

System Study: Emergency Power System 1998–2018

Zhegang Ma
Kellie J. Kvarfordt
John A. Schroeder
Thomas E. Wierman

December 2019



The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

NOTICE

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or process disclosed herein, or represents that its use by such third party would not infringe privately owned rights. The views expressed herein are not necessarily those of the U.S. Nuclear Regulatory Commission.

**System Study:
Emergency Power System
1998–2018**

**Zhegang Ma¹, Kellie J. Kvarfordt¹,
John A. Schroeder², Thomas E. Wierman²**

Update Completed December 2019

**¹Idaho National Laboratory, Risk Assessment and Management
Services Department, Idaho Falls, Idaho 83415**

**²Schroeder Incorporated, 3945 Wise Owl Way, Island Park, Idaho
83429**

<http://www.inl.gov>

**Prepared for the
Division of Risk Assessment
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
NRC Agreement Number NRC-HQ-14-D-0018**

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 1998 through 2018 for selected components were obtained from the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS), formerly the 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. No statistically significant increasing or decreasing trends were identified in the EPS results.

CONTENTS

ABSTRACT.....	iii
ACRONYMS.....	vii
1. INTRODUCTION.....	1
2. SUMMARY OF FINDINGS.....	3
3. INDUSTRY-WIDE UNRELIABILITY.....	4
4. INDUSTRY-WIDE TRENDS.....	6
5. BASIC EVENT GROUP IMPORTANCES.....	8
6. DATA TABLES.....	11
7. SYSTEM DESCRIPTION.....	16
8. REFERENCES.....	21

FIGURES

Figure 1. EPS start-only mission unreliability for Class 2, 3, and 4 and industry-wide groupings.....	5
Figure 2. EPS 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.....	5
Figure 3. Trend of EPS system unreliability (start-only model), as a function of year.....	7
Figure 4. Trend of EPS system unreliability (8-hour model), as a function of year.....	7
Figure 5. EPS industry-wide basic event group importances.....	8
Figure 6. EPS Class 2 basic event group importances.....	9
Figure 7. EPS Class 3 basic event group importances.....	10
Figure 8. EPS Class 4 basic event group importances.....	10
Figure 9. Simplified EPS system schematic.....	20

TABLES

Table 1. Plant EPS class listing.....	2
Table 2. Industry-wide unreliability values.....	4
Table 3. EPS model basic event importance group descriptions.....	9
Table 4. Plot data for EPS start-only trend, Figure 3.....	11
Table 5. Plot data for EPS 8-hour trend, Figure 4.....	12
Table 6. Basic event reliability trending data.....	13
Table 7. Basic event UA trending data.....	15
Table 8. Failure mode acronyms.....	15
Table 9. EPS configurations at U.S. commercial nuclear power plants.....	17

ACRONYMS

CCF	common-cause failure
EDG	emergency diesel generator
EPIX	Equipment Performance and Information Exchange
EPS	emergency power system
FTLR	fail to load/run
FTR	fail to run
FTS	fail to start
GTG	gas turbine generator
HTG	hydro turbine generator
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
IRIS	Industry Reporting and Information System
LOOP	loss-of-offsite power
MSPI	Mitigating Systems Performance Index
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment
ROP	Reactor Oversight Process
SBO	station blackout
SPAR	standardized plant analysis risk
SSU	safety system unavailability
UA	unavailability (maintenance or state of another component)

System Study: Emergency Power System 1998–2018

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 1998 through 2018 for selected components in the EPS were obtained from the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS), formerly the INPO Consolidated Events Database (ICES) and the Equipment Performance and Information Exchange Database (EPIX). Train unavailability data (outages from test or maintenance) were obtained from the Reactor Oversight Process (ROP) Safety System Unavailability (SSU) database (1998 through 2001) and the Mitigating Systems Performance Index (MSPI) database (2002 through 2018). 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 2015 Component Reliability Update [1], which is an update to NUREG/CR-6928 [2] and the 2010 Component Reliability Update [3]. Baseline EPS unreliability results using basic event values from the 2010 Component Reliability Update^a 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 and recovery events in the models are set to False in the study for the results to represent the mechanical part of the system. An overview of the trending methods, glossary of terms, and abbreviations can be found in the paper Overview and Reference [4] on the Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases web page (<https://nrcoe.inl.gov/resultsdb/>).

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 human error and recovery events to False, and setting all cooling basic events to False. The 8-hour mission model sets all human error and recovery events to False.

^a For comparison purposes, in order to keep the SPAR models and basic event data the same as those used in the previous (2016) EPS system study, the 2010 Component Reliability Update data is used here. The only variables subject to change in this analysis were the demand, run hours, failure, and unavailability data for selected components in the EPS system.

Table 1. Plant EPS class listing.

Class	Plant	Version	Class	Plant	Version	Class	Plant	Version
Class 2	Beaver Valley 1	8.22	Class 2	Vermont Yankee	8.19	Class 3	San Onofre 3	8.22
Class 2	Beaver Valley 2	8.23	Class 2	Waterford 3	8.16	Class 3	Sequoyah 1	8.16
Class 2	Brunswick 1	8.2	Class 2	Wolf Creek	8.2	Class 3	Sequoyah 2	8.16
Class 2	Brunswick 2	8.2	Class 3	Arkansas 1	8.19	Class 3	South Texas 1	8.17
Class 2	Callaway	8.21	Class 3	Arkansas 2	8.21	Class 3	South Texas 2	8.17
Class 2	Clinton 1	8.17	Class 3	Braidwood 1	8.21	Class 3	St. Lucie 1	8.19
Class 2	Columbia 2	8.16	Class 3	Braidwood 2	8.21	Class 3	St. Lucie 2	8.19
Class 2	Comanche Peak 1	8.21	Class 3	Byron 1	8.21	Class 3	Surry 1	8.19
Class 2	Comanche Peak 2	8.21	Class 3	Byron 2	8.21	Class 3	Surry 2	8.15
Class 2	Cook 1	8.2	Class 3	Calvert Cliffs 1	8.22	Class 3	Susquehanna 1	8.23
Class 2	Cook 2	8.2	Class 3	Calvert Cliffs 2	8.21	Class 3	Susquehanna 2	8.21
Class 2	Cooper	8.22	Class 3	Catawba 1	8.2	Class 3	Three Mile Isl 1	8.2
Class 2	Crystal River 3	8.16	Class 3	Catawba 2	8.2	Class 3	Turkey Point 3	8.2
Class 2	Davis-Besse	8.19	Class 3	Diablo Canyon 1	8.19	Class 3	Turkey Point 4	8.2
Class 2	Duane Arnold	8.22	Class 3	Diablo Canyon 2	8.19	Class 3	Vogtle 1	8.21
Class 2	Fort Calhoun	8.2	Class 3	Farley 1	8.18	Class 3	Vogtle 2	8.21
Class 2	Ginna	8.23	Class 3	Farley 2	8.18	Class 3	Watts Bar 1	8.16
Class 2	Grand Gulf	8.22	Class 3	Hatch 1	8.2	Class 4	Browns Ferry 1	8.22
Class 2	Harris	8.23	Class 3	Hatch 2	8.2	Class 4	Browns Ferry 2	8.22
Class 2	Kewaunee	8.2	Class 3	Hope Creek	8.18	Class 4	Browns Ferry 3	8.18
Class 2	McGuire 1	8.2	Class 3	Indian Point 2	8.19	Class 4	Dresden 2	8.18
Class 2	McGuire 2	8.2	Class 3	Indian Point 3	8.2	Class 4	Dresden 3	8.18
Class 2	Monticello	8.2	Class 3	La Salle 1	8.21	Class 4	Fermi 2	8.2
Class 2	Nine Mile Pt. 1	8.21	Class 3	La Salle 2	8.21	Class 4	FitzPatrick	8.17
Class 2	Nine Mile Pt. 2	8.17	Class 3	Millstone 2	8.17	Class 4	Limerick 1	8.2
Class 2	Oconee 1	8.19	Class 3	Millstone 3	8.2	Class 4	Limerick 2	8.19
Class 2	Oconee 2	8.19	Class 3	Palo Verde 1	8.2	Class 4	North Anna 1	8.2
Class 2	Oconee 3	8.19	Class 3	Palo Verde 2	8.2	Class 4	North Anna 2	8.2
Class 2	Oyster Creek	8.22	Class 3	Palo Verde 3	8.2	Class 4	Point Beach 1	8.2
Class 2	Palisades	8.2	Class 3	Peach Bottom 2	8.25	Class 4	Point Beach 2	8.2
Class 2	Perry	8.19	Class 3	Peach Bottom 3	8.21	Class 4	Prairie Island 1	8.19
Class 2	Pilgrim	8.21	Class 3	River Bend	8.2	Class 4	Prairie Island 2	8.19
Class 2	Robinson 2	8.17	Class 3	Salem 1	8.2	Class 4	Quad Cities 1	8.18
Class 2	Seabrook	8.2	Class 3	Salem 2	8.2	Class 4	Quad Cities 2	8.18
Class 2	Summer	8.23	Class 3	San Onofre 2	8.22			

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. In this update, **no statistically significant increasing or decreasing trends were identified** in the EPS unreliability trend results.

The industry-wide EPS start-only and 8-hour basic event group importances were evaluated and are shown in Figure 5:

- In the *Start-Only* case—the leading contributor to EPS system unreliability is the **1E Generator** group of basic events followed by the Cooling and AC Power groups.
- In the *8-Hour* case—the leading contributor to EPS system unreliability is also the **1E Generator** group of basic events followed by the Cooling and AC Power groups.

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 (1998 through 2010).^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 unique 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	3.94E-06	1.56E-04	5.39E-04	2.06E-03
	Class 2	1.02E-05	4.11E-04	9.31E-04	3.16E-03
	Class 3	1.02E-05	1.32E-04	3.45E-04	1.22E-03
	Class 4	1.06E-07	8.33E-06	4.38E-05	1.84E-04
8-hour Mission	Industry	6.84E-06	4.00E-04	1.11E-03	3.61E-03
	Class 2	3.80E-05	1.06E-03	1.76E-03	5.08E-03
	Class 3	3.33E-05	3.51E-04	8.71E-04	2.45E-03
	Class 4	5.86E-07	1.72E-05	8.78E-05	3.37E-04

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

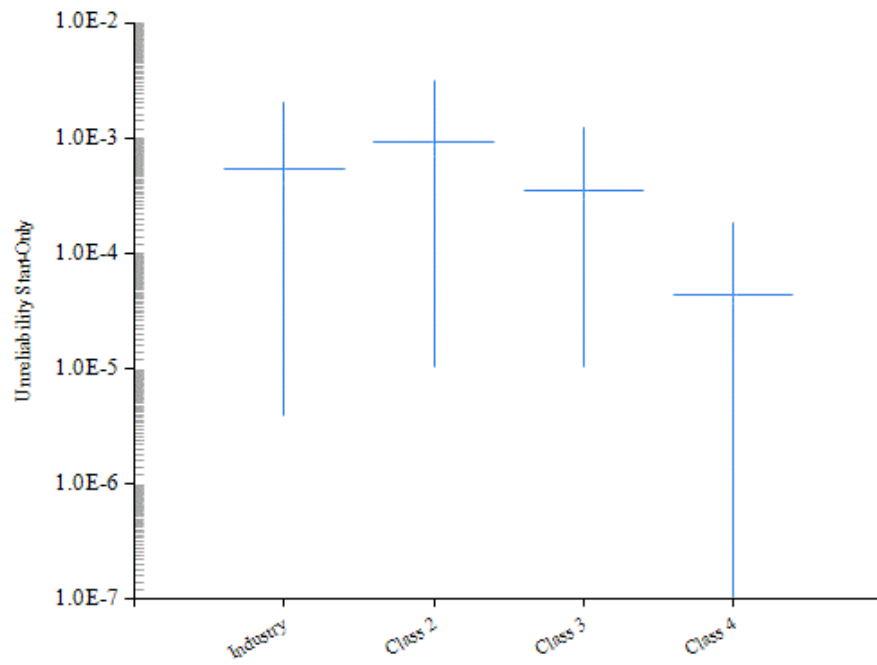


Figure 1. EPS start-only mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

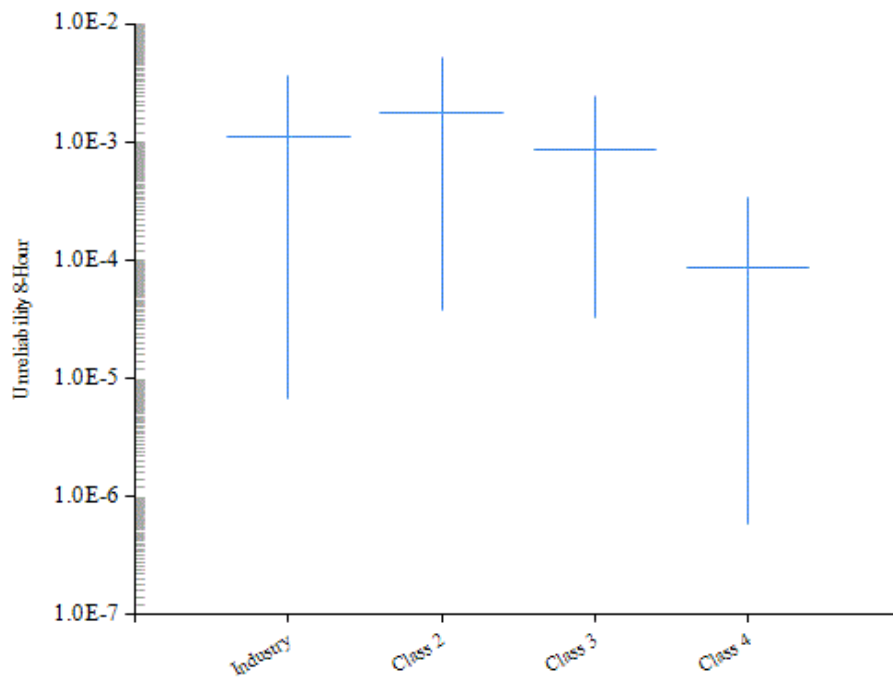


Figure 2. EPS 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly (1998 through 2018) 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 program 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 [4]. 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 (or constrained noninformative distributions, refer to Section 2 of the Overview and Reference document) using data for each year. In addition, for comparison, this update (current SPAR/ICES) is shown. Section 4 of the Overview and Reference document 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. **No statistically significant trend was identified** within the industry-wide estimates of EPS system start-only mission on a per fiscal year basis.

Figure 4 shows the trend in the 8-hour mission unreliability. Table 5 shows the data points for Figure 4. **No statistically significant trend was identified** within the industry-wide estimates of EPS system unreliability (8-hour mission) on a per fiscal year basis.

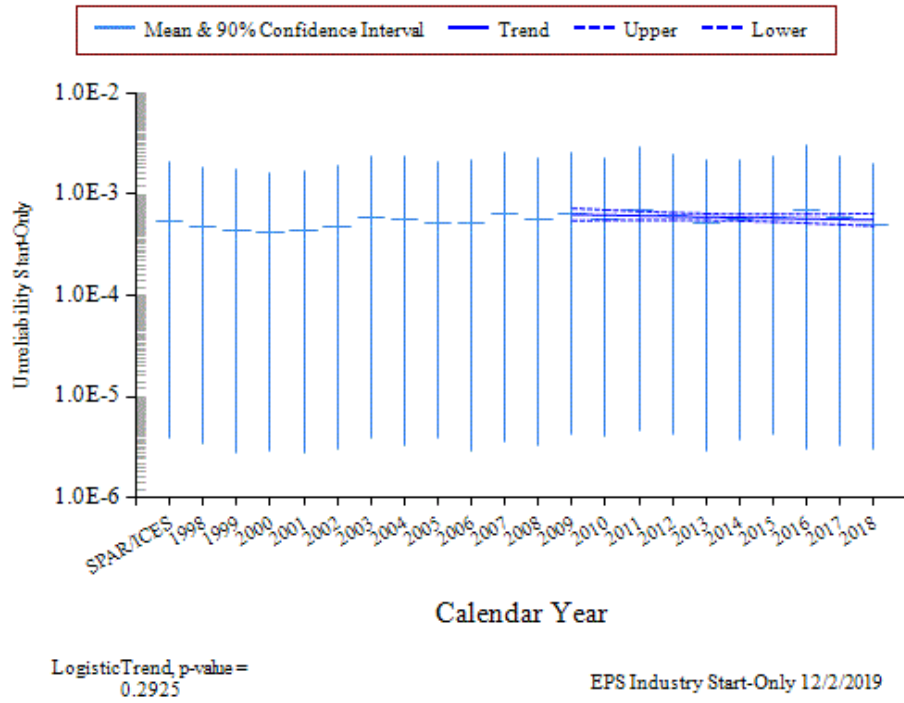


Figure 3. Trend of EPS system unreliability (start-only model), as a function of year.

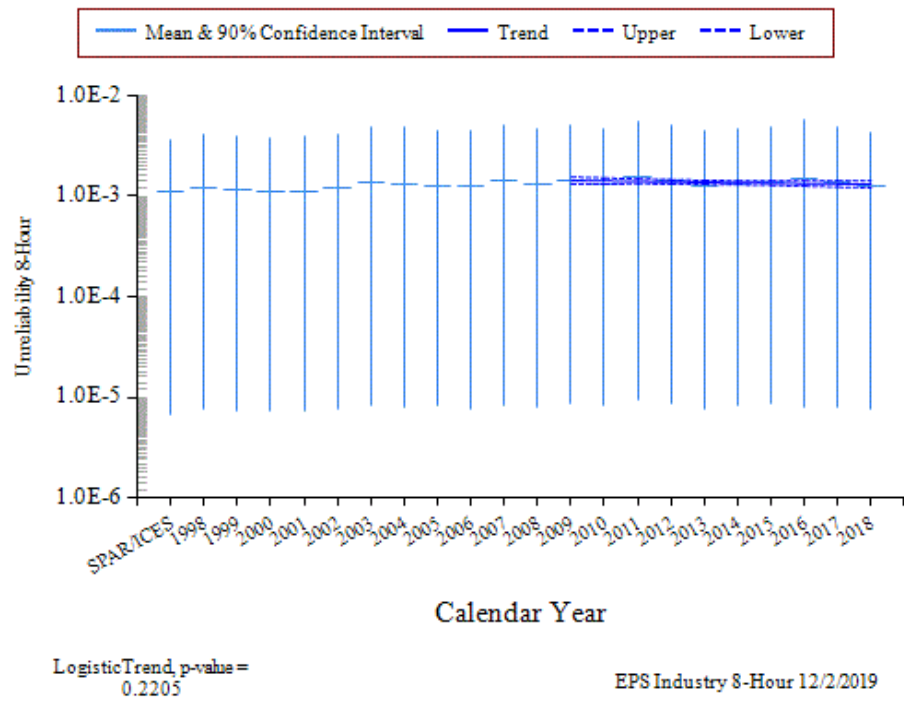


Figure 4. Trend of EPS system unreliability (8-hour model), as a function of year.

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 the **Start-Only** case—the leading contributor to EPS system unreliability is the **1E Generator** group of basic events followed by the Cooling and AC Power groups.
- In the **8-Hour** case—the leading contributor to EPS system unreliability is also the **1E Generator** group of basic events followed by the Cooling and AC Power groups.

For more discussion on the EPS diesel generators, see the emergency diesel generator component reliability study at the NRC Reactor Operational Experience Results and Databases web page (<https://nrcoe.inl.gov/resultsdb/>). Table 3 shows the SPAR model EPS importance groups and their descriptions.

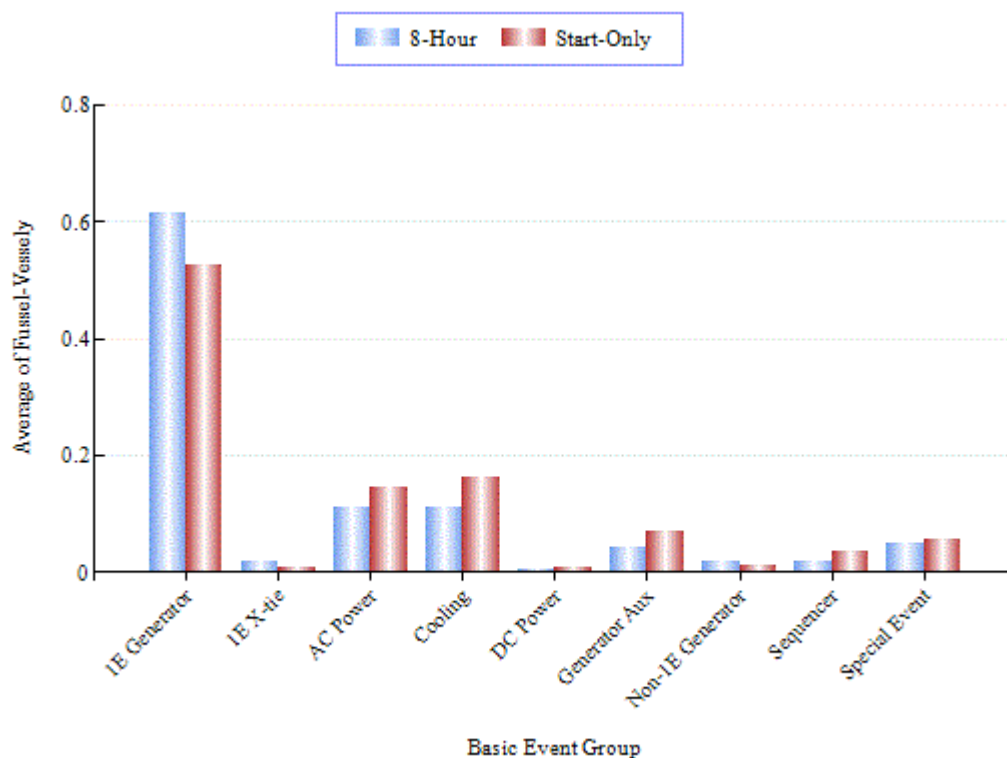


Figure 5. EPS industry-wide basic event group importances.

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 typically from a sister unit at the same site.
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.
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.

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

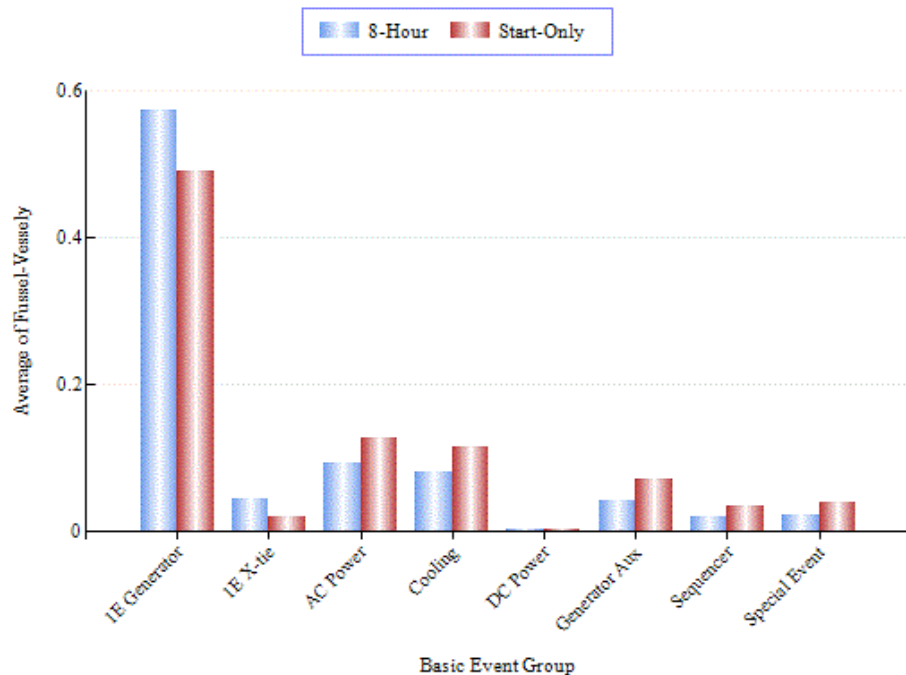


Figure 6. EPS Class 2 basic event group importances.

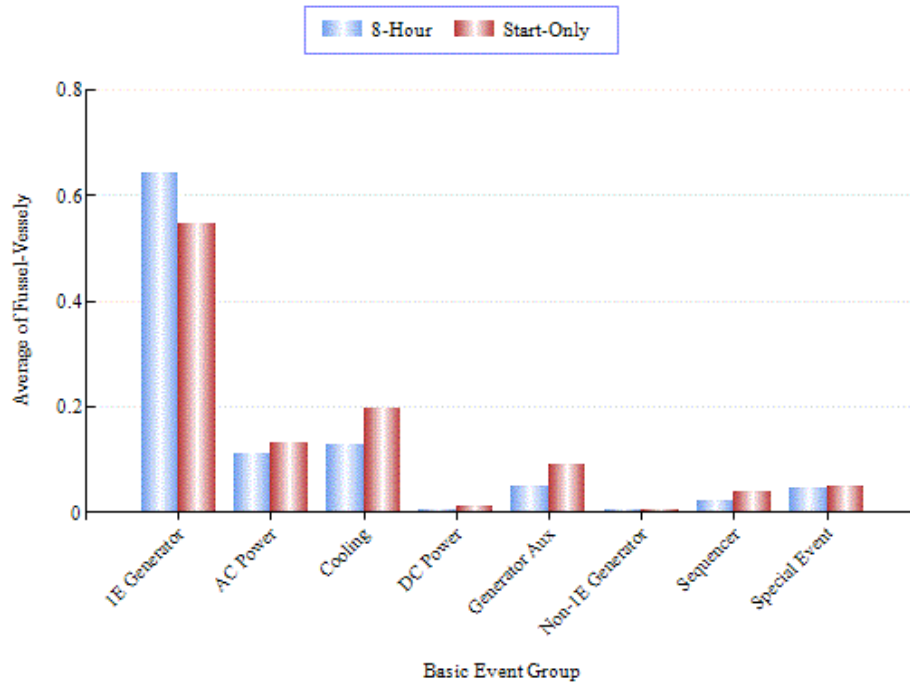


Figure 7. EPS Class 3 basic event group importances.

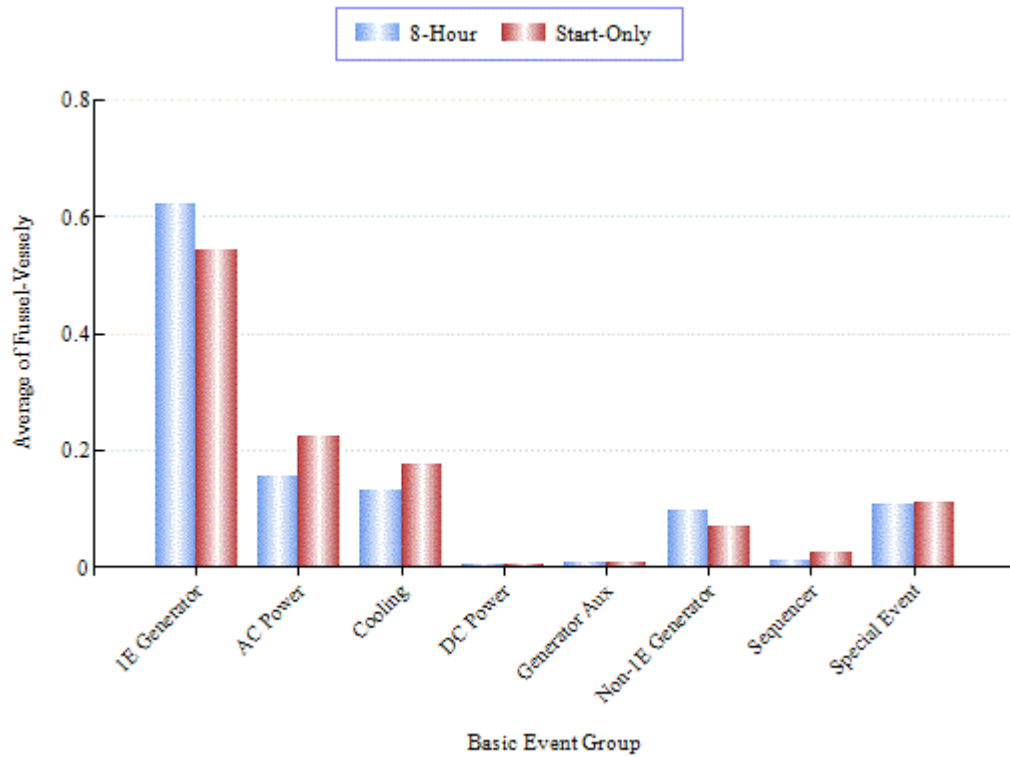


Figure 8. EPS Class 4 basic event group importances.

6. DATA TABLES

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

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	3.94E-06	5.39E-04	2.06E-03
1998	--	--	--	3.43E-06	4.71E-04	1.82E-03
1999	--	--	--	2.75E-06	4.43E-04	1.73E-03
2000	--	--	--	2.92E-06	4.25E-04	1.62E-03
2001	--	--	--	2.76E-06	4.35E-04	1.70E-03
2002	--	--	--	3.01E-06	4.81E-04	1.90E-03
2003	--	--	--	3.82E-06	5.78E-04	2.34E-03
2004	--	--	--	3.27E-06	5.71E-04	2.38E-03
2005	--	--	--	3.82E-06	5.27E-04	2.06E-03
2006	--	--	--	2.89E-06	5.24E-04	2.15E-03
2007	--	--	--	3.63E-06	6.27E-04	2.60E-03
2008	--	--	--	3.31E-06	5.67E-04	2.30E-03
2009	5.49E-04	6.31E-04	7.26E-04	4.18E-06	6.33E-04	2.56E-03
2010	5.53E-04	6.23E-04	7.01E-04	4.13E-06	5.68E-04	2.23E-03
2011	5.56E-04	6.14E-04	6.79E-04	4.64E-06	7.09E-04	2.89E-03
2012	5.57E-04	6.06E-04	6.60E-04	4.16E-06	6.22E-04	2.49E-03
2013	5.54E-04	5.98E-04	6.45E-04	2.85E-06	5.25E-04	2.14E-03
2014	5.46E-04	5.89E-04	6.36E-04	3.75E-06	5.54E-04	2.19E-03
2015	5.34E-04	5.81E-04	6.33E-04	4.14E-06	5.91E-04	2.33E-03
2016	5.19E-04	5.73E-04	6.34E-04	2.98E-06	6.91E-04	3.06E-03
2017	5.02E-04	5.66E-04	6.37E-04	3.31E-06	5.77E-04	2.37E-03
2018	4.85E-04	5.58E-04	6.42E-04	3.03E-06	4.98E-04	1.97E-03

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

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	6.84E-06	1.11E-03	3.61E-03
1998	--	--	--	7.74E-06	1.18E-03	4.06E-03
1999	--	--	--	7.28E-06	1.14E-03	3.94E-03
2000	--	--	--	7.33E-06	1.11E-03	3.80E-03
2001	--	--	--	7.30E-06	1.13E-03	3.89E-03
2002	--	--	--	7.57E-06	1.20E-03	4.17E-03
2003	--	--	--	8.35E-06	1.34E-03	4.78E-03
2004	--	--	--	8.03E-06	1.33E-03	4.83E-03
2005	--	--	--	8.14E-06	1.27E-03	4.39E-03
2006	--	--	--	7.64E-06	1.26E-03	4.51E-03
2007	--	--	--	8.39E-06	1.41E-03	5.12E-03
2008	--	--	--	8.01E-06	1.33E-03	4.71E-03
2009	1.32E-03	1.43E-03	1.55E-03	8.74E-06	1.43E-03	5.08E-03
2010	1.32E-03	1.41E-03	1.52E-03	8.46E-06	1.34E-03	4.61E-03
2011	1.32E-03	1.40E-03	1.48E-03	9.34E-06	1.53E-03	5.53E-03
2012	1.32E-03	1.39E-03	1.46E-03	8.69E-06	1.41E-03	4.99E-03
2013	1.31E-03	1.37E-03	1.44E-03	7.64E-06	1.27E-03	4.49E-03
2014	1.30E-03	1.36E-03	1.42E-03	8.20E-06	1.32E-03	4.57E-03
2015	1.28E-03	1.35E-03	1.42E-03	8.50E-06	1.37E-03	4.75E-03
2016	1.26E-03	1.34E-03	1.42E-03	8.09E-06	1.47E-03	5.77E-03
2017	1.23E-03	1.32E-03	1.42E-03	8.10E-06	1.34E-03	4.83E-03
2018	1.21E-03	1.31E-03	1.42E-03	7.63E-06	1.23E-03	4.27E-03

Table 6. Basic event reliability trending data.

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
FTLR	GEN	1998	14	3,688	3.79E-03	16.77	4.40E+03	Beta
FTLR	GEN	1999	5	3,648	1.77E-03	7.77	4.37E+03	Beta
FTLR	GEN	2000	8	3,585	2.49E-03	10.77	4.31E+03	Beta
FTLR	GEN	2001	13	3,715	3.55E-03	15.77	4.43E+03	Beta
FTLR	GEN	2002	14	3,638	3.84E-03	16.77	4.36E+03	Beta
FTLR	GEN	2003	15	3,790	3.93E-03	17.77	4.51E+03	Beta
FTLR	GEN	2004	10	3,822	2.80E-03	12.77	4.54E+03	Beta
FTLR	GEN	2005	15	3,784	3.93E-03	17.77	4.50E+03	Beta
FTLR	GEN	2006	15	3,757	3.96E-03	17.77	4.47E+03	Beta
FTLR	GEN	2007	21	3,645	5.43E-03	23.77	4.36E+03	Beta
FTLR	GEN	2008	16	3,729	4.21E-03	18.77	4.44E+03	Beta
FTLR	GEN	2009	18	3,668	4.72E-03	20.77	4.38E+03	Beta
FTLR	GEN	2010	11	3,571	3.20E-03	13.77	4.29E+03	Beta
FTLR	GEN	2011	16	3,605	4.33E-03	18.77	4.32E+03	Beta
FTLR	GEN	2012	17	3,569	4.60E-03	19.77	4.28E+03	Beta
FTLR	GEN	2013	12	3,577	3.43E-03	14.77	4.30E+03	Beta
FTLR	GEN	2014	12	3,603	3.41E-03	14.77	4.32E+03	Beta
FTLR	GEN	2015	13	3,534	3.70E-03	15.77	4.25E+03	Beta
FTLR	GEN	2016	11	3,527	3.23E-03	13.77	4.25E+03	Beta
FTLR	GEN	2017	9	3,484	2.79E-03	11.77	4.21E+03	Beta
FTLR	GEN	2018	13	3,484	3.74E-03	15.77	4.20E+03	Beta
FTR	GEN	1998	4	10,000	5.69E-04	7.55	1.33E+04	Gamma
FTR	GEN	1999	1	10,319	3.35E-04	4.55	1.36E+04	Gamma
FTR	GEN	2000	7	11,538	7.13E-04	10.55	1.48E+04	Gamma
FTR	GEN	2001	2	11,977	3.64E-04	5.55	1.52E+04	Gamma
FTR	GEN	2002	7	12,341	6.76E-04	10.55	1.56E+04	Gamma
FTR	GEN	2003	10	11,699	9.06E-04	13.55	1.50E+04	Gamma
FTR	GEN	2004	13	11,747	1.10E-03	16.55	1.50E+04	Gamma
FTR	GEN	2005	14	12,307	1.13E-03	17.55	1.56E+04	Gamma
FTR	GEN	2006	4	11,369	5.16E-04	7.55	1.46E+04	Gamma
FTR	GEN	2007	17	11,365	1.40E-03	20.55	1.46E+04	Gamma
FTR	GEN	2008	20	11,238	1.62E-03	23.55	1.45E+04	Gamma
FTR	GEN	2009	8	11,223	7.97E-04	11.55	1.45E+04	Gamma
FTR	GEN	2010	13	10,777	1.18E-03	16.55	1.40E+04	Gamma
FTR	GEN	2011	21	11,810	1.63E-03	24.55	1.51E+04	Gamma
FTR	GEN	2012	11	7,257	1.38E-03	14.55	1.05E+04	Gamma
FTR	GEN	2013	17	7,796	1.86E-03	20.55	1.11E+04	Gamma
FTR	GEN	2014	17	7,133	1.98E-03	20.55	1.04E+04	Gamma
FTR	GEN	2015	12	7,614	1.43E-03	15.55	1.09E+04	Gamma
FTR	GEN	2016	10	7,425	1.27E-03	13.55	1.07E+04	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
FTR	GEN	2017	22	7,223	2.44E-03	25.55	1.05E+04	Gamma
FTR	GEN	2018	10	7,670	1.24E-03	13.55	1.09E+04	Gamma
FTS	GEN	1998	18	4,285	3.68E-03	26.11	7.06E+03	Beta
FTS	GEN	1999	8	4,168	2.31E-03	16.11	6.96E+03	Beta
FTS	GEN	2000	12	3,909	2.99E-03	20.11	6.69E+03	Beta
FTS	GEN	2001	12	4,023	2.94E-03	20.11	6.81E+03	Beta
FTS	GEN	2002	10	4,272	2.56E-03	18.11	7.06E+03	Beta
FTS	GEN	2003	17	4,329	3.52E-03	25.11	7.11E+03	Beta
FTS	GEN	2004	14	4,338	3.10E-03	22.11	7.12E+03	Beta
FTS	GEN	2005	16	4,383	3.35E-03	24.11	7.16E+03	Beta
FTS	GEN	2006	9	4,371	2.38E-03	17.11	7.16E+03	Beta
FTS	GEN	2007	11	4,288	2.69E-03	19.11	7.07E+03	Beta
FTS	GEN	2008	8	4,331	2.26E-03	16.11	7.12E+03	Beta
FTS	GEN	2009	15	4,224	3.29E-03	23.11	7.01E+03	Beta
FTS	GEN	2010	15	4,091	3.35E-03	23.11	6.87E+03	Beta
FTS	GEN	2011	19	4,127	3.91E-03	27.11	6.91E+03	Beta
FTS	GEN	2012	14	4,035	3.23E-03	22.11	6.82E+03	Beta
FTS	GEN	2013	6	4,103	2.04E-03	14.11	6.89E+03	Beta
FTS	GEN	2014	12	4,081	2.92E-03	20.11	6.87E+03	Beta
FTS	GEN	2015	13	4,022	3.09E-03	21.11	6.81E+03	Beta
FTS	GEN	2016	13	4,039	3.08E-03	21.11	6.82E+03	Beta
FTS	GEN	2017	10	3,987	2.67E-03	18.11	6.78E+03	Beta
FTS	GEN	2018	7	3,957	2.23E-03	15.11	6.75E+03	Beta

Table 7. Basic event UA trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
UA	EDG	1998	21,235	1,874,166	1.04E-02	2.12	201.18	Beta
UA	EDG	1999	22,769	2,005,223	1.10E-02	2.51	225.77	Beta
UA	EDG	2000	18,409	2,042,467	9.53E-03	2.59	269.13	Beta
UA	EDG	2001	19,233	2,075,373	9.72E-03	1.83	186.04	Beta
UA	EDG	2002	24,631	2,093,196	1.20E-02	2.13	175.15	Beta
UA	EDG	2003	28,961	2,047,203	1.39E-02	1.65	116.86	Beta
UA	EDG	2004	29,617	2,099,392	1.36E-02	1.29	93.55	Beta
UA	EDG	2005	26,350	2,070,016	1.29E-02	2.36	180.2	Beta
UA	EDG	2006	28,713	2,083,212	1.33E-02	1.59	118.69	Beta
UA	EDG	2007	34,106	2,104,023	1.62E-02	1.74	105.51	Beta
UA	EDG	2008	31,755	2,089,978	1.52E-02	2.09	135.51	Beta
UA	EDG	2009	33,204	2,059,429	1.61E-02	1.98	121.6	Beta
UA	EDG	2010	30,037	2,081,690	1.44E-02	2.5	171.26	Beta
UA	EDG	2011	36,401	2,023,479	1.75E-02	1.9	106.8	Beta
UA	EDG	2012	32,470	1,977,596	1.59E-02	2.1	130.02	Beta
UA	EDG	2013	30,642	2,007,371	1.39E-02	1.88	133.37	Beta
UA	EDG	2014	28,292	2,027,147	1.43E-02	2.39	164.68	Beta
UA	EDG	2015	30,706	2,008,809	1.54E-02	2.56	164.02	Beta
UA	EDG	2016	29,859	2,025,233	1.51E-02	0.72	46.82	Beta
UA	EDG	2017	30,463	1,997,343	1.47E-02	1.64	109.93	Beta
UA	EDG	2018	25,907	1,990,438	1.31E-02	2.39	179.78	Beta

Table 8. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTLR	Fail to load/run
FTR	Fail to run
FTS	Fail to start
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 (for sister units at the same site) 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 station blackout (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 the components are related to the support needed for the emergency power source success. Some 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 Generators	1E Generator	1E X-tie (to sister unit)	Non-1E Generator
Class 2	Beaver Valley 1	4	2	2	
Class 2	Beaver Valley 2	4	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 Generators	1E Generator	1E X-tie (to sister unit)	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 included in SPAR model)	2 (need both)
Class 3	Palo Verde 2	8	2	4 (not included in SPAR model)	2 (need both)
Class 3	Palo Verde 3	8	2	4 (not included in SPAR model)	2 (need both)
Class 3	Peach Bottom 2	4	4 (2 of 4 required)		
Class 3	Peach Bottom 3	4	4 (2 of 4 required)		
Class 3	River Bend	4	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

Table 9. (continued).

Class	Plant	Total Generators	1E Generator	1E X-tie (to sister unit)	Non-1E Generator
Class 3	Surry 2	4	3		1
Class 3	Susquehanna 1	5	5 (2 of the EDGs cannot 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

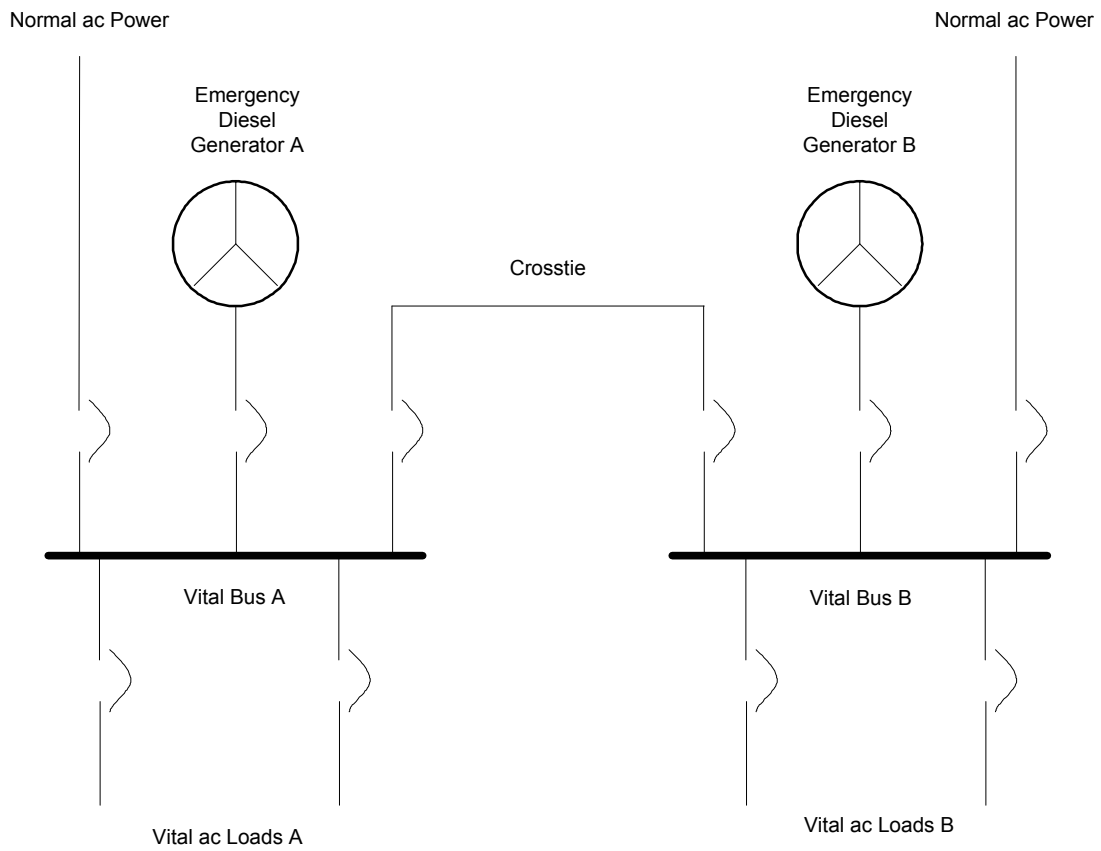


Figure 9. Simplified EPS system schematic.

8. REFERENCES

- [1] United States Nuclear Regulatory Commission, "Component Reliability Data Sheets Update 2015," February 2017. [Online]. Available: <https://nrcoe.inl.gov/resultsdb/publicdocs/AvgPerf/ComponentUR2015.pdf>.
- [2] S. A. Eide, T. E. Wierman, C. D. Gentillon, D. M. Rasmuson and C. L. Atwood, "Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants," NUREG/CR-6928, U.S. Nuclear Regulatory Commission, February 2007.
- [3] United States Nuclear Regulatory Commission, "Component Reliability Data Sheets Update 2010," January 2012. [Online]. Available: <https://nrcoe.inl.gov/resultsdb/publicdocs/AvgPerf/ComponentUR2010.pdf>.
- [4] C. D. Gentillon, "Overview and Reference Document for Operational Experience Results and Databases Trending," February 2016. [Online]. Available: <https://nrcoe.inl.gov/resultsdb/publicdocs/Overview-and-Reference.pdf>.