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System Study: Emergency Power System 1998–2014

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ABSTRACT

This report presents an unreliability evaluation of the emergency power system (EPS) at 104 U.S. commercial nuclear power plants. Demand, run hours, and failure data from fiscal year 1998 through 2014 for selected components were obtained from the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). The unreliability results are trended for the most recent 10-year period while yearly estimates for system unreliability are provided for the entire active period. An extremely statistically significant increasing trend was observed for EPS system unreliability for an 8-hour mission. A statistically significant increasing trend was observed for EPS system start-only unreliability.

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ACRONYMS

BWR	boiling water reactor
CCF	common-cause failure
EDG	emergency diesel generator
EPIX	Equipment Performance and Information Exchange
EPS	emergency power system
FTLR	fail to load/run
FTOC	fail to open/close
FTOP	fail to operate
FTR	fail to run
FTR<1H	fail to run less than one hour (after start)
FTS	fail to start
FY	fiscal year
GTG	gas turbine generator
HPCI	high-pressure coolant injection
HTG	hydro turbine generator
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
LOOP	loss-of-offsite power
MSPI	Mitigating Systems Performance Index
PRA	probabilistic risk assessment
SO	spurious operation
SPAR	standardized plant analysis risk
SSU	safety system unavailability
UA	unavailability (maintenance or state of another component)

System Study:
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1. INTRODUCTION

This report presents an unreliability evaluation of the emergency power system (EPS) at 104 U.S. commercial nuclear power plants listed in Table 1. For each plant, the corresponding Standardized Plant Analysis Risk (SPAR) model (version model indicated in Table 1) was used in the yearly calculations. Demand, run hours, and failure data from fiscal year (FY)-98 through FY-14 for selected components in the EPS were obtained from the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). Train unavailability data (outages from test or maintenance) were obtained from the Reactor Oversight Process Safety System Unavailability (SSU) database (FY-98 through FY-01) and the Mitigating Systems Performance Index (MSPI) database (FY-02 through FY-14). Common-cause failure (CCF) data used in the models are from the 2010 update to the CCF database. The system unreliability results are trended for the most recent 10-year period while yearly estimates for system unreliability are provided for the entire active period.

This report does not attempt to estimate basic event values for use in a probabilistic risk assessment (PRA). Suggested values for such use are presented in the 2010 Component Reliability Update (Reference 1), which is an update to Reference 2 (NUREG/CR-6928). Baseline EPS unreliability results using basic event values from that report are summarized in Section 3. Trend results for EPS (using system-specific data) are presented in Section 4. Similar to previous system study updates, Section 5 contains importance information (using the baseline results from Section 3), and Section 7 describes the EPS.

The EPS model is evaluated using the loss-of-offsite power (LOOP) flag set in the SPAR model. The LOOP flag set assumes all ac power is unavailable and that the EPS is required to perform to mitigate the effects of the LOOP initiating event. All models include failures due to unavailability while in test or maintenance. Human error has not been included in the SPAR model logic. 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.

Two modes of the models for the EPS are calculated. The EPS start-only model is the EPS SPAR model modified by setting all fail-to-run basic events to zero (False), setting unit cross-tie events to False, setting all recovery events to False, and setting all cooling basic events to False. The 8-hour mission model includes all basic events in the EPS SPAR model.

Table 1. Plant EPS class listing.

Class	Plant	Version
Class 2	Beaver Valley 1	8.22
Class 2	Beaver Valley 2	8.23
Class 2	Brunswick 1	8.2
Class 2	Brunswick 2	8.2
Class 2	Callaway	8.21
Class 2	Clinton 1	8.17
Class 2	Columbia 2	8.16
Class 2	Comanche Peak 1	8.21
Class 2	Comanche Peak 2	8.21
Class 2	Cook 1	8.2
Class 2	Cook 2	8.2
Class 2	Cooper	8.22
Class 2	Crystal River 3	8.16
Class 2	Davis-Besse	8.19
Class 2	Duane Arnold	8.22
Class 2	Fort Calhoun	8.2
Class 2	Ginna	8.23
Class 2	Grand Gulf	8.22
Class 2	Harris	8.23
Class 2	Kewaunee	8.2
Class 2	McGuire 1	8.2
Class 2	McGuire 2	8.2
Class 2	Monticello	8.2
Class 2	Nine Mile Pt. 1	8.21
Class 2	Nine Mile Pt. 2	8.17
Class 2	Oconee 1	8.19
Class 2	Oconee 2	8.19
Class 2	Oconee 3	8.19
Class 2	Oyster Creek	8.22
Class 2	Palisades	8.2
Class 2	Perry	8.19
Class 2	Pilgrim	8.21
Class 2	Robinson 2	8.17
Class 2	Seabrook	8.2
Class 2	Summer	8.23

Class	Plant	Version
Class 2	Vermont Yankee	8.19
Class 2	Waterford 3	8.16
Class 2	Wolf Creek	8.2
Class 3	Arkansas 1	8.19
Class 3	Arkansas 2	8.21
Class 3	Braidwood 1	8.21
Class 3	Braidwood 2	8.21
Class 3	Byron 1	8.21
Class 3	Byron 2	8.21
Class 3	Calvert Cliffs 1	8.22
Class 3	Calvert Cliffs 2	8.21
Class 3	Catawba 1	8.2
Class 3	Catawba 2	8.2
Class 3	Diablo Canyon 1	8.19
Class 3	Diablo Canyon 2	8.19
Class 3	Farley 1	8.18
Class 3	Farley 2	8.18
Class 3	Hatch 1	8.2
Class 3	Hatch 2	8.2
Class 3	Hope Creek	8.18
Class 3	Indian Point 2	8.19
Class 3	Indian Point 3	8.2
Class 3	La Salle 1	8.21
Class 3	La Salle 2	8.21
Class 3	Millstone 2	8.17
Class 3	Millstone 3	8.2
Class 3	Palo Verde 1	8.2
Class 3	Palo Verde 2	8.2
Class 3	Palo Verde 3	8.2
Class 3	Peach Bottom 2	8.25
Class 3	Peach Bottom 3	8.21
Class 3	River Bend	8.2
Class 3	Salem 1	8.2
Class 3	Salem 2	8.2
Class 3	San Onofre 2	8.22

Class	Plant	Version
Class 3	San Onofre 3	8.22
Class 3	Sequoyah 1	8.16
Class 3	Sequoyah 2	8.16
Class 3	South Texas 1	8.17
Class 3	South Texas 2	8.17
Class 3	St. Lucie 1	8.19
Class 3	St. Lucie 2	8.19
Class 3	Surry 1	8.19
Class 3	Surry 2	8.15
Class 3	Susquehanna 1	8.23
Class 3	Susquehanna 2	8.21
Class 3	Three Mile Isl 1	8.2
Class 3	Turkey Point 3	8.2
Class 3	Turkey Point 4	8.2
Class 3	Vogtle 1	8.21
Class 3	Vogtle 2	8.21
Class 3	Watts Bar 1	8.16
Class 4	Browns Ferry 1	8.22
Class 4	Browns Ferry 2	8.22
Class 4	Browns Ferry 3	8.18
Class 4	Dresden 2	8.18
Class 4	Dresden 3	8.18
Class 4	Fermi 2	8.2
Class 4	FitzPatrick	8.17
Class 4	Limerick 1	8.2
Class 4	Limerick 2	8.19
Class 4	North Anna 1	8.2
Class 4	North Anna 2	8.2
Class 4	Point Beach 1	8.2
Class 4	Point Beach 2	8.2
Class 4	Prairie Island 1	8.19
Class 4	Prairie Island 2	8.19
Class 4	Quad Cities 1	8.18
Class 4	Quad Cities 2	8.18

2. SUMMARY OF FINDINGS

The results of this EPS system unreliability 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

- EPS system unreliability for an 8-hour mission was found to be increasing.

2.1.2 Highly Statistically Significant

- None

2.1.3 Statistically Significant

- Start-only EPS system unreliability was found to be increasing.

2.2 Decreasing Trends

2.2.1 Extremely Statistically Significant

- None

2.2.2 Highly Statistically Significant

- None.

2.2.3 Statistically Significant

- None.

2.3 Importance Measure Results

The industry-wide EPS start-only and 8-hour basic event group importances were evaluated and are shown in Figure 5. In both cases, the leading contributors to EPS system unreliability are the 1E Generator group of basic events and AC Power. In addition, generator auxiliary equipment and the sequencer are important to the start-only model. In addition, cooling and human action are important for the 8-hour mission model.

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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).

3. INDUSTRY-WIDE UNRELIABILITY

The EPS fault trees from the SPAR models were evaluated for each of the 104 operating U.S. commercial nuclear power plants.

The industry-wide unreliability of the EPS has been estimated for two modes of operation. A start-only model and an 8-hour mission model were evaluated, see Table 2. The uncertainty distributions for the EPS classes include both plant design variability (within a class) and parameter uncertainty while using industry-wide component failure data (FY-98 through FY-10).[a] Table 2 shows the percentiles and mean of the aggregated sample data (Latin hypercube, 1000 samples for each model) collected from the uncertainty calculations of the EPS fault trees in the SPAR models. In Figure 1 and Figure 2, the 5th and 95th percentiles and mean point estimates are shown each class and for the industry.

In Figure 1 and Figure 2, the width of the distribution for a class is affected by the differences in the plant modeling and the parameter uncertainty used in the models. Because the width is affected by the plant modeling, the width is also affected by the number of different plant models in a class. For those classes with very few plants that share a design, the width can be very small.

Table 2. Industry-wide unreliability values.

Model	EPS Grouping	Lower (5%)	Median	Mean	Upper (95%)
Start-Only	Industry	2.45E−07	3.98E−05	1.92E−04	5.45E−04
	Class 2	2.00E−06	1.40E−04	3.07E−04	7.23E−04
	Class 3	1.29E−06	2.57E−05	1.56E−04	4.76E−04
	Class 4	1.59E−08	4.83E−06	2.46E−05	6.79E−05
8-hour Mission	Industry	6.37E−06	2.25E−04	9.07E−04	2.54E−03
	Class 2	2.33E−05	7.13E−04	1.47E−03	3.30E−03
	Class 3	1.69E−05	2.24E−04	7.33E−04	2.05E−03
	Class 4	5.74E−07	1.88E−05	8.49E−05	2.63E−04

a. By using industry-wide component failure data, individual plant performance is not included in the distribution of results.

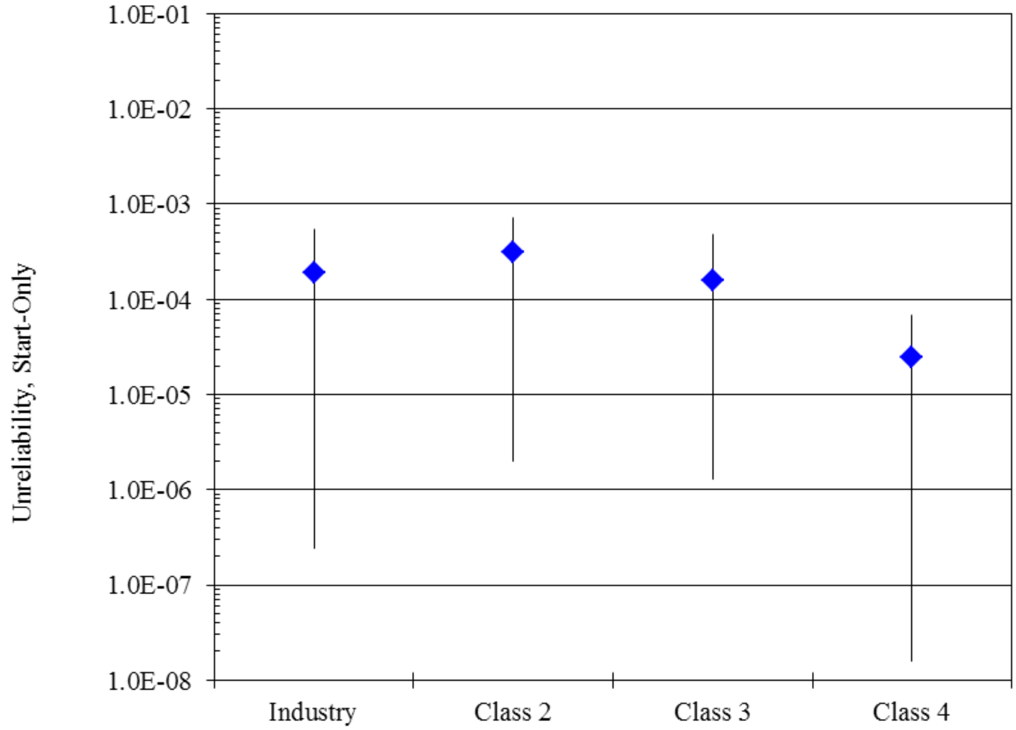

Figure 1. EPS start-only mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

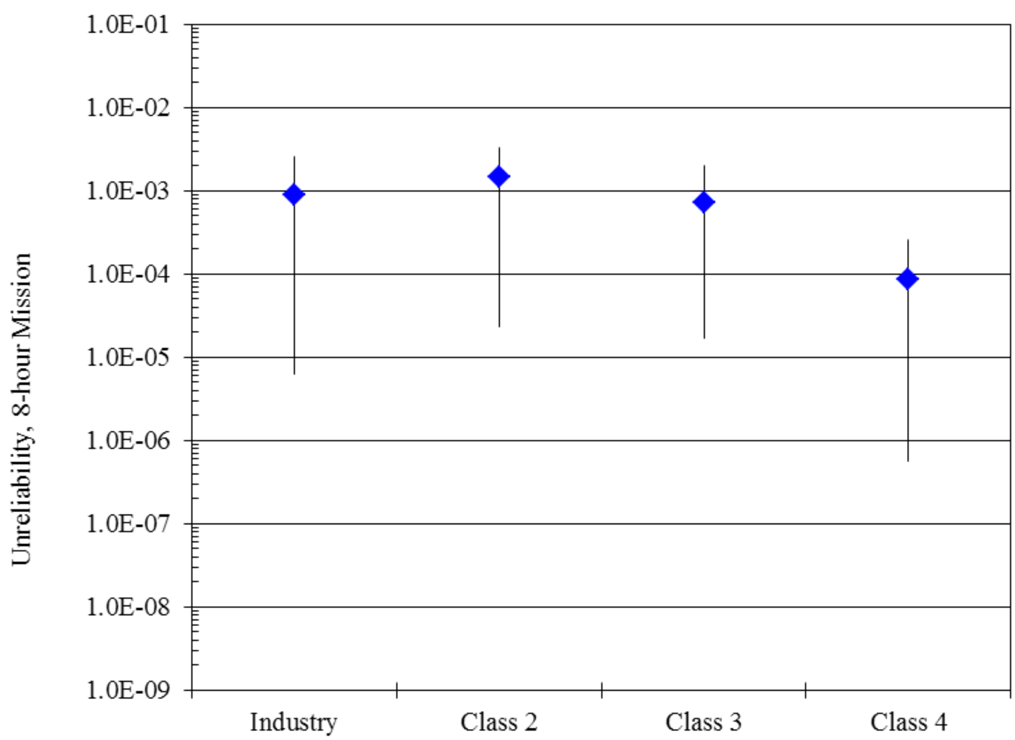

Figure 2. EPS 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly (FY-98 through FY-14) failure and demand or run time data were obtained from ICES for the EPS system. EPS train maintenance unavailability data for trending are from the same time period, as reported in the ROP and ICES. The component basic event uncertainty was calculated for the EPS system components using the trending methods described in Section 1 and 2 of the Overview and Reference document. Tables 6 and 7 show the yearly data values for each EPS system specific component and failure mode combination that was varied in the model. These data were loaded into the EPS system fault tree in each SPAR model (see Table 1).

The trend charts show the results of varying component reliability data over time and updating generic, relatively flat prior distributions using data for each year. In addition, for comparison, this update (current SPAR/ICES) is shown. Section 4 of the Overview and Reference link on the System Studies main web page provides more detailed discussion of the trending methods. In the lower left hand corner of the trend figures, the regression method is reported.

The components and failure modes that were varied in the EPS model are

- EPS diesel generator start, run, and test and maintenance.

Figure 3 shows the trend in the EPS start-only model unreliability. Table 4 shows the data points for Figure 3. Figure 4 shows the trend in the 8-hour mission unreliability. Table 5 shows the data points for Figure 4.

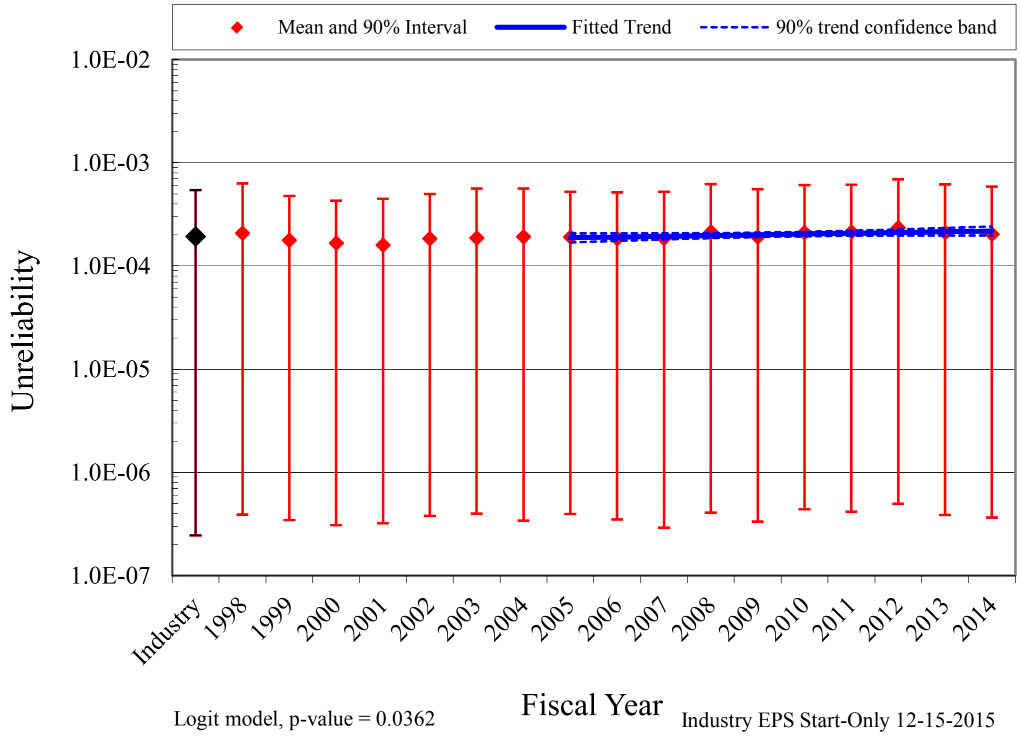

Figure 3. Trend of EPS system unreliability (start-only model), as a function of fiscal year.

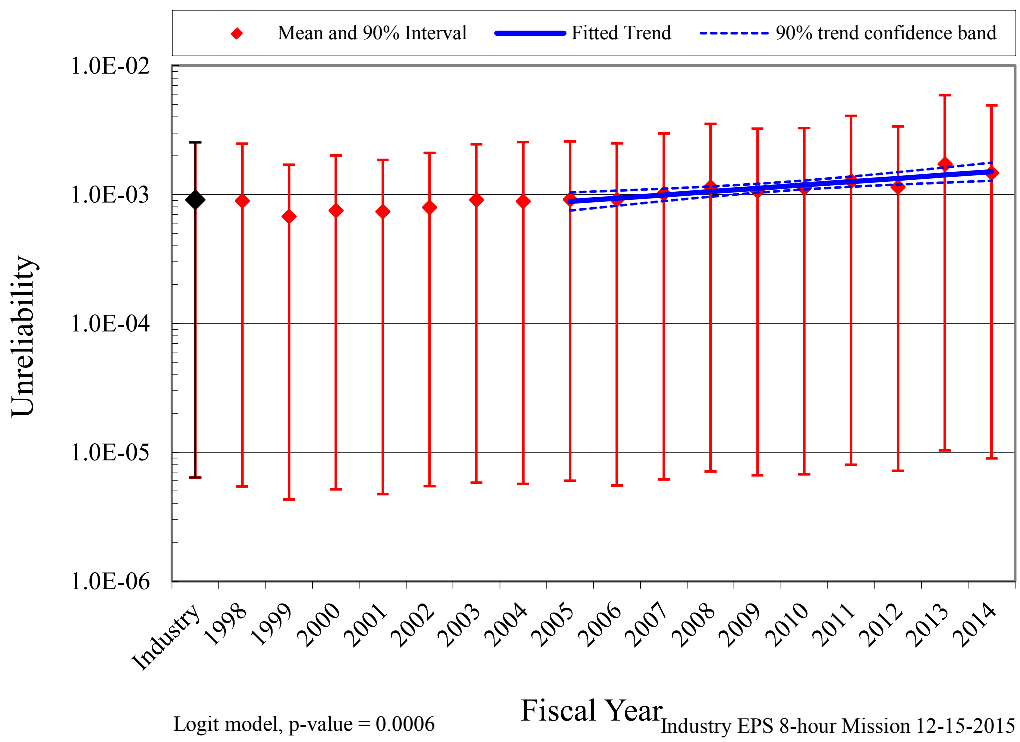

Figure 4. Trend of EPS system unreliability (8-hour model), as a function of fiscal year.

5. BASIC EVENT GROUP IMPORTANCES

The EPS basic event group Fussell-Vesely importances were calculated for the failure to start and 8-hour model for each plant using the industry-wide data (1998–2010). These basic event group importances were then averaged across all plants to represent an industry-wide basic event group importance. The industry-wide EPS start-only and 8-hour basic event group importances are shown in Figure 5. In both cases, the leading contributors to EPS system unreliability are the 1E Generator group of basic events and AC Power. In addition, generator auxiliary equipment and the sequencer are important to the start-only model. In addition, cooling and human action are important for the 8-hour mission model. For more discussion on the EPS diesel generators, see the emergency diesel generator component reliability study at NRC Reactor Operational Experience Results and Databases. Table 3 shows the SPAR model EPS importance groups and their descriptions.

The basic event group importances were also averaged across plants of the same EPS class to represent class basic event group importances. The class EPS start-only and 8-hour basic event group importances are shown in Figure 6, Figure 7, and Figure 8. In both cases, for all classes, the leading contributor to EPS system unreliability is the 1E Generator group of basic events.

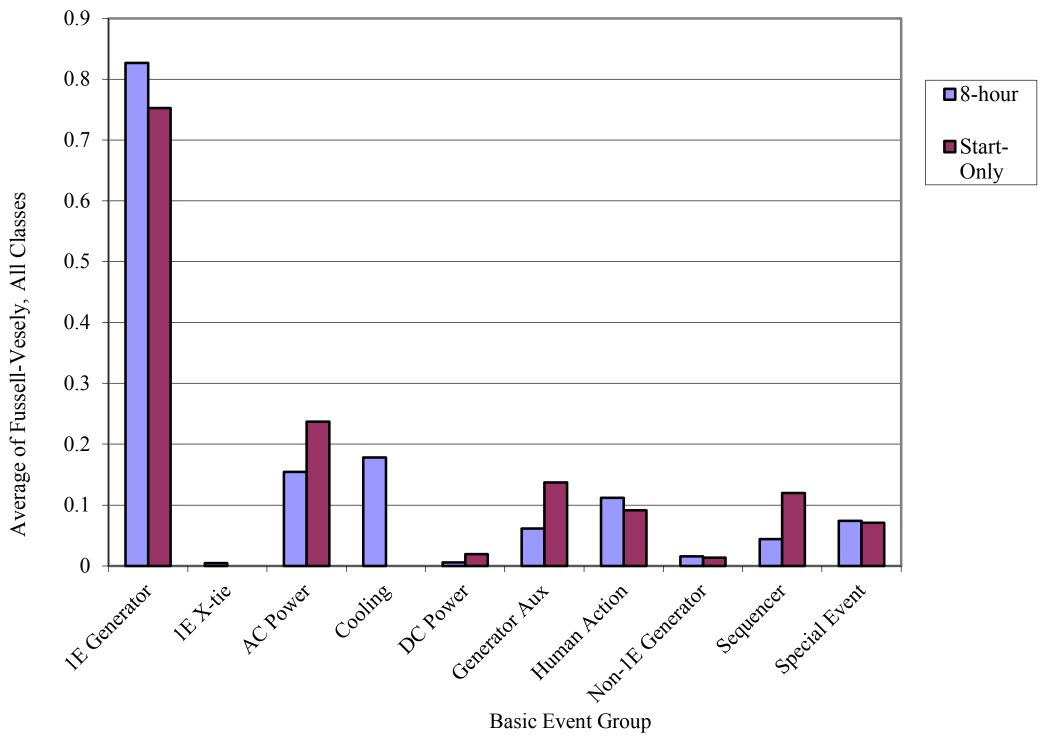

Figure 5. EPS industry-wide basic event group importances.

Table 3. EPS model basic event importance group descriptions.

Group	Description
1E Generator	All basic events associated with the primary emergency power supplies. Includes diesel, gas turbine, and hydro powered equipment. The start, run, common-cause, and test and maintenance are included in this group of basic events.
1E X-tie	Cross-tie or swing 1E qualified generating equipment available to the EPS in the model.
AC Power	Buses and circuit breakers in the EPS model.
Cooling	Cooling support components: service water or component cooling pumps, valves, and heat exchangers.
DC Power	Buses, circuit breakers, battery chargers, and batteries in the EPS model.
Generator Aux	This group includes the emergency power auxiliary components that are explicitly modeled in the EPS system. Includes the fuel oil, starting air, room cooling, and electrical dedicated to the generators.
Human Action	This group contains the events that allow operator recovery from expected automatic actions.
Non 1E Generator	All basic events associated with the secondary emergency power supplies. Includes diesel, gas turbine, and hydro powered equipment. The start, run, common-cause, and test and maintenance are included in the group of basic events.
Sequencer	The sequencer includes all basic events associated with the sequencer.
Special Event	These are various special events that are added to the model to model plant-specific conditions that affect the EPS.

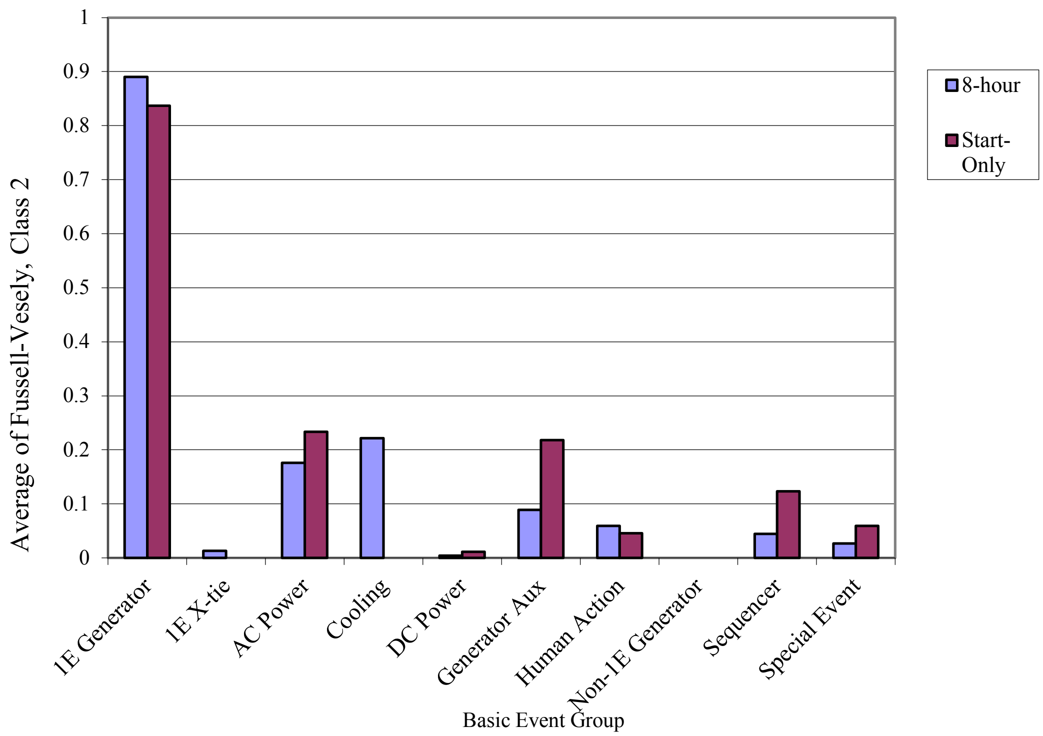

Figure 6. EPS Class 2 basic event group importances.

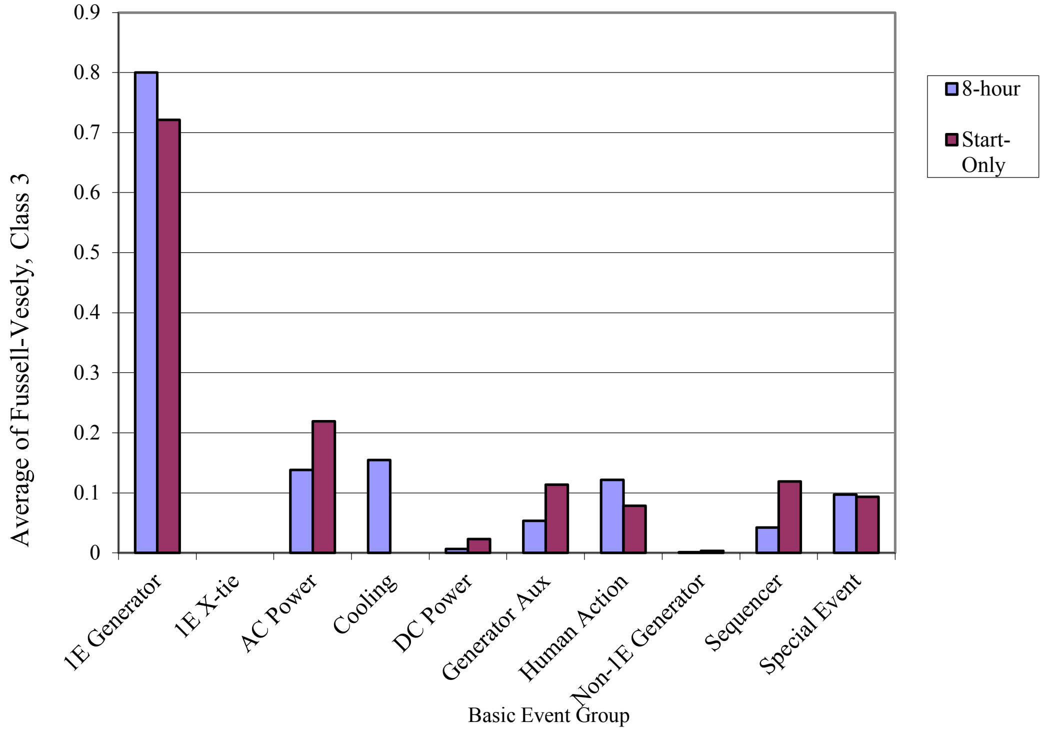

Figure 7. EPS Class 3 basic event group importances.

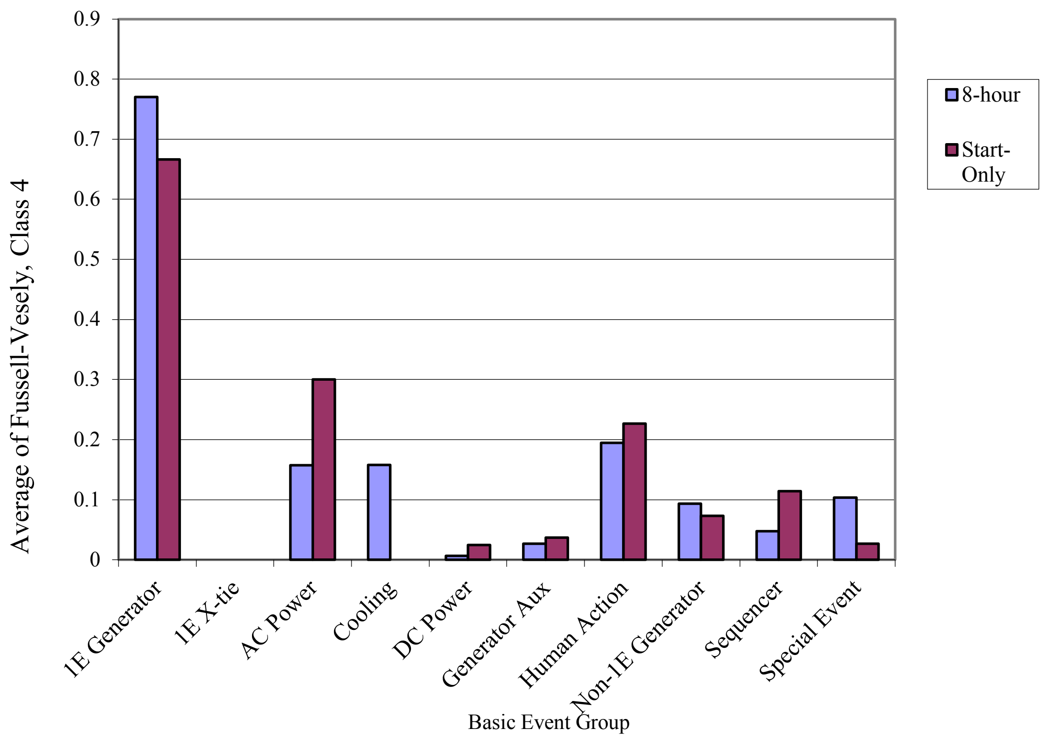

Figure 8. EPS Class 4 basic event group importances.

6. DATA TABLES

Table 4. Plot data for EPS start-only trend, Figure 3.

FY/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ICES				2.45E−07	5.45E−04	1.92E−04
1998				3.89E-07	6.33E-04	2.07E-04
1999				3.45E-07	4.80E-04	1.77E-04
2000				3.07E-07	4.29E-04	1.66E-04
2001				3.20E-07	4.47E-04	1.59E-04
2002				3.78E-07	5.00E-04	1.84E-04
2003				3.98E-07	5.61E-04	1.87E-04
2004				3.40E-07	5.62E-04	1.92E-04
2005	1.87E-04	1.69E-04	2.07E-04	3.96E-07	5.25E-04	1.90E-04
2006	1.91E-04	1.75E-04	2.07E-04	3.49E-07	5.16E-04	1.83E-04
2007	1.94E-04	1.81E-04	2.08E-04	2.91E-07	5.25E-04	1.84E-04
2008	1.97E-04	1.86E-04	2.09E-04	4.05E-07	6.21E-04	2.12E-04
2009	2.01E-04	1.91E-04	2.11E-04	3.32E-07	5.55E-04	1.90E-04
2010	2.04E-04	1.94E-04	2.14E-04	4.39E-07	6.09E-04	2.10E-04
2011	2.08E-04	1.96E-04	2.20E-04	4.14E-07	6.16E-04	2.12E-04
2012	2.11E-04	1.97E-04	2.26E-04	4.97E-07	6.93E-04	2.34E-04
2013	2.15E-04	1.97E-04	2.34E-04	3.88E-07	6.18E-04	2.09E-04
2014	2.18E-04	1.98E-04	2.42E-04	3.65E-07	5.87E-04	2.03E-04

Table 5. Plot data for EPS 8-hour trend, Figure 4.

	Regression Curve Data Points			Annual Estimate Data Points		
FY/Source	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ICES				6.37E−06	2.54E−03	9.07E−04
1998				5.43E-06	2.48E-03	8.88E-04
1999				4.31E-06	1.71E-03	6.72E-04
2000				5.16E-06	2.00E-03	7.47E-04
2001				4.72E-06	1.85E-03	7.33E-04
2002				5.44E-06	2.10E-03	7.92E-04
2003				5.82E-06	2.45E-03	9.05E-04
2004				5.68E-06	2.55E-03	8.78E-04
2005	8.82E-04	7.50E-04	1.04E-03	6.02E-06	2.58E-03	9.12E-04
2006	9.36E-04	8.18E-04	1.07E-03	5.53E-06	2.49E-03	9.05E-04
2007	9.93E-04	8.89E-04	1.11E-03	6.16E-06	2.98E-03	1.01E-03
2008	1.05E-03	9.61E-04	1.15E-03	7.10E-06	3.53E-03	1.14E-03
2009	1.12E-03	1.03E-03	1.21E-03	6.61E-06	3.24E-03	1.06E-03
2010	1.19E-03	1.09E-03	1.28E-03	6.73E-06	3.28E-03	1.12E-03
2011	1.26E-03	1.15E-03	1.38E-03	8.00E-06	4.06E-03	1.27E-03
2012	1.33E-03	1.19E-03	1.49E-03	7.19E-06	3.38E-03	1.14E-03
2013	1.42E-03	1.24E-03	1.62E-03	1.04E-05	5.90E-03	1.72E-03
2014	1.50E-03	1.28E-03	1.76E-03	8.97E-06	4.91E-03	1.47E-03

Table 6. Basic event reliability trending data.

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTLR	GEN	1998	20	3807	5.02E-03	22.8	4518	Beta
FTLR	GEN	1999	9	3752	2.62E-03	11.8	4474	Beta
FTLR	GEN	2000	11	3761	3.06E-03	13.8	4482	Beta
FTLR	GEN	2001	8	3711	2.42E-03	10.8	4434	Beta
FTLR	GEN	2002	18	3709	4.68E-03	20.8	4422	Beta
FTLR	GEN	2003	16	3714	4.22E-03	18.8	4429	Beta
FTLR	GEN	2004	14	3781	3.72E-03	16.8	4498	Beta
FTLR	GEN	2005	11	3805	3.03E-03	13.8	4525	Beta
FTLR	GEN	2006	16	3707	4.23E-03	18.8	4422	Beta
FTLR	GEN	2007	21	3683	5.38E-03	23.8	4393	Beta
FTLR	GEN	2008	17	3709	4.45E-03	19.8	4423	Beta
FTLR	GEN	2009	19	3595	5.03E-03	21.8	4307	Beta
FTLR	GEN	2010	13	3697	3.56E-03	15.8	4415	Beta
FTLR	GEN	2011	14	3646	3.83E-03	16.8	4363	Beta
FTLR	GEN	2012	11	3486	3.26E-03	13.8	4207	Beta
FTLR	GEN	2013	14	3570	3.90E-03	16.8	4287	Beta
FTLR	GEN	2014	12	3445	3.54E-03	14.8	4164	Beta
FTR	GEN	1998	4	6779	7.52E-04	7.6	10046	Gamma
FTR	GEN	1999	0	6928	3.48E-04	3.6	10195	Gamma
FTR	GEN	2000	6	7787	8.64E-04	9.6	11054	Gamma
FTR	GEN	2001	4	8162	6.61E-04	7.6	11429	Gamma
FTR	GEN	2002	6	8761	7.94E-04	9.6	12028	Gamma
FTR	GEN	2003	8	8717	9.64E-04	11.6	11984	Gamma
FTR	GEN	2004	9	8935	1.03E-03	12.6	12202	Gamma
FTR	GEN	2005	12	9536	1.21E-03	15.6	12803	Gamma
FTR	GEN	2006	9	8740	1.05E-03	12.6	12007	Gamma
FTR	GEN	2007	14	9018	1.43E-03	17.6	12285	Gamma
FTR	GEN	2008	16	8006	1.73E-03	19.6	11273	Gamma
FTR	GEN	2009	15	8048	1.64E-03	18.6	11315	Gamma
FTR	GEN	2010	14	7880	1.57E-03	17.6	11147	Gamma
FTR	GEN	2011	23	8738	2.21E-03	26.6	12005	Gamma
FTR	GEN	2012	9	5298	1.47E-03	12.6	8565	Gamma
FTR	GEN	2013	26	5405	3.41E-03	29.6	8672	Gamma
FTR	GEN	2014	18	4429	2.80E-03	21.6	7696	Gamma
FTS	GEN	1998	14	4177	3.17E-03	22.1	6961	Beta
FTS	GEN	1999	12	4200	2.87E-03	20.1	6986	Beta
FTS	GEN	2000	10	3986	2.67E-03	18.1	6774	Beta
FTS	GEN	2001	11	4012	2.80E-03	19.1	6799	Beta
FTS	GEN	2002	15	4358	3.23E-03	23.1	7141	Beta
FTS	GEN	2003	15	4315	3.25E-03	23.1	7098	Beta

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTS	GEN	2004	13	4428	2.92E-03	21.1	7213	Beta
FTS	GEN	2005	16	4399	3.35E-03	24.1	7181	Beta
FTS	GEN	2006	11	4292	2.69E-03	19.1	7079	Beta
FTS	GEN	2007	7	4333	2.12E-03	15.1	7124	Beta
FTS	GEN	2008	14	4365	3.08E-03	22.1	7149	Beta
FTS	GEN	2009	9	4174	2.45E-03	17.1	6963	Beta
FTS	GEN	2010	17	4230	3.57E-03	25.1	7011	Beta
FTS	GEN	2011	15	4201	3.30E-03	23.1	6984	Beta
FTS	GEN	2012	19	3958	4.01E-03	27.1	6737	Beta
FTS	GEN	2013	13	4107	3.05E-03	21.1	6892	Beta
FTS	GEN	2014	11	3975	2.82E-03	19.1	6762	Beta

Table 7. Basic event UA trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	EDG	1998	22880	1388150	1.66E-02	1.339	79.3	Beta
UA	EDG	1999	23400	1985627	1.17E-02	2.659	224.5	Beta
UA	EDG	2000	18405	2051800	9.36E-03	3.075	325.5	Beta
UA	EDG	2001	19096	2063455	9.90E-03	1.649	165.0	Beta
UA	EDG	2002	23651	2087422	1.16E-02	2.320	198.1	Beta
UA	EDG	2003	27824	2051652	1.35E-02	1.563	114.3	Beta
UA	EDG	2004	30926	2102001	1.41E-02	1.003	70.0	Beta
UA	EDG	2005	24607	2059515	1.19E-02	2.662	220.2	Beta
UA	EDG	2006	28741	2096727	1.35E-02	1.803	131.4	Beta
UA	EDG	2007	31475	2091220	1.49E-02	1.866	123.3	Beta
UA	EDG	2008	34612	2088040	1.66E-02	2.147	127.5	Beta
UA	EDG	2009	33146	2086914	1.58E-02	2.501	156.2	Beta
UA	EDG	2010	30683	2061553	1.49E-02	2.326	153.9	Beta
UA	EDG	2011	31131	2026957	1.54E-02	2.725	174.3	Beta
UA	EDG	2012	35049	2008250	1.69E-02	1.914	111.3	Beta
UA	EDG	2013	31132	1976666	0.0148701	2.119	140.4	Beta
UA	EDG	2014	31142	2024242	1.53E-02	2.675	172.5	Beta

Table 8. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTLR	Fail to load/run
FTOC	Fail to open/close
FTOP	Fail to operate
FTR	Fail to run
FTR<1H	Fail to run less than one hour (after start)
FTS	Fail to start
SO	Spurious operation
UA	Unavailability (maintenance or state of another component)

7. SYSTEM DESCRIPTION

The EPS is designed to provide backup, onsite ac power to vital buses given a LOOP until offsite power can be restored to the plant. EPS designs vary widely among the 104 U.S. commercial nuclear power plants. A summary of those designs is presented in Table 9. Typical EPS designs include two, three, or four EDGs, with only one of the EDGs required for success. However, as indicated in Table 9, there are many variations of these typical designs, including shared EDGs and/or the ability to cross-tie to other EDGs (at multi-plant sites), and availability of alternate ac sources such as gas turbine generators (GTGs) or hydro turbine generators (HTGs). In addition, several of the plants require two EDGs for long-term success, rather than one.

SPAR modeling of the EPS incorporates the plant-to-plant design and operational differences indicated in Table 9. Table 9 shows the generating equipment used in the EPS SPAR model. In some cases, two models use the same equipment. These are repeated for each entry to show how the SPAR models calculate. All ac emergency power sources that either are automatically started and aligned to essential buses given a LOOP or can be manually started and aligned within approximately 30 minutes are included in the EPS SPAR fault trees. Additional emergency power sources such as GTGs or HTGs that require more than 30 minutes to start and align to essential buses are included in other parts of the SBO event tree, typically as additional credit for recovery of ac power. Included in the EPS SPAR fault trees are dependencies such as room cooling, service water cooling, and dc power.

The typical EPS consists of two or more emergency power sources, usually diesel generators, connected to two or more vital or safety buses. These vital buses power equipment needed for safe shutdown during most transients that are postulated at nuclear power plants.

Figure 9 shows the simplest EPS configuration. Variations are: more buses, usually with their own emergency power sources, swing power sources that can power vital buses at either of two units, and alternate emergency power sources typically referred to as station blackout generators.

The SPAR models of the EPS include many more components than those shown in Figure 9. Most of these components are related to the support needed for the emergency power source success. Some of these are explicitly modeled in SPAR if there is a common-mode failure of multiple generators. Generally, these include

Cooling—Cooling is required to remove heat from the lubricating oil and the engine itself. Cooling is provided by service water either directly or through a closed loop cooling system such as component cooling water. Some emergency power sources have dedicated cooling systems that are independent of the service water systems.

Room Cooling—Room cooling is usually required for extended performance of the EPS. The room cooling is provided by air conditioning heat exchangers that may be cooled by a chilled water source.

Fuel Oil—Fuel oil is usually provided from a common fuel oil tank to separate ‘day tanks’ for each emergency power source. Pumps, valves, and instrumentation are required to maintain day tank levels and to supply fuel oil to the engine itself.

Sequencer—The sequencer strips loads from the dead bus prior to attempting to load the bus with the emergency power source. Then the sequencer sequences loads back onto the bus once it has been re-energized.

dc Power—dc power is provided by the vital batteries. DC power provides the energy to operate breakers and powers the control circuitry for the EPS.

Table 9. EPS configurations at U.S. commercial nuclear power plants.

Class	Plant	Total	1E Generator	1E X-tie	Non-1E Generator
Class 2	Beaver Valley 1	2	2	2	
Class 2	Beaver Valley 2	2	2	2	
Class 2	Brunswick 1	4	2	2	
Class 2	Brunswick 2	4	2	2	
Class 2	Callaway	2	2		
Class 2	Clinton 1	2	2		
Class 2	Columbia 2	2	2		
Class 2	Comanche Peak 1	2	2		
Class 2	Comanche Peak 2	2	2		
Class 2	Cook 1	2	2		
Class 2	Cook 2	2	2		
Class 2	Cooper	2	2		
Class 2	Crystal River 3	2	2		
Class 2	Davis-Besse	2	2		
Class 2	Duane Arnold	2	2		
Class 2	Fort Calhoun	2	2		
Class 2	Ginna	2	2		
Class 2	Grand Gulf	2	2		
Class 2	Harris	2	2		
Class 2	Kewaunee	2	2		
Class 2	McGuire 1	2	2		
Class 2	McGuire 2	2	2		
Class 2	Monticello	2	2		
Class 2	Nine Mile Pt. 1	2	2		
Class 2	Nine Mile Pt. 2	2	2		
Class 2	Oconee 1	2	1	1	
Class 2	Oconee 2	2	1	1	
Class 2	Oconee 3	2	1	1	
Class 2	Oyster Creek	2	2		
Class 2	Palisades	2	2		
Class 2	Perry	2	2		
Class 2	Pilgrim	2	2		
Class 2	Robinson 2	3	2		1
Class 2	Seabrook	2	2		
Class 2	Summer	2	2		
Class 2	Vermont Yankee	2	2		
Class 2	Waterford 3	2	2		
Class 2	Wolf Creek	2	2		
Class 3	Arkansas 1	3	2		1
Class 3	Arkansas 2	3	2		1
Class 3	Braidwood 1	4	4		

Table 9. (continued).

Class	Plant	Total	1E Generator	1E X-tie	Non-1E Generator
Class 3	Braidwood 2	4	4		
Class 3	Byron 1	4	2	2	
Class 3	Byron 2	4	2	2	
Class 3	Calvert Cliffs 1	5	2	2	1
Class 3	Calvert Cliffs 2	5	2	2	1
Class 3	Catawba 1	4	2	2	
Class 3	Catawba 2	4	2	2	
Class 3	Diablo Canyon 1	3	3		
Class 3	Diablo Canyon 2	3	3		
Class 3	Farley 1	5	3	2	
Class 3	Farley 2	5	3	2	
Class 3	Hatch 1	5	3	2	
Class 3	Hatch 2	5	3	2	
Class 3	Hope Creek	4	4		
Class 3	Indian Point 2	3	3		
Class 3	Indian Point 3	3	3		
Class 3	La Salle 1	4	2	2	
Class 3	La Salle 2	4	2	2	
Class 3	Millstone 2	3	2		1
Class 3	Millstone 3	3	2		1
Class 3	Palo Verde 1	8	2	4 (not effective in model)	2 (need both)
Class 3	Palo Verde 2	8	2	4 (not effective in model)	2 (need both)
Class 3	Palo Verde 3	8	2	4 (not effective in model)	2 (need both)
Class 3	Peach Bottom 2	4	4 (2 of 4)		
Class 3	Peach Bottom 3	4	4 (2 of 4)		
Class 3	River Bend	3	3 (C EDG is different)		1
Class 3	Salem 1	4	3		1
Class 3	Salem 2	4	3		1
Class 3	San Onofre 2	4	2	2	
Class 3	San Onofre 3	4	2	2	
Class 3	Sequoyah 1	4	2	2	
Class 3	Sequoyah 2	4	2	2	
Class 3	South Texas 1	3	3		
Class 3	South Texas 2	3	3		
Class 3	St. Lucie 1	4	2	2	
Class 3	St. Lucie 2	4	2	2	
Class 3	Surry 1	4	3		1
Class 3	Surry 2	4	3		1
Class 3	Susquehanna 1	5	5 (2 of the EDGs cannot		

Table 9. (continued).

Class	Plant	Total	1E Generator	1E X-tie	Non-1E Generator
			support all loads)		
Class 3	Susquehanna 2	5	5 (2 of the EDGs cannot support all loads)		
Class 3	Three Mile Isl 1	3	2		1
Class 3	Turkey Point 3	4	2	2	
Class 3	Turkey Point 4	4	2	2	
Class 3	Vogtle 1	3	2	1	
Class 3	Vogtle 2	3	2	1	
Class 3	Watts Bar 1	4	2	2	
Class 4	Browns Ferry 1	8	4	4	
Class 4	Browns Ferry 2	6	4	2	
Class 4	Browns Ferry 3	8	4	4	
Class 4	Dresden 2	5	2	1	2
Class 4	Dresden 3	5	2	1	2
Class 4	Fermi 2	9	4		5
Class 4	FitzPatrick	4	4		
Class 4	Limerick 1	6	4	2	
Class 4	Limerick 2	6	4	2	
Class 4	North Anna 1	5	2	2	1
Class 4	North Anna 2	5	2	2	1
Class 4	Point Beach 1	5	4		1
Class 4	Point Beach 2	5	4		1
Class 4	Prairie Island 1	4	2	2	
Class 4	Prairie Island 2	4	2	2	
Class 4	Quad Cities 1	5	1	2	2
Class 4	Quad Cities 2	5	1	2	2

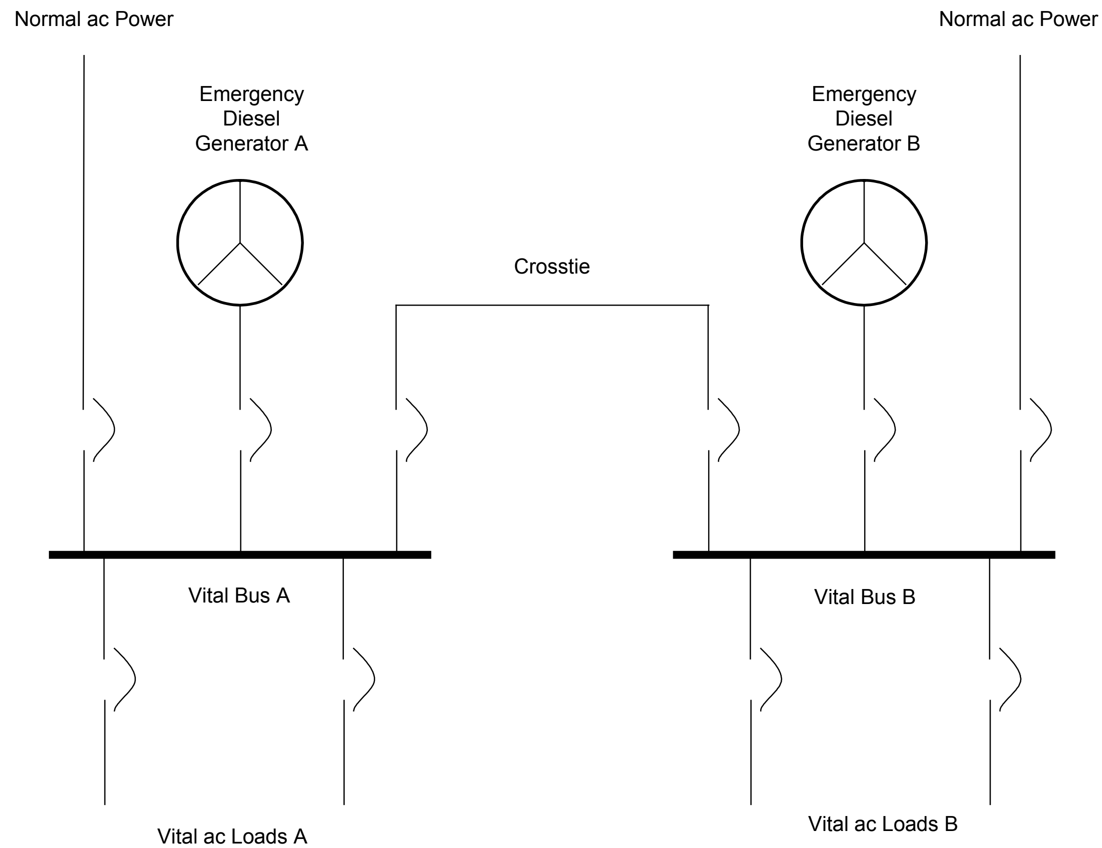

Figure 9. Simplified EPS system schematic.

8. REFERENCES

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