10E-04
2001	4	8,162.4				1.98E-04	1.17E-03	5.36E-04
2002	6	8,760.9				3.27E-04	1.39E-03	7.22E-04
2003	8	8,716.8				4.84E-04	1.68E-03	9.49E-04
2004	9	8,935.1				5.51E-04	1.78E-03	1.04E-03
2005	12	9,536.2	1.10E-03	7.24E-04	1.68E-03	7.47E-04	2.05E-03	1.28E-03
2006	9	8,740.0	1.26E-03	8.83E-04	1.80E-03	5.63E-04	1.82E-03	1.06E-03
2007	14	9,018.0	1.45E-03	1.07E-03	1.95E-03	9.56E-04	2.43E-03	1.57E-03
2008	16	8,005.7	1.66E-03	1.29E-03	2.13E-03	1.27E-03	3.02E-03	2.00E-03
2009	15	8,047.7	1.90E-03	1.53E-03	2.36E-03	1.16E-03	2.86E-03	1.87E-03
2010	14	7,880.2	2.18E-03	1.78E-03	2.67E-03	1.09E-03	2.77E-03	1.79E-03
2011	23	8,738.3	2.50E-03	2.00E-03	3.11E-03	1.80E-03	3.69E-03	2.62E-03
2012	9	5,297.5	2.86E-03	2.21E-03	3.69E-03	9.14E-04	2.95E-03	1.72E-03
2013	26	5,405.5	3.28E-03	2.41E-03	4.45E-03	3.30E-03	6.49E-03	4.69E-03
2014	18	4,429.0	3.76E-03	2.61E-03	5.41E-03	2.58E-03	5.84E-03	3.96E-03
Total	193	131,167.7						

Table 17. Plot data for Figure 4, HPCS EDG FTS industry trend

FY/ Source	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2010 Update						1.45E-03	4.74E-03	2.89E-03
1998	0	152.0				5.25E-06	1.09E-02	1.39E-03
1999	1	171.2				4.64E-04	1.46E-02	3.97E-03
2000	0	162.1				5.11E-06	1.06E-02	1.35E-03
2001	0	142.8				5.39E-06	1.12E-02	1.43E-03
2002	0	144.7				5.36E-06	1.11E-02	1.42E-03
2003	0	156.9				5.18E-06	1.07E-02	1.37E-03
2004	0	142.4				5.40E-06	1.12E-02	1.43E-03
2005	0	134.4	1.32E-03	6.89E-04	2.52E-03	5.52E-06	1.14E-02	1.46E-03
2006	0	134.4	1.44E-03	8.34E-04	2.50E-03	5.52E-06	1.14E-02	1.46E-03
2007	0	127.4	1.58E-03	9.96E-04	2.51E-03	5.64E-06	1.17E-02	1.49E-03
2008	0	156.7	1.73E-03	1.16E-03	2.58E-03	5.18E-06	1.07E-02	1.37E-03
2009	1	134.6	1.90E-03	1.32E-03	2.74E-03	5.15E-04	1.62E-02	4.40E-03
2010	0	160.9	2.08E-03	1.42E-03	3.03E-03	5.12E-06	1.06E-02	1.36E-03
2011	0	136.2	2.28E-03	1.48E-03	3.49E-03	5.50E-06	1.14E-02	1.45E-03
2012	0	153.6	2.49E-03	1.50E-03	4.13E-03	5.23E-06	1.08E-02	1.38E-03
2013	1	159.0	2.73E-03	1.50E-03	4.97E-03	4.80E-04	1.51E-02	4.11E-03
2014	1	149.1	2.99E-03	1.48E-03	6.04E-03	4.93E-04	1.55E-02	4.22E-03
Total	4	2,518.6						

Table 18. Plot data for Figure 5, HPCS EDG FTLR industry trend

FY/ Source	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2010 Update						9.59E-04	8.11E-03	3.78E-03
1998	0	112.8				6.35E-06	1.32E-02	1.69E-03
1999	1	120.1				5.81E-04	1.83E-02	4.97E-03
2000	0	126.3				6.07E-06	1.26E-02	1.62E-03
2001	0	121.6				6.17E-06	1.28E-02	1.64E-03
2002	1	125.6				5.71E-04	1.79E-02	4.88E-03
2003	0	129.7				6.01E-06	1.25E-02	1.60E-03
2004	1	130.7				5.61E-04	1.76E-02	4.80E-03
2005	0	120.7	1.46E-03	7.80E-04	2.72E-03	6.19E-06	1.29E-02	1.65E-03
2006	0	122.7	1.60E-03	9.45E-04	2.72E-03	6.15E-06	1.28E-02	1.63E-03
2007	0	119.9	1.76E-03	1.13E-03	2.75E-03	6.20E-06	1.29E-02	1.65E-03
2008	0	141.2	1.94E-03	1.32E-03	2.84E-03	5.79E-06	1.21E-02	1.54E-03
2009	0	116.5	2.14E-03	1.50E-03	3.04E-03	6.27E-06	1.30E-02	1.67E-03
2010	1	135.5	2.35E-03	1.64E-03	3.37E-03	5.53E-04	1.74E-02	4.73E-03
2011	0	121.0	2.59E-03	1.72E-03	3.89E-03	6.18E-06	1.29E-02	1.64E-03
2012	1	137.6	2.85E-03	1.76E-03	4.61E-03	5.49E-04	1.73E-02	4.70E-03
2013	0	134.7	3.13E-03	1.77E-03	5.55E-03	5.91E-06	1.23E-02	1.57E-03
2014	1	124.7	3.45E-03	1.76E-03	6.74E-03	5.72E-04	1.80E-02	4.90E-03
Total	6	2,141.3						

Table 19. Plot data for Figure 6, HPCS EDG FTR>1H industry trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
FY/ Source	Failures	Run Time (hr)	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2010 Update						3.40E-04	2.18E-03	1.09E-03
1998	0	209.9				3.67E-06	7.28E-03	9.32E-04
1999	1	285.5				2.87E-04	9.04E-03	2.45E-03
2000	0	222.9				3.58E-06	7.11E-03	9.10E-04
2001	0	200.7				3.73E-06	7.41E-03	9.48E-04
2002	0	198.0				3.75E-06	7.45E-03	9.53E-04
2003	0	288.4				3.20E-06	6.35E-03	8.13E-04
2004	0	193.0				3.78E-06	7.52E-03	9.62E-04
2005	1	272.6	1.10E-03	4.75E-04	2.54E-03	2.94E-04	9.24E-03	2.50E-03
2006	0	221.8	1.13E-03	5.56E-04	2.31E-03	3.59E-06	7.13E-03	9.12E-04
2007	0	199.0	1.17E-03	6.42E-04	2.13E-03	3.74E-06	7.43E-03	9.51E-04
2008	0	320.6	1.21E-03	7.24E-04	2.02E-03	3.04E-06	6.04E-03	7.73E-04
2009	0	222.1	1.25E-03	7.88E-04	1.98E-03	3.58E-06	7.12E-03	9.11E-04
2010	1	278.6	1.29E-03	8.16E-04	2.03E-03	2.91E-04	9.15E-03	2.48E-03
2011	0	271.3	1.33E-03	8.04E-04	2.20E-03	3.29E-06	6.54E-03	8.36E-04
2012	0	157.7	1.37E-03	7.63E-04	2.48E-03	4.06E-06	8.07E-03	1.03E-03
2013	0	208.7	1.42E-03	7.06E-04	2.85E-03	3.67E-06	7.30E-03	9.34E-04
2014	1	133.5	1.47E-03	6.44E-04	3.34E-03	3.82E-04	1.20E-02	3.26E-03
Total	4	3,884.2						

Table 20. Plot data for Figure 7, EPS EDG UA trend

FY	UA Hours	Critical Hours	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2010 Update						4.64E-03	2.84E-02	1.44E-02
1998	22,880	1,388,150				1.62E-03	4.46E-02	1.66E-02
1999	23,400	1,985,627				2.87E-03	2.53E-02	1.17E-02
2000	18,405	2,051,800				2.62E-03	1.94E-02	9.36E-03
2001	19,096	2,063,455				1.36E-03	2.49E-02	9.90E-03
2002	23,651	2,087,421				2.47E-03	2.61E-02	1.16E-02
2003	27,824	2,051,652				1.71E-03	3.44E-02	1.35E-02
2004	30,926	2,102,001				7.41E-04	4.20E-02	1.41E-02
2005	24,607	2,059,515	1.37E-02	1.18E-02	1.58E-02	2.93E-03	2.58E-02	1.19E-02
2006	28,741	2,096,727	1.40E-02	1.23E-02	1.58E-02	2.12E-03	3.30E-02	1.35E-02
2007	31,475	2,091,219	1.42E-02	1.28E-02	1.58E-02	2.45E-03	3.59E-02	1.49E-02
2008	34,612	2,088,040	1.45E-02	1.33E-02	1.59E-02	3.24E-03	3.81E-02	1.66E-02
2009	33,146	2,086,914	1.48E-02	1.37E-02	1.60E-02	3.64E-03	3.47E-02	1.58E-02
2010	30,683	2,061,553	1.51E-02	1.39E-02	1.63E-02	3.19E-03	3.35E-02	1.49E-02
2011	31,131	2,026,957	1.54E-02	1.41E-02	1.68E-02	3.87E-03	3.30E-02	1.54E-02
2012	35,049	2,008,250	1.57E-02	1.41E-02	1.74E-02	2.87E-03	4.04E-02	1.69E-02
2013	31,132	1,976,666	1.60E-02	1.41E-02	1.81E-02	2.86E-03	3.44E-02	1.49E-02
2014	31,142	2,024,242	1.63E-02	1.41E-02	1.89E-02	3.78E-03	3.29E-02	1.53E-02
Total	477,900	34,250,189						

Table 21. Plot data for Figure 8, HPCS EDG UA trend

FY	UA Hours	Critical Hours	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
2010 Update						8.05E-03	1.33E-02	1.06E-02
1998	231	29,073				4.91E-04	1.59E-02	5.77E-03
1999	782	53,269				1.54E-03	3.51E-02	1.35E-02
2000	933	64,615				7.12E-04	4.25E-02	1.42E-02
2001	427	64,319				9.05E-04	1.67E-02	6.65E-03
2002	444	65,661				5.22E-04	1.91E-02	6.80E-03
2003	796	64,216				5.50E-03	2.16E-02	1.24E-02
2004	848	66,423				3.55E-03	2.64E-02	1.27E-02
2005	635	63,864	8.36E-03	5.11E-03	1.36E-02	1.94E-03	2.21E-02	9.65E-03
2006	524	66,917	8.94E-03	5.89E-03	1.36E-02	2.12E-03	1.62E-02	7.74E-03
2007	593	64,802	9.57E-03	6.74E-03	1.36E-02	3.72E-03	1.63E-02	9.07E-03
2008	779	65,346	1.02E-02	7.60E-03	1.38E-02	9.81E-04	3.38E-02	1.22E-02
2009	507	64,536	1.10E-02	8.38E-03	1.43E-02	1.12E-03	1.92E-02	7.74E-03
2010	1,064	65,869	1.17E-02	8.96E-03	1.53E-02	2.17E-03	4.03E-02	1.60E-02
2011	606	63,381	1.25E-02	9.31E-03	1.69E-02	1.31E-03	2.51E-02	9.89E-03
2012	1,205	63,798	1.34E-02	9.45E-03	1.90E-02	6.27E-03	3.84E-02	1.95E-02
2013	661	64,826	1.43E-02	9.47E-03	2.17E-02	1.61E-03	2.45E-02	1.01E-02
2014	1,140	66,262	1.53E-02	9.40E-03	2.50E-02	5.22E-03	3.55E-02	1.75E-02
Total	12,174	1,057,177						

Table 22. Plot data for Figure 9, EPS EDG unreliability trend

	Regression Curve Data Points			Plot Trend Error Bar Points		
FY	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998				1.43E-02	5.41E-02	2.92E-02
1999				1.04E-02	3.45E-02	1.98E-02
2000				1.37E-02	3.18E-02	2.12E-02
2001				1.02E-02	3.42E-02	1.92E-02
2002				1.50E-02	3.79E-02	2.47E-02
2003				1.47E-02	4.96E-02	2.76E-02
2004				1.39E-02	5.49E-02	2.79E-02
2005	2.77E-02	2.44E-02	3.13E-02	1.67E-02	4.10E-02	2.64E-02
2006	2.90E-02	2.61E-02	3.22E-02	1.53E-02	4.60E-02	2.73E-02
2007	3.04E-02	2.78E-02	3.32E-02	1.89E-02	5.51E-02	3.22E-02
2008	3.19E-02	2.96E-02	3.43E-02	2.15E-02	5.73E-02	3.56E-02
2009	3.34E-02	3.12E-02	3.57E-02	2.14E-02	5.51E-02	3.49E-02
2010	3.50E-02	3.27E-02	3.74E-02	1.98E-02	5.23E-02	3.23E-02
2011	3.67E-02	3.40E-02	3.95E-02	2.48E-02	5.56E-02	3.71E-02
2012	3.84E-02	3.52E-02	4.19E-02	1.87E-02	5.85E-02	3.46E-02
2013	4.02E-02	3.63E-02	4.46E-02	3.08E-02	6.72E-02	4.52E-02
2014	4.22E-02	3.73E-02	4.76E-02	2.62E-02	5.97E-02	4.02E-02

Table 23. Plot data for Figure 10, HPCS EDG unreliability trend

FY	Regression Curve Data Points			Plot Trend Error Bar Points		
	Mean	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998				1.00E-02	3.07E-02	1.88E-02
1999				1.50E-02	5.35E-02	2.95E-02
2000				1.10E-02	5.53E-02	2.68E-02
2001				1.04E-02	3.19E-02	1.96E-02
2002				1.09E-02	3.45E-02	2.08E-02
2003				1.54E-02	3.57E-02	2.48E-02
2004				1.57E-02	4.30E-02	2.70E-02
2005	2.15E-02	1.68E-02	2.74E-02	1.32E-02	3.87E-02	2.47E-02
2006	2.22E-02	1.80E-02	2.74E-02	1.16E-02	3.13E-02	2.04E-02
2007	2.31E-02	1.94E-02	2.75E-02	1.37E-02	3.10E-02	2.17E-02
2008	2.39E-02	2.06E-02	2.78E-02	1.06E-02	4.60E-02	2.47E-02
2009	2.48E-02	2.17E-02	2.84E-02	1.10E-02	3.32E-02	2.09E-02
2010	2.57E-02	2.25E-02	2.94E-02	1.59E-02	5.59E-02	3.15E-02
2011	2.67E-02	2.30E-02	3.09E-02	1.17E-02	3.90E-02	2.26E-02
2012	2.77E-02	2.32E-02	3.29E-02	1.86E-02	5.20E-02	3.34E-02
2013	2.87E-02	2.33E-02	3.53E-02	1.17E-02	3.84E-02	2.33E-02
2014	2.97E-02	2.33E-02	3.79E-02	1.91E-02	5.14E-02	3.35E-02

Table 24. Plot data for Figure 11, EPS and HPCS EDG start demands trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
FY	**Demands**	**Reactor Years**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998	4,329	95.0				4.44E+01	4.67E+01	4.56E+01
1999	4,371	95.0				4.49E+01	4.72E+01	4.60E+01
2000	4,148	95.3				4.24E+01	4.47E+01	4.35E+01
2001	4,155	95.0				4.26E+01	4.49E+01	4.37E+01
2002	4,503	95.0				4.62E+01	4.86E+01	4.74E+01
2003	4,472	95.0				4.59E+01	4.82E+01	4.71E+01
2004	4,570	95.3				4.68E+01	4.92E+01	4.80E+01
2005	4,534	95.0	4.74E+01	4.60E+01	4.89E+01	4.66E+01	4.89E+01	4.77E+01
2006	4,426	95.0	4.71E+01	4.59E+01	4.84E+01	4.54E+01	4.78E+01	4.66E+01
2007	4,461	95.0	4.68E+01	4.58E+01	4.78E+01	4.58E+01	4.81E+01	4.70E+01
2008	4,521	95.3	4.65E+01	4.56E+01	4.73E+01	4.63E+01	4.86E+01	4.75E+01
2009	4,308	95.0	4.61E+01	4.54E+01	4.69E+01	4.42E+01	4.65E+01	4.54E+01
2010	4,391	95.0	4.58E+01	4.50E+01	4.66E+01	4.51E+01	4.74E+01	4.62E+01
2011	4,337	95.0	4.55E+01	4.46E+01	4.64E+01	4.45E+01	4.68E+01	4.57E+01
2012	4,112	95.3	4.52E+01	4.42E+01	4.62E+01	4.21E+01	4.43E+01	4.32E+01
2013	4,266	93.6	4.49E+01	4.37E+01	4.61E+01	4.44E+01	4.68E+01	4.56E+01
2014	4,124	91.0	4.46E+01	4.32E+01	4.60E+01	4.42E+01	4.65E+01	4.53E+01
Total	74,028	1,610.6						

Table 25. Plot data for Figure 12, EPS and HPCS EDG load and run ≤1-hour demands trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
FY	Demands	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	3,920	95.0				4.02E+01	4.24E+01	4.13E+01
1999	3,872	95.0				3.97E+01	4.19E+01	4.08E+01
2000	3,888	95.3				3.97E+01	4.19E+01	4.08E+01
2001	3,832	95.0				3.93E+01	4.14E+01	4.03E+01
2002	3,835	95.0				3.93E+01	4.15E+01	4.04E+01
2003	3,843	95.0				3.94E+01	4.15E+01	4.05E+01
2004	3,912	95.3				4.00E+01	4.22E+01	4.11E+01
2005	3,925	95.0	4.08E+01	3.98E+01	4.18E+01	4.02E+01	4.24E+01	4.13E+01
2006	3,830	95.0	4.05E+01	3.97E+01	4.14E+01	3.93E+01	4.14E+01	4.03E+01
2007	3,803	95.0	4.03E+01	3.96E+01	4.10E+01	3.90E+01	4.11E+01	4.00E+01
2008	3,850	95.3	4.01E+01	3.95E+01	4.07E+01	3.94E+01	4.15E+01	4.04E+01
2009	3,711	95.0	3.99E+01	3.94E+01	4.04E+01	3.80E+01	4.01E+01	3.91E+01
2010	3,833	95.0	3.97E+01	3.91E+01	4.02E+01	3.93E+01	4.14E+01	4.03E+01
2011	3,767	95.0	3.95E+01	3.89E+01	4.01E+01	3.86E+01	4.07E+01	3.97E+01
2012	3,624	95.3	3.93E+01	3.86E+01	4.00E+01	3.70E+01	3.91E+01	3.80E+01
2013	3,705	93.6	3.91E+01	3.82E+01	3.99E+01	3.85E+01	4.07E+01	3.96E+01
2014	3,570	91.0	3.88E+01	3.79E+01	3.98E+01	3.82E+01	4.03E+01	3.92E+01
Total	64,721	1,610.6						

Table 26. Plot data for Figure 13, EPS and HPCS EDG run hours (greater than 1H) trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
FY	Run Hours	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	6,989	95.0				7.21E+01	7.50E+01	7.36E+01
1999	7,214	95.0				7.45E+01	7.74E+01	7.59E+01
2000	8,010	95.3				8.25E+01	8.56E+01	8.41E+01
2001	8,363	95.0				8.65E+01	8.96E+01	8.80E+01
2002	8,959	95.0				9.27E+01	9.60E+01	9.43E+01
2003	9,005	95.0				9.32E+01	9.65E+01	9.48E+01
2004	9,128	95.3				9.42E+01	9.75E+01	9.58E+01
2005	9,809	95.0	1.08E+02	9.11E+01	1.29E+02	1.02E+02	1.05E+02	1.03E+02
2006	8,962	95.0	1.01E+02	8.75E+01	1.17E+02	9.27E+01	9.60E+01	9.43E+01
2007	9,217	95.0	9.45E+01	8.36E+01	1.07E+02	9.54E+01	9.87E+01	9.70E+01
2008	8,326	95.3	8.83E+01	7.93E+01	9.82E+01	8.58E+01	8.90E+01	8.74E+01
2009	8,270	95.0	8.24E+01	7.45E+01	9.12E+01	8.55E+01	8.86E+01	8.70E+01
2010	8,159	95.0	7.70E+01	6.91E+01	8.58E+01	8.43E+01	8.75E+01	8.59E+01
2011	9,010	95.0	7.19E+01	6.34E+01	8.15E+01	9.32E+01	9.65E+01	9.48E+01
2012	5,455	95.3	6.71E+01	5.78E+01	7.80E+01	5.60E+01	5.86E+01	5.73E+01
2013	5,614	93.6	6.27E+01	5.25E+01	7.49E+01	5.87E+01	6.13E+01	6.00E+01
2014	4,562	91.0	5.86E+01	4.75E+01	7.21E+01	4.89E+01	5.14E+01	5.01E+01
Total	135,052	1,610.6						

Table 27. Plot data for Figure 14, EPS and HPCS EDG FTS events trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
FY	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	14	95.0				8.99E-02	2.28E-01	1.47E-01
1999	13	95.0				8.20E-02	2.16E-01	1.37E-01
2000	10	95.3				5.87E-02	1.78E-01	1.06E-01
2001	11	95.0				6.65E-02	1.91E-01	1.17E-01
2002	15	95.0				9.79E-02	2.41E-01	1.57E-01
2003	15	95.0				9.79E-02	2.41E-01	1.57E-01
2004	13	95.3				8.18E-02	2.15E-01	1.37E-01
2005	16	95.0	1.20E-01	7.90E-02	1.83E-01	1.06E-01	2.53E-01	1.68E-01
2006	11	95.0	1.24E-01	8.68E-02	1.77E-01	6.65E-02	1.91E-01	1.17E-01
2007	7	95.0	1.28E-01	9.48E-02	1.73E-01	3.69E-02	1.40E-01	7.62E-02
2008	14	95.3	1.32E-01	1.02E-01	1.70E-01	8.97E-02	2.28E-01	1.47E-01
2009	10	95.0	1.36E-01	1.09E-01	1.70E-01	5.88E-02	1.79E-01	1.07E-01
2010	17	95.0	1.41E-01	1.13E-01	1.75E-01	1.14E-01	2.65E-01	1.78E-01
2011	15	95.0	1.45E-01	1.14E-01	1.84E-01	9.79E-02	2.41E-01	1.57E-01
2012	19	95.3	1.50E-01	1.13E-01	1.98E-01	1.30E-01	2.88E-01	1.97E-01
2013	14	93.6	1.54E-01	1.11E-01	2.15E-01	9.12E-02	2.32E-01	1.49E-01
2014	12	91.0	1.59E-01	1.08E-01	2.36E-01	7.73E-02	2.12E-01	1.32E-01
Total	226	1,610.6						

Table 28. Plot data for Figure 15, EPS EDG FTLR events trend

			Regression Curve Data Points			Plot Trend Error Bar Points		
FY	**Failures**	**Reactor Years**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998	20	95.0				1.39E-01	3.02E-01	2.09E-01
1999	9	95.0				5.15E-02	1.66E-01	9.68E-02
2000	11	95.3				6.65E-02	1.91E-01	1.17E-01
2001	8	95.0				4.42E-02	1.54E-01	8.66E-02
2002	18	95.0				1.23E-01	2.78E-01	1.88E-01
2003	16	95.0				1.06E-01	2.54E-01	1.68E-01
2004	14	95.3				8.99E-02	2.28E-01	1.47E-01
2005	11	95.0	1.69E-01	1.23E-01	2.30E-01	6.67E-02	1.92E-01	1.17E-01
2006	16	95.0	1.65E-01	1.27E-01	2.15E-01	1.06E-01	2.54E-01	1.68E-01
2007	21	95.0	1.62E-01	1.30E-01	2.02E-01	1.48E-01	3.14E-01	2.19E-01
2008	17	95.3	1.58E-01	1.31E-01	1.91E-01	1.14E-01	2.65E-01	1.78E-01
2009	19	95.0	1.55E-01	1.30E-01	1.84E-01	1.31E-01	2.90E-01	1.99E-01
2010	13	95.0	1.52E-01	1.27E-01	1.81E-01	8.23E-02	2.17E-01	1.37E-01
2011	14	95.0	1.49E-01	1.22E-01	1.81E-01	9.02E-02	2.29E-01	1.48E-01
2012	11	95.3	1.46E-01	1.15E-01	1.84E-01	6.65E-02	1.91E-01	1.17E-01
2013	14	93.6	1.43E-01	1.08E-01	1.89E-01	9.15E-02	2.32E-01	1.50E-01
2014	12	91.0	1.40E-01	1.00E-01	1.94E-01	7.76E-02	2.13E-01	1.33E-01
Total	244	1,610.6						

Table 29. Plot data for Figure 16, EPS EDG FTR>1H events trend

FY	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	4	95.0				1.70E-02	1.00E-01	4.59E-02
1999	0	95.0				2.01E-05	3.99E-02	5.10E-03
2000	6	95.3				3.00E-02	1.27E-01	6.61E-02
2001	4	95.0				1.70E-02	1.00E-01	4.59E-02
2002	6	95.0				3.01E-02	1.28E-01	6.63E-02
2003	8	95.0				4.42E-02	1.54E-01	8.67E-02
2004	9	95.3				5.15E-02	1.66E-01	9.67E-02
2005	12	95.0	1.19E-01	7.18E-02	1.99E-01	7.45E-02	2.05E-01	1.28E-01
2006	9	95.0	1.27E-01	8.22E-02	1.96E-01	5.16E-02	1.67E-01	9.69E-02
2007	14	95.0	1.35E-01	9.35E-02	1.94E-01	9.03E-02	2.29E-01	1.48E-01
2008	16	95.3	1.43E-01	1.05E-01	1.95E-01	1.06E-01	2.53E-01	1.68E-01
2009	15	95.0	1.52E-01	1.16E-01	1.99E-01	9.83E-02	2.42E-01	1.58E-01
2010	14	95.0	1.62E-01	1.25E-01	2.08E-01	9.03E-02	2.29E-01	1.48E-01
2011	23	95.0	1.72E-01	1.31E-01	2.25E-01	1.65E-01	3.38E-01	2.40E-01
2012	9	95.3	1.82E-01	1.33E-01	2.50E-01	5.15E-02	1.66E-01	9.67E-02
2013	26	93.6	1.94E-01	1.33E-01	2.81E-01	1.93E-01	3.79E-01	2.74E-01
2014	18	91.0	2.06E-01	1.32E-01	3.20E-01	1.28E-01	2.90E-01	1.97E-01
Total	193	1,610.6						

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