INL/EXT-20-59569

Reliability Study: On-Site Electrical System, 1998–2015

Zhegang Ma
Nancy Lybeck
John Schroeder
Vivek Agarwal

September 2017

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

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Zhegang Ma
Nancy Lybeck
John Schroeder (retired)
Vivek Agarwal

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Idaho National Laboratory
Regulatory Support Department
P.O. Box 1625
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
Division of Risk Assessment
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Under U.S. Department of Energy Idaho Operations Office
Contract DE-AC07-05ID14517
NRC Agreement Number NRC-HQ-60-14-D-0018

ABSTRACT

This report documents an analysis of the reliability of on-site electrical systems at U.S. commercial nuclear plants during the period 1998-2015. The study contains both individual component studies and system studies. The component studies are focused on key electrical components including circuit breakers, battery chargers, buses, batteries, and transformers. Data from the range of 1998 to 2015 were gathered, reviewed, and statistically evaluated for impacts on reliability as a function of relevant parameters: manufacturer, system, operating environment, inspection/testing regimen, operating range (voltages, amperes), setpoints, and other factors. The system studies identify seven operating nuclear power plants/units that represent different designs of offsite power sources and interconnecting power circuit paths, develop electrical single line diagrams and detailed fault tree models for the representing designs, and evaluate the electrical system reliability using the reliability data obtained from the component studies.

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EXECUTIVE SUMMARY

This report presents an engineering study of on-site electrical system performance in commercial nuclear power plants during the period 1998-2015. The study contains both individual electrical component studies and electrical system studies. The component studies are focused on key electrical components including circuit breakers, battery chargers, buses, batteries, and transformers. Data from the range of 1998 to 2015 were gathered, reviewed, and statistically evaluated for impacts on reliability as a function of relevant parameters: manufacturer, system, operating environment, inspection/testing regimen, operating range (voltages, amperes), setpoints, and other factors. The system studies use a categorization and grouping scheme that has been used previously. It identifies seven operating nuclear power plants/units that represent different designs of offsite power sources and interconnecting power circuit paths, develop electrical single line diagrams and detailed fault tree models and evaluate the electrical system reliability using the reliability data obtained from the component studies. While the scope, major assumptions, and the details of this study can be found in the main report, the following presents the summary and major findings from the study.

Electrical Component Study

The electric components included in this study are circuit breakers, battery chargers, buses, batteries, and transformers. The data for circuit breakers, battery chargers, and batteries are available in Integrated Data Collection and Coding System (IDCCS) maintained at the Idaho National Laboratory (INL) for calendar years 1998 through 2015. The data for buses (for calendar years 2006 through 2015) and transformers (for calendar years 2005 through 2015) were obtained from the Institute of Nuclear Power Operations (INPO) Consolidated Event System (ICES) and then reviewed and coded. These data were statistically evaluated for impacts on reliability as a function of relevant parameters: manufacturer, system, operating environment, inspection/testing regimen, operating range (voltages, amperes), setpoints, and other factors.

- Circuit Breakers: The study is limited to components within the power distribution system, so that circuit breakers, whenever they are an integral part of larger components, are not included in this study. There are a total of 579 failures in a population of 4880 circuit breakers during the time frame under consideration. Three groups of circuit breakers are used in the analysis: all circuit breakers, medium voltage circuit breakers (from 4.16 kV to 6.9 kV), and high voltage circuit breakers (13.8 kV and above). Data shows that the higher voltage breakers seem to have higher failure counts than might otherwise be expected.
- Battery Chargers: There are a total of 390 monitored battery chargers with 156 recorded failures during the time frame under consideration. Data shows that a large population of very old battery chargers are currently in use.
- Transformers: The study focuses on large power transformers (>15kV). There are a total of 506 monitored large power transformers with 185 recorded failures during the time frame under consideration. Data shows that a large population of old large power transformers are currently in use.
- Batteries: There are a total of 415 monitored batteries with 23 recorded failures during the time frame under consideration.
- Buses: there are a total of 1255 monitored AC buses with 62 recorded failures during the time frame under consideration. The most failures (about 40%) occurred in the oldest AC buses, those older than 40 years. Approximately 25% of the current AC buses are older than 40 years.

Trend analyses are performed on the component data from 2006 to 2015 using a general linear model based on a Poisson distribution with a log link function and an offset. This methodology is most

applicable to failure rates associated with hours of usage but can also be used for failure rates that are associated with demands. The following statistically significant trends were identified in the study:

- Statistically significant decreasing trend was identified for the rate of high voltage circuit breakers (13.8 kV and above) failing to open/close.
- Statistically significant decreasing trend was identified for the spurious operation rate for all circuit breakers.
- Statistically significant increasing trend was identified for the failure rate of battery charger.

Table ES-1 presents the failure rates estimated for the above electrical components by applying Empirical Bayes analysis or Bayesian update of the Jeffreys noninformative prior with 10 years of data (2006-2015). The 10 year time period represents the largest time span available for some of the components.

Table ES-1. Estimated electrical component failure rates with data from 2006-2015

		Data			Industry-average Failure Probability or Rate Distribution			
Component Failure Mode	Description	Failures	Demands or Hours	d or h	Distribution	Mean	α	β
BAT FTOP	Battery fails to operate	18	34975050	h	Gamma	5.29E–07	1.85E+01	3.50E+07
TFM FTOP	Large Power Transformer fails to operate	98	39641332	h	Gamma	2.74E–06	1.12E+00	4.08E+05
BUS FTOP	BUS Fails to operate	62	105426616	h	Gamma	7.60E–07	6.64E–01	8.74E+05
CBK SOP	Circuit Breaker operates spuriously	42	401781824	h	Gamma	1.64E–07	4.03E–01	2.45E+06
CBKMV SOP	Medium voltage circuit breaker operates spuriously	12	101949500	h	Gamma	1.23E–07	1.25E+01	1.02E+08
CBKHV SOP	High voltage circuit breaker operates spuriously	6	23802900	h	Gamma	2.73E–07	6.50E+00	2.38E+07
CBK FTOC	Circuit Breaker fails to open &/or close	78	82422.8	d	Beta	1.82E–03	5.79E–01	3.18E+02
CBKMV FTOC	Medium voltage circuit breaker fails to open &/or close	40	33893.4	d	Beta	1.19E–03	4.05E+01	3.39E+04
CBKHV FTOC	High voltage circuit breaker fails to open &/or close	15	6130.6	d	Beta	2.53E–03	1.55E+01	6.12E+03
BCH FTOP	Class 1E Battery Charger fails to operate	73	32977438	h	Gamma	2.22E–06	1.85E+00	8.33E+05

Electrical System Study - AC System

This AC system study uses three plant categories to classify the design of offsite power systems and interconnecting power circuit paths: Category I deals with the independence of offsite power sources to the nuclear power plant (NPP); Category II classifies the power sources for the Class 1E buses during normal operation; and Category III classifies the automatic or manual transfer schemes for the Class 1E buses when both the normal and the backup sources of offsite AC power fail. Seven plant designs were used in this study. For each design, one nuclear plant site was chosen as the representative by considering the level of development of the Standardized Plant Analysis Risk (SPAR) model as well as the availability of plant PRA and related information. An existing SPAR model for the selected site or unit was used as the base model that can be revised properly for reliability analysis. The latest available Updated Safety Analysis Reports were used to verify whether the current electrical distribution designs of the representing plants remain in the same categories as defined. For this study, a Class 1E 4.16 kV AC system failure or a single train AC bus failure was used as the top event of the fault tree model and as the surrogate for the electrical system unreliability. Electrical single line diagrams (ESLDs) were developed with the available plant information. The associated fault trees in the base SPAR models were revised with necessary changes (for example, revised the fault tree logic as necessary based on the ESLDs developed, added new basic events for additional transformer/circuit breaker/bus failures and manual actions, used the new failure rates developed in this study, added CCF events as necessary, etc.). Two scenarios are considered in the system reliability evaluation: Normal (with offsite power supplies being available) and LOOP (with normal offsite power supplies not available).

Table ES-2 presents the electrical system reliability analysis results (for single train and a system of Class 1E 4.16 kV AC buses, under either normal plant operation or LOOP condition) conducted for the seven representing plants. All but one plant have almost the same failure probability of a single train under normal plant operation, about 2E-5, which is dominated by the failure of the associated Class 1E bus. The failure probabilities of the system are mostly around 6E-7 under normal plant operation. The failure probabilities of single train and system have much wider ranges under LOOP condition (from 1E-3 to 6E-2 for single train, and from 1E-4 to 7E-4 for the system) due to the various plant design features on standby AC power sources such as cross-tie emergency diesel generators (EDGs) between different units in multiple-unit plants and availability of station blackout (SBO) EDG or SBO lines.

One of the representing plants (Plant A) shows higher failure probabilities of single bus and system under normal plant operation than other plants. This is caused by its inclusion of the 480 V AC bus failures in the associated Class 1E 4.16 kV AC bus fault tree in the SPAR model. Even so, the plant still has a reliable onsite AC electrical system with a failure probability of about 4E-4 for single bus and about 5E-6 for the system under normal plant operation.

Other observations that are gained from the AC system reliability study are presented below:

- Different plant configurations of offsite power systems and interconnecting power circuit paths appear to have relatively small impacts on the reliability of onsite AC electrical system.
- Under normal plant operation, AC bus failures are the most significant contributors to the single train unreliability, while the CCF of the buses is the dominant contributor to the Class 1E 4.16 kV system unreliability.
- The onsite electrical system reliability for the LOOP condition depends on the plant design and performance of the standby AC power sources (for example, EDGs, SBO EDG, cross-tie features, SBO lines, etc.) and their support systems.
- EDG failures and unavailability and the SBO crosstie-related failures are the most significant contributors to single train unreliability during the LOOP condition.
- CCF of EDGs to run or the combinations of individual failures or unavailability of the EDGs are the most significant contributors to Class 1E 4.16 kV AC system unreliability during the LOOP condition. Other risk significant basic events include the operator actions, the random failures of the Class 1E buses, DC buses and batteries, and related circuit breakers.

Table ES-2. Summary of AC system unreliability results

Plant Type (Electrical System Category II, III)	Plant/Unit	AC System Unreliability			
		Normal Plant Operation		LOOP Condition	
		Single Train	System	Single Train	System
1, 1	Plant A	3.63E–04	5.12E–06	6.84E–02	6.13E–04
1, 2	Plant B	1.89E–05	5.59E–07	1.36E–03	2.52E–04
1, 3	Plant C	1.90E–05	5.59E–07	9.64E–03	5.41E–04
1, 4	Plant D	1.88E–05	5.63E–07	4.64E–03	1.08E–04
2, 1	Plant E	1.95E–05	5.60E–07	9.46E–03	7.33E–04
2, 2	Plant F	1.84E–05	1.00E–07	3.70E–03	2.37E–04
2, 3	Plant G	1.88E–05	5.59E–07	1.85E–03	1.16E–04

Electrical System Study - DC System

The DC system study employs a typical SPAR model to conduct system reliability analysis, then applies model variances to study their impact on the results. The failure probability of single division of DC power in a typical SPAR model is about 2E-5. The results are dominated by the failure of battery and DC bus, which contribute about 68% and 28%, respectively, to the total failure probability. Some DC system modeling variances in SPAR and their impacts are presented below:

- DC Success Requires either Battery or Charger

  In the above typical SPAR model, the success of DC power requires both battery and battery charger. For some SPAR models, however, the success of DC power only requires either the battery or battery charger to function, but not both. For these models, the failure probability of a single division of DC power is decreased to 5E-6, with 99.9% of the contribution coming from the failure of DC bus.

- CCF of DC Buses

  Although CCFs of batteries and battery chargers are included in 125V DC models, CCF of DC buses is often not modeled. The CCF of DC buses may contributes as little as 0.1% of the single division failure. However, its significance increases dramatically when evaluating the reliability of a 125V DC power system with 4 divisions and 1-of-4 divisions is required for success. The failure probability for such DC power system is about 6E-8, with the CCF of DC bus failures contributing 45% of the system failure.

- DC Room Cooling

  Some SPAR models include the failure of battery room cooling in the DC fault tree. If DC room cooling is required for DC success, the failure probability of the DC system could increase significantly, from 5E-6 (with no room cooling requirement) to 1E-4, while the cut sets are dominated by the failures of battery room cooling and operator actions.

ACKNOWLEDGMENTS

The authors wish to thank John C. Lane of the U.S. Nuclear Regulatory Commission (NRC) for his management support and technical inputs to this project. We also acknowledge Don Marksberry, Gary Wang and Steven Wessels for their contributions during the development of this document. Technical support from Robert Buell and other analysts of Idaho National Laboratory (INL) is greatly appreciated.

ACRONYMS

AAC	alternate AC
AC	alternating current
CCF	common cause failure
DC	direct current
EIIS	Energy Industry Identification System
EDG	emergency diesel generator
ESF	engineered safety feature
ESLD	electrical single line diagrams
FV	Fussell-Vesely
ICES	INPO Consolidated Event System
IDCCS	Integrated Data Collection and Coding System
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
LOOP	loss of offsite power
MCC	motor control center
MDP	motor driven pump
MOV	motor operated valve
NRC	U.S. Nuclear Regulatory Commission
NROD	NRC Reactor Operating Experience Data
PRA	probabilistic risk assessment
RADS	Reliability and Availability Data System
RIR	risk increase ratio
SBO	station blackout
SPAR	standardized plant analysis risk
SQL	structured query language
UAT	unit auxiliary transformer

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1. INTRODUCTION

1.1 Background

In commercial nuclear power plants, the electrical power system is designed to provide a diversity of reliable power sources to plant equipment. The reliability of the on-site electrical system is very important for operating a nuclear power plant safely. General Design Criteria 17 requires that the on-site electrical power sources (including the batteries) and electrical distribution system must have sufficient independence, redundancy and testability to perform their safety function assuming a single failure.

The electrical distribution system in a nuclear power plant could be broadly divided into two subsystems: Class 1E systems and Non-Class 1E systems. The AC Class 1E systems are responsible for providing reliable and redundant power supply to Class 1E subsystems, equipment, and components. The AC Non-Class 1E systems are responsible for providing reliable and redundant power supply to Non-Class 1E subsystems, equipment, and components. In addition to AC Class 1E and Non-Class 1E classification, the plant electrical distribution system also includes the DC electrical system for Class 1E and Non-Class 1E to provide reliable and redundant power supply for control circuits, instrumentation and operation of DC equipment and components.

The U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES), Division of Risk Analysis (DRA) has contracted Idaho National laboratory (INL) to perform a new engineering study for on-site electrical system performance of U.S. commercial nuclear power plants. The study contains aspects of individual component studies and system studies, including the development of system fault trees, as appropriate. The component studies are focused on key electrical components that have data available in the Integrated Data Collection and Coding System (IDCCS), such as circuit breakers, batteries, and battery chargers, as well as those that require new data such as transformers, AC buses, and DC buses. Data from the range of 1998 to 2015 were gathered, reviewed, and statistically evaluated for impacts on reliability as a function of relevant parameters: manufacturer, system, operating environment, inspection/testing regimen, operating range (voltages, amperes), setpoints, and other factors. The system studies develop detailed fault tree models for electrical system reliability and use the reliability data obtained from the component studies.

This study selected the designs that were representative of operating nuclear power plants in the United States based on the classification scheme provided below, which proposed three main categories to classify the design of offsite power systems and interconnecting power circuit paths.

- Category I addressed independence of offsite power sources to the NPP.
- Category II classified the power sources for the Class 1E buses during normal operation (i.e., main generator or offsite source). Two subcategories were included:
    - Subcategory II.1 − During normal operation, the Class 1E buses are supplied by the main generator through a unit transformer so that the circuit from the main generator to the Class 1E system is normally closed.
    - Subcategory II.2 − During normal operation the Class 1E power is supplied by a preferred off-site power source so that the circuit from the 230-kV switchyard to the Class 1E buses are normally closed.
- Category III classifies the automatic or manual transfer schemes for the Class 1E buses when both the normal and the backup sources of offsite AC power fail.

- Subcategory III.1 − If the normal source of AC power fails, there are no automatic transfers and one or more manual transfers to preferred or alternate off-site power sources. Normally open, manually operated circuits to the Class 1E buses are representative of this design feature.
- Subcategory III.2 − If the normal source of AC power fails, there is one automatic transfer but no manual transfers to preferred or alternate offsite power sources.
- Subcategory III.3 − After loss of the normal AC power source, there is one automatic transfer. If this source fails, there may be one or more manual transfers of power sources to preferred or alternate off-site power sources.
- Subcategory III.4 − If the normal source of AC power fails, there is an automatic transfer to a preferred source of power. If this preferred source of power fails, there is an automatic transfer to another source of off-site power.

Seven designs were identified with combinations of subcategories within Categories II and III (Category I was not used due to lesser importance to the objectives). The study then developed electrical single line diagrams (ESLDs) for the representative designs based upon the Updated Safety Analysis Reports. The equipment reliability was evaluated and detailed fault tree models were developed to calculate the frequency of loss of electrical supply to the Class 1E buses.

Seven nuclear plants were chosen to represent the seven designs identified above. ESLDs were developed with the best available plant information. Detailed fault tree models were developed with the updated equipment reliability data to calculate the failure probabilities of Class 1E buses. The DG, DC Class 1E system, and support systems to the Class 1E busses, such as cooling systems and ventilating systems, are included in the developed fault tree models for this INL study.

1.2 Scope of Study

This study includes both individual electrical component studies and electrical system studies.

- The component studies are focused on key electrical components that have data available in IDCCS, such as circuit breakers, batteries, and battery chargers, as well as those for which new data need be added to IDCCS, such as transformers, AC buses, and DC buses. Data from the range of 1998 to 2015 were gathered, reviewed, and statistically evaluated for impacts on reliability as a function of relevant parameters: manufacturer, system, operating environment, inspection/testing regimen, operating range (voltages, amperes), setpoints, and other factors.
- The system studies are focused on Class 1E electrical systems, specifically, the Class 1E 4.16 kV AC buses and the Class 1E DC batteries. Operating nuclear power plants in the U.S. are categorized by their design of offsite power systems and interconnecting power circuit paths. One plant is selected as representative for each category. Existing SPAR models for selected plants are used in the study. The fault tree models for Class 1E 4.16 kV AC buses and Class 1E DC batteries in SPAR are revised by adding new logic and incorporating the component study results. The system study results provide an understanding of the contributions from key components to electrical system unreliability.

The system reliability study performed in this study has the following assumptions:

1. The plant is operating normally at 100% power.
2. The reliability of offsite power sources is not evaluated. However, with the recognition that the loss of offsite power (LOOP) is a major risk contributor to the loss of electrical power and core damage, two scenarios are considered in the system reliability evaluation: Normal and LOOP. In the Normal scenario, the supply from all offsite sources is assumed to be reliable. In the LOOP scenario, all

"regular" offsite power sources (i.e., the normal offsite power supply to the Class 1E buses) are assumed to be unavailable.

3. Individual Class 1E 4.16 kV AC bus failure is used as the top event of fault tree model and the surrogate of the electrical system unreliability.
4. The Class 1E buses feed many major and minor loads. Short circuits in the major or minor loads are not considered in this study due to lack of data.
5. Diesel generators, along with support systems, are included in the fault tree models to provide supply to Class 1E 4.16 kV AC buses when offsite power is lost. Existing SPAR modeling of DGs is used in the study.
6. The support systems to the Class 1E AC buses such as the cooling systems, ventilating systems, and Class 1E DC system are included in the Class 1E electrical system fault tree models. Existing SPAR modeling of these support systems is used in the study.
7. Circuit breakers are modeled by the following failure modes: Fail to Open, Fail to Close, Fail to Remain Closed, Common Cause Failure (CCF) to Open or Close. CCF of spurious operation is not modeled as it is estimated to be orders of magnitude lower in risk than the CCF to open or close.
8. DC power to the circuit breakers is modeled assuming that the DC supplies are the same as those that supply the Class 1E buses.
9. There is some variability from model to model in the details for these systems.
10. Transformers are modeled as well as the CCF of similar transformers.
11. Operator actions are modeled for manual transfers, crossties, etc. The Sequencer logic was updated with recent data. LOOP logic was modeled with its associated house events.

1.3 Outlines

The remainder of this report is arranged as follows. Section 2 describes the on-site electrical system and the scope of the study. Section 3 provides the unreliability data analysis on key electrical components: circuit breakers, battery chargers, buses, batteries, and transformers. Section 4 provides the electrical system analysis on selected nuclear power plants. Section 5 provides the summary and major findings.

2. SYSTEM DESCRIPTION

The electric power system of a nuclear power plant is designed to provide a diversity of dependable power sources to plant systems. It includes offsite power system and onsite power system. The plant receives power from two or more separate offsite sources. The offsite power system provides reliable facilities to accept the electrical output of the plant as well as provide offsite power to plant auxiliary power system for station startup, shutdown, and when auxiliary power is unavailable from the unit auxiliary transformers. The onsite power systems (AC and DC) are designed with redundancy and independence to provide reliable power supply to both safety-related and non-safety-related electrical loads for all modes of plant operation. In the event of total loss of power from offsite sources, auxiliary power is supplied from emergency diesel generators (EDG) located on the site. In the event that all offsite and diesel generator sources of power are unavailable, i.e., station blackout, an alternate, non-safety-related AC source maybe available in many plants to provide power supply. The design features and configurations of electric power systems vary among plants. This section presents a generic description of the system; Section 4 provides characteristic categorizations and detailed descriptions for the plants representing each category.

2.1 Offsite Power System

The offsite power system provides reliable facilities to accept the electrical output of the plant as well as provide offsite power to the plant auxiliary power system for station startup, shutdown, and when auxiliary power is unavailable from the unit auxiliary transformers. The plant receives power from two or more separate offsite sources.

2.1.1 Switchyard

The switchyard (230 kV, 345 kV, or 500 kV) provides switching capability for main generator output, startup transformers, and outgoing transmission lines. It may also provide switching capability for the main generator output of the other unit and additional startup transformers if it is a multi-unit site. The switchyard includes two full capacity main buses that are tied to the main generator, startup transformers and outgoing transmission lines through circuit breakers connected to each bus. There are protective features that provide reliable protection for isolation of faults to ensure continuity of power supply from alternate sources.

2.1.2 Main Generator

The main generator provides electric power generated at the station to the offsite transmission network after main transformers step up the voltage. In an example plant, the main generator produces power at 22 kV. The main transformer steps it up to 230 kV which then connects to one bay of the outdoor switchyard consisting of circuit breakers, disconnect switches, buses, and associated equipment. The main transformer is provided with lightning arresters on the high voltage side.

2.1.3 Startup Transformers

Auxiliary power is supplied from startup transformers for plant startup and shut down. The startup transformers have sufficient capacity to accommodate the auxiliary power requirements of the unit under plant normal operating or accident conditions. The startup transformers in some plants have double winding with 6.9 kV secondary and 4.16 kV secondary.

2.2 Onsite Power System

The onsite electrical power systems (AC and DC) are designed with redundancy and independence to provide reliable power supply to both safety-related and non-safety-related electrical loads for all modes of plant operation. The onsite electrical power systems could be broadly divided into two subsystems: Class 1E systems and Non-Class 1E systems. The AC Class 1E systems are responsible for providing reliable and redundant power supply to Class 1E subsystems, equipment, and components. The AC Non-Class 1E systems are responsible for providing reliable and redundant power supply to Non-Class 1E subsystems, equipment, and components. In addition to AC Class 1E and Non-Class 1E power systems, the plant electrical distribution system also includes the DC power systems (Class 1E and Non-Class 1E) to provide reliable and redundant power supply for control circuits, instrumentation and operation of DC equipment and components.

2.2.1 AC Power System

2.2.1.1 Power Source

The normal source of auxiliary AC power for plant startup or shutdown is from the offsite transmission lines through the plant switchyard and startup transformers. The startup transformers step down the offsite power voltage from 230 kV (or 345 kV, 500 kV) to 6.9 kV and 4.16 kV. During normal plant operation, AC power is provided from the main generator through the unit auxiliary transformers. The unit auxiliary transformers step down the main generator output voltage from 22 kV to 6.9 kV and 4.16 kV. Normal transfer of the 6.9 kV or 4.16 kV auxiliary buses between the startup and unit auxiliary transformers is initiated by the operator from the control room, while emergency transfer between the transformers may be initiated manually or automatically by protective relay action.

Bus transfer in a unit could be either “live bus” or “fast-dead” transfer. In a “live bus” transfer, the incoming source feeder circuit breaker will be momentarily paralleled with the running source feeder circuit breaker, which results in transfers without power interruption. In a “fast-dead” transfer, the auxiliary transformer secondary circuit breaker is simultaneously tripped along with the closing of the startup transformer secondary breaker. There is a dead bus time of about 3 cycle duration.

In the event of a complete loss of the normal offsite power sources, i.e., Loss of Offsite Power (LOOP), the AC power system will be supplied by the onsite emergency diesel generators and station batteries.

In the event that all offsite and onsite power sources fail, i.e., Station Blackout (SBO), many plants may utilize an alternate AC source or SBO cross tie for multi-unit sites to provide power supply.

Each of the startup and unit auxiliary transformers and each emergency diesel generator has sufficient capacity to supply the safety-related loads for safe plant shutdown and mitigate the consequences of a design basis accident.

All power sources and loads for safety-related equipment are controlled from the control room, with control power supplied by either 125 V DC or 120 V AC.

2.2.1.2 6.9 kV AC Power System

The 6.9 kV AC power system is a Non-Class 1E system as it provides power to non-safety-related equipment such as reactor coolant pumps and steam generator feed water pumps. The 6.9 kV buses are supplied from unit auxiliary or startup transformer.

2.2.1.3 4.16 kV AC Power System

The 4.16 kV AC power system consists of Class 1E and Non-Class 1E buses. The Non-Class 1E buses provide power to loads which are non-safety related. The 4.16 kV Class 1E buses are the source of power for the Class 1E electrical loads which are backed up by two EDGs in the event of loss of the offsite power supply and main generators. The safety-related portion of the 4.16 kV power system is arranged into two redundant load groups (A and B). Each of the load groups consists of safety-related equipment needed to achieve safe plant shutdown or to mitigate the consequences of a design basis accident. Some plants may have an additional "swing" load group AB which consists of equipment which can be used as back-up or replacement to the equipment in the main load groups A or B. The 4.16 kV power is reduced to 480 and 120 volts for distribution to smaller loads and instrument and control power systems. The typical loads supplied directly by the 4.16 kV power system are listed below:

- Component cooling water pumps
- Residual heat removal pump
- Auxiliary feed water motor driven pump
- Safety injection pump
- Nuclear service cooling water pumps
- Containment spray pump
- Chemical volume and control system centrifugal charging pump
- Auxiliary component cooling water pump
- Control building ESF chiller
- 480 V Class 1E buses
- 480 V Non-Class 1E buses

2.2.1.4 480 Volts AC Power System

The 480 V AC power system also consists of Class 1E and Non-Class 1E buses, which are powered by 4.16 kV Class 1E and Non-Class 1E buses, respectively, through station service transformers. The 480 V AC power system distributes power to the Class 1E and Non-Class 1E 480 V loads. It also supplies power to the 125 V DC systems through battery chargers, and to the 120 V instrument AC power systems through regulated transformers. The 480 V buses supply power either directly to motors or to 480 V motor control centers (MCCs) which provide power to smaller motors.

2.2.1.5 120/208 Volts AC Power System

The 120/208 V AV power system consists of distribution panels and transformers fed from 480 volt MCCs. It supplies power to normal lighting and other plant loads requiring an unregulated power supply. For 120 volt panels that feed safety-related loads such as engineered safety feature process monitoring instrumentation, the stepdown transformer is fed from an emergency MCC and a Class 1E power panel. Safety-related loads (and some non-safety-related loads) are connected to these panels.

2.2.1.6 Instrument Power Supply System

The instrument power supply system consists of four redundant 120 V AC buses that provide power to essential instrumentation and control loads under all operating conditions. Each bus is supplied separately from an inverter connected to one of the two Class 1E 125 V DC buses. Each of the four redundant measurement channels of the nuclear instrumentation and reactor protective systems equipment is supplied from a separate bus of the four 120 V AC buses. Also, each instrumentation channel of the four measurement channels of the engineered safety features actuation system is supplied from a separate bus of the four 120 V AC buses.

Meanwhile, a separate 120 V vital AC system, consisting of a distribution panel, is provided to supply non-emergency instrumentation and control power. The panel is powered by a static uninterruptible power supply which is fed either from the common emergency MCC or the common DC bus.

2.2.1.7 Standby AC Power Supply

The standby AC power supply consists of two redundant diesel generator sets, the air starting and fuel supply system, and automatic control circuitry. The diesel generator sets supply power to those electrical loads which are needed to achieve safe shutdown of the plant or to mitigate the consequences of a LOCA in the event of a coincident loss of offsite power sources. The diesel generator sets are started by the air starting systems which include the air receivers, which have sufficient air charge for starting a cold diesel generator set, and air compressors, which provide charging air to the air receivers. The fuel supply system includes diesel oil day tanks, the oil storage tanks, and the oil transfer pumps. The capacity of the oil storage tanks allows for at least 7 days of post-LOCA load profile operation of one diesel generator set.

The diesel generator sets will start upon the loss of/degraded voltage in the Class 1E 4.16 kV buses and/or actuation of safety injection actuation signal. After each diesel generator set has attained normal frequency and voltage, if normal AC power has been lost, the breaker will close and the diesel generator is connected to the Class 1E 4.16 kV buses to start loading sequentially. The loading sequence is arranged to provide power to engineered safety feature components required in the event of a design basis accident. If normal AC power is not lost, the diesel generator breaker will not close and the set remain at full frequency and voltage until shut down manually. Each diesel generator can be manually started or stopped both locally and from the control room.

2.2.2 DC Power System

The DC power system provides reliable and continuous 125 V DC power for plant control, instrumentation, and DC motor operated equipment such as valve operators and emergency lube oil pumps. The Class 1E 125 V DC system is arranged into two main redundant load groups A and B. Load groups A and B are served by Class 1E 125 V DC buses and are capable of supply the minimum DC power requirements to safety shut down the plant and mitigate the consequences of a LOCA event. The 125 V DC buses are supplied by their corresponding battery chargers which are sized to carry normal DC load and to recharge the batteries. The Non-Class 1E 125 V DC system consists of non-safety-related batteries and DC buses that supplies non-safety-related loads such as the turbine generator DC emergency pump motors, as well as the uninterruptible power supplies during a loss of offsite power.

Two separate DC systems are provided for the 230 kV switchyard oil circuit breakers, and control and protective relaying. The systems consist of 125 V batteries, battery chargers, and DC distribution panels.

3. COMPONENT UNRELIABILITY DATA ANALYSIS

Data analysis of the failure event data for key components in the AC and DC electrical power systems consisted of a detailed analysis of power distribution circuit breakers, battery chargers, buses, batteries, and transformers. Results from that effort are provided in this section. There are data available for circuit breakers, batteries, and battery chargers in IDCCS. For buses and transformers, new data was added to IDCCS. Data from the range of 1998 to 2015 were gathered, reviewed, and statistically evaluated for impacts on reliability as a function of relevant parameters: manufacturer, system, operating environment, inspection/testing regimen, operating range (voltages, amperes), setpoints, and other factors.

The initial work involved data collection and coding for components that have no failure data in IDCCS. Proprietary failure data for transformers for calendar years 2005 through 2015 from the Institute of Nuclear Power Operations (INPO) Consolidated Event System (ICES) were reviewed and coded. This provided quality-reviewed data for use by the IDCCS and the NRC Reliability and Availability Data System (RADS). Based on initial AC and DC system fault tree analysis, AC and DC electrical buses were added to the list of components for which ICES failure data is reviewed. ICES failure data for buses for calendar years 2006 through 2015 were reviewed and coded. Similar quality-reviewed data for calendar years 1998 through 2015 was already available in IDCCS for AC power distribution system circuit breakers, DC power system chargers, and DC power system batteries.

Failure rate data was obtained from proprietary information contained in the RADS reliability calculator. In order to look more thoroughly for common threads within the failures, data was queried using structured query language (SQL) directly from the IDCCS database that supports the reliability rules. This database provides information such as in-service date, manufacturer, component subtype, normal operating state, and the system in which the component resides.

The Institute for Electronical and Electronics Engineers (IEEE) developed the Energy Industry Identification Systems (EIIS) to provides a single source of unique identification for systems, structures, and components for power generation [IEEE Std 805-1984, withdrawn]. The system descriptions concentrate on system function and include such internal details as necessary to clearly support the system function description. A list of the EIIS system codes relevant to this study is given in Table 1.

The results presented below summarize the patterns in failure data for circuit breakers, battery chargers, buses, batteries, and transformers. Records are tabulated by component age, manufacturer, and EIIS system code. Additional tabulations are presented where they are relevant. For each component, Empirical Bayes analysis (Atwood et al., 2003) and trending by year were performed for the primary failure modes. In the trending analysis, the p-value is used to define whether a trend is statistically significant or not. 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 there is a 95% confidence that there is a trend in the data (reject the null hypothesis of no trend.) By convention, this study uses the "Michelin Guide" scale: p-value < 0.05 (statistically significant), p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant). An overview of the trending methods can be found in the Overview and Reference document (NRC, 2012) on the Reactor Operational Experience Results and Databases web page (http://nrcoe.inl.gov/resultsdb).

Table 1. EIIS System Codes relevant to this study

Code	Description
AA	Control Rod Drive System
AB	Reactor Coolant System
BB	Containment Combustible Gas Control System
BG	High-Pressure Core Spray System
BI	Essential Service Water System

BK	Containment Fan Cooling System (PWR)
DC	Diesel Fuel Oil System
EA	Medium-Voltage Power System (601V through 35 kV)
EB	Medium Voltage Power System-Class 1E
EC	Low Voltage Power System (600-V and less)
ED	Low Voltage Power System-Class 1E
EE	Instrument and Uninterruptible Power System
EF	Instrument and Uninterruptible Power System—Class 1E
EI	DC Power System
EJ	DC Power System-Class 1E
EK	Emergency Onsite Power Supply System
EL	Main Generator Output Power System
FH	Emergency DC Lighting System
FI	Communications System
FK	Switchyard System
JA	Integrated Control System
JC	Plant Protection System
JD	Reactor Power Control System
LA	Diesel Lube Oil System
LD	Instrument Air Supply System
NB	Emergency Onsite Power Supply Building
NC	Emergency Operations Facility (Offsite)
SB	Main/Reheat Steam System
TB	Main Generator System
TL	Main Generator Excitation System
UA	Pumping Station Environmental Control System
VF	Auxiliary Building Environmental Control System
XG	Switchyard
XT	Unknown

3.1 Circuit Breakers

3.1.1 Scope

This section focuses on circuit breaker failures reported during 1998-2015 at U.S. commercial nuclear power plants. This study is limited to circuit breakers within the power distribution system; reactor trip breakers and Emergency Diesel Generator Output Breakers were not considered.

The data used in this study are associated with the failure records that have circuit breaker as the "component" type in the database. There are significant numbers of failure records in which the circuit breaker is coded as "subcomponent" or "piecepart" of other "component" types such as EDG or motor operated valve (MOV). For example, a search of the NRC Reactor Operating Experience Data's (NROD) proprietary records found that there are 262 records from 1998 through June 2016 where the subcomponent is Breaker, AC Breaker, or DC Breaker. These records were not used in this study. (Note that not all of the associated reports contain the component ID for the breaker itself). Similarly, there are 687 records in the same time period where the piecepart is Circuit Breaker or Breaker. These were not included in the results either. Table 2 provides four examples of failure records for circuit breakers as a subcomponent or piecepart of a larger component.

Table 2. Examples of failed circuit breakers that were listed as a subcomponent or piecepart

Component	Subcomponent	Piecepart	Explanation
Blower	Breaker 300-699 VAC		Failure of light bulb/socket in Low Voltage Power System (600-V and less) circuit breaker that supports Instrument Air Supply System rotary vane compressor 2SAS-C21A. Caused a failure to close in the breaker.
EDG	Breaker (4,000-5,999 VAC)		AP-913 high critical component failure and MSPI monitored component failure due to failure of contact(s) in EDG Output Circuit Breaker that supports EDG 1DG01KB.
Centrifugal Pump	Driver	Breaker 4,000-5,999 VAC	Failure of electrical termination (lug/connector) in RHR Pump Motor Circuit Breaker that supports RHR Pump P34A.
Motor Operated Valve	Actuator	Breaker 300-699 VAC	Failure of Reactor Pressurizer PORV Block Valve Circuit Breaker that supports Reactor Pressurizer PORV Block Valve HCV-151.

A review of the failed circuit breakers listed as piecepart found that more than 70% of them have motor-driven pump (MDP) as the component type, and 20% have MOV as the component type. For failed circuit breakers listed as subcomponent, about 50% of them have EDG as the component type, nearly 30% have battery charger as the component type, 20% have air compressor as the component type.

Only the data associated with the records that have circuit breaker as the "component" type are used in this study. The failure records associated with circuit breaker as subcomponent or piecepart are not used because:

- The "component" type in the database describes the equipment that fails and reflects operational system components that are normally modeled in probabilistic risk assessment (PRA), while the subcomponent and piecepart types are used to further identify which part of the component failed.
- Component boundary is a key part in data collection, classification, and analysis. For example, under the Circuit Breaker (CBK) Data Sheet of NUREG/CR-6928 (NRC, 2007), it states that

  The circuit breaker (CRB) is defined as the breaker itself and local instrumentation and control circuitry. The circuit breaker data presented here is limited to circuit breakers used in the distribution of power. Circuit breakers used to supply power to a specific load are included within that component's boundary.

Under the Motor-Driven Pump (MDP) Data Sheet, it states that

The motor-driven pump (MDP) boundary includes the pump, motor, local circuit breaker, local lubrication or cooling systems, and local instrumentation and control circuitry.

The above classifications would exclude double counting the failures of a local circuit breaker as a piecepart of MDP (or other components such as EDG, MOV) under the CRB component type.

- The failure modes in the failure records are associated with the component instead of subcomponent or piecepart. For example, MDP includes failure modes of FTS (fail to start) and FTR (fail to run), while CBK has failure modes of FTO/C (failure to open or failure to close) and SO (spurious operation). The failure records in the database with breaker as piecepart of MDP would have failure mode of FTS or FTR, rather than FTO/C or SO.

Circuit breakers were broken into three mutually exclusive groups for this analysis: all circuit breakers, medium voltage circuit breakers, and high voltage circuit breakers. The circuit breaker types included in each group are listed in Table 3. The value in parenthesis is the subtype label used in the SQL database. Analysis is based on the following failure modes: failure to open and close, and spurious operation.

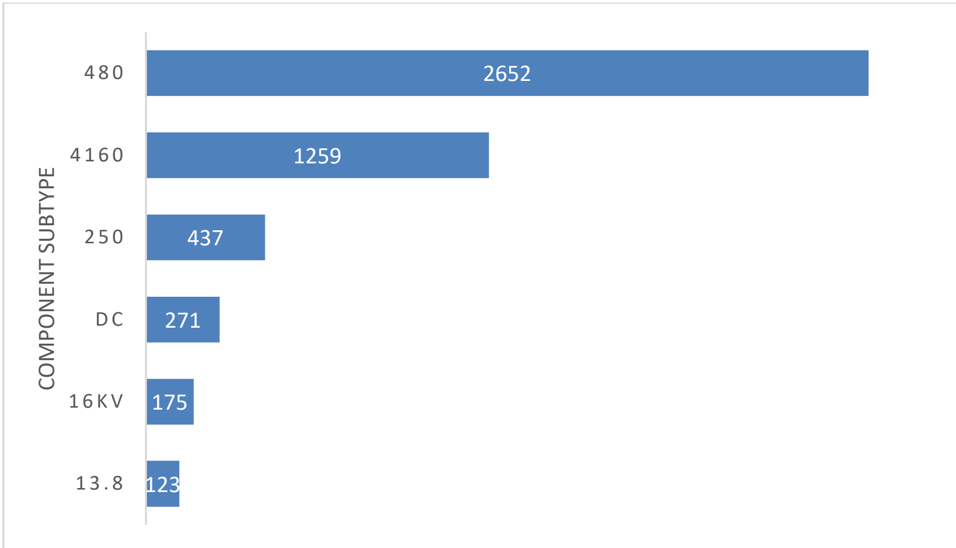
Table 3. Circuit breaker types included in the groups used for analysis

All	Medium Voltage	High Voltage
480 Volt (480)	4160-6900 Volt	13.8 kV
250V DC (250)		Greater than 16 kV
4160-6900 Volt (4160)		
DC Bus (DC)		
13.8 kV (13.8)		
Greater than 16 kV (16kV)		

Trend analyses were performed on the data from the 10 year period from 2006 to 2015. The analyses were performed using a general linear model based on a Poisson distribution with a log link function and an offset. This methodology is most applicable to failure rates associated with hours of usage but may also be used for failure rates that are associated with demands. This is justifiable because the demands are relatively high compared to the failures.

3.1.2 Breakdown of Failure Counts

The total number of failures recorded in the database for the circuit breakers in time frame under consideration is 579. Figure 1 shows the relative proportions of each breaker subtype in the population (top) and in the failure records (bottom). The circuit breaker population of interest was identified by looking at the individual device IDs being monitored for reliability on the RADS web site. It is interesting to note that the higher voltage breakers seem to have higher failure counts than might be expected based on their relative proportions in the population. This does not, of course, take into account the demands/hours that the breakers are in use.



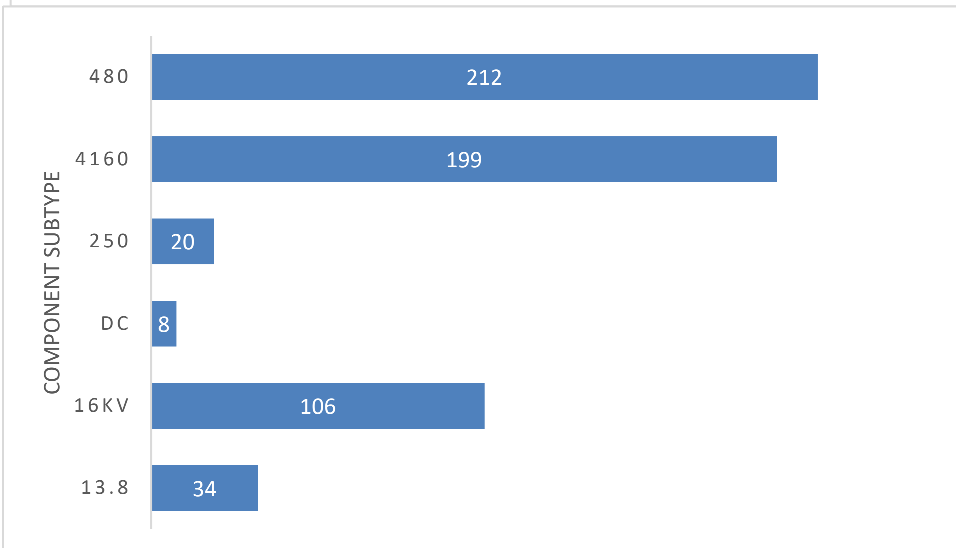


Figure 1. Breaker types studied (top) and number of failures by breaker type (bottom)

Table 4 lists three functional groupings of breaker subcomponents. Some failure records identify a component within the breaker that failed. Figure 2 shows the breaker subcomponent that failed.

Table 4. Breaker subcomponent categories used for analysis

Mechanical	I&C	Cubicle
Arc Chute	Control Switch	Aux. Contactor
Closing Coil	I&C	Latch Assembly
Limit Switch	Load Sequencer	Mechanical Assembly
Main Contacts	Logic Circuit	Wires--Connectors—Board Fuse
Miscellaneous	OC Relay	
Spring	Relay	
Spring Charging Motor	Shunt Trip	
Stabs – Connectors	Switch	
Unknown	UV Trip Assembly	
Various		

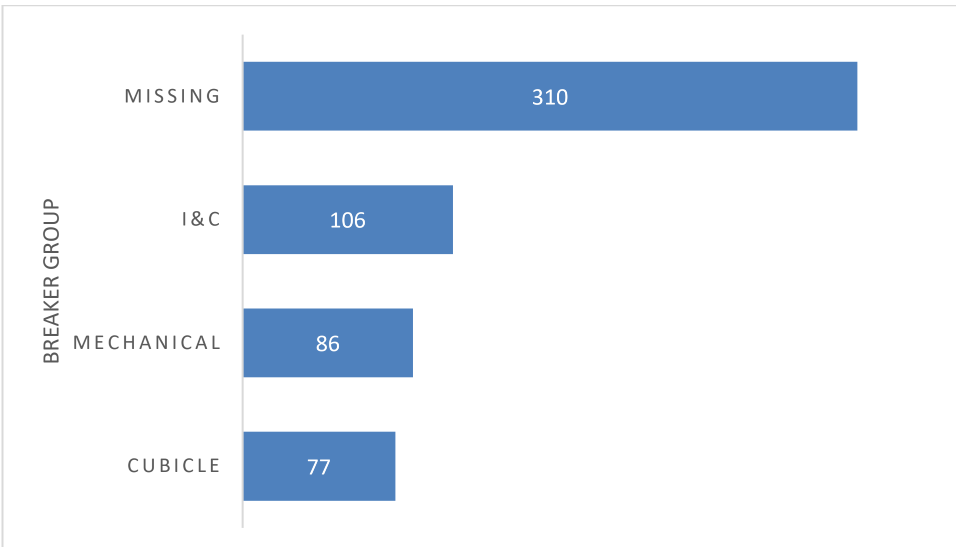


Figure 2. Failures of breakers by subcomponent

INPO 12-009 defines the normal operating state of each component by their status when the reactor is at 100% power (INPO, 2012):

- *Blank*—No status is provided.
- *Alternating Run Times*—The device alternates between standby and operating at steady state.
- *Closed*—Valve or circuit breaker is normally closed during plant operations.
- *Locked Closed*—The device is closed and padlocked to prevent inadvertent opening.
- *Locked Open*—The device is open and padlocked to prevent inadvertent closing.
- *Modulating*—This option refers to valves that are neither open nor closed continuously but are instrumented to change position depending on system operation. Modulating devices are typically operating continuously.
- *Off*—The device is normally in the off position during normal plant operations.
- *Open*—The valve or circuit breaker is normally open during plant operations.

- *Operating*—The device is normally running or operating at steady-state conditions.
- *Standby*—The device is normally idle but is aligned for automatic start or position change during abnormal plant conditions.

Circuit breaker failures were tabulated by breaker type and normal operating state in Table 5, and by breaker type and failure mode in Table 6. Note that Table 6 includes a special category of "IDCCS Not Applicable" which represents those failure records obtained from INPO ICES in which the exact failure modes could not be determined due to insufficient information.

All components have an in-service date listed that is used to calculate both current age (relative to January 1, 2016) and age at failure. The age distribution of currently active circuit breakers of interest (i.e., no out-of-service date was listed) is tabulated in Table 7 and graphed in Figure 3. Table 8 and Figure 4 show the number of failures by type of breaker and age, which is the physical age of the component at failure and does not take refurbishment into consideration. All failure records reported the age of the component.

Tabulations of all monitored circuit breakers of interest and of failures by EIIS system code are shown in Tables 9 and 10, respectively; the breakdown of failures can be seen graphically in Figures 5 and 6, respectively.

Circuit breakers of interest and of failures were also tabulated by manufacturer (Table 11 and Figure 7; and Table 12 and Figure 8). It should be noted that failure rates, especially for long-lived equipment in difficult working environments, are impacted significantly by the level of maintenance and repair received over its working life, so that care must be exercised in drawing conclusions based solely upon the manufacturer itself.

Table 5. Failure counts tabulated by type of breaker and normal operating state

	Component Subtype												Total	
	13.8		16kV		250		4160		480		DC			
Normal State	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Alternating run times	0	0	0	0	0	0	5	3	6	3	0	0	11	2
Closed	4	12	37	35	4	20	16	8	33	16	2	25	96	17
Locked closed	0	0	0	0	0	0	1	1	0	0	0	0	1	0
Locked open	0	0	0	0	0	0	2	1	0	0	0	0	2	0
Modulating	0	0	0	0	1	5	0	0	2	1	0	0	3	1
Not Reported	9	26	3	3	4	20	43	22	52	25	3	38	114	20
Open	0	0	0	0	0	0	11	6	5	2	0	0	16	3
Operating	19	56	55	52	7	35	89	45	91	43	2	25	263	45
Standby	2	6	11	10	4	20	32	16	23	11	1	13	73	13
Total	34	100	106	100	20	100	199	100	212	100	8	100	579	100

Table 6. Failure counts by type of breaker and failure mode

Failure Mode	Component Subtype												Total	
	13.8		16kV		250		4160		480		DC			
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Fail to Close	10	29	12	11	6	30	65	33	37	17	2	25	132	23
Fail to Open	1	3	4	4	1	5	16	8	28	13	0	0	50	9

Fail to Open/Close	0	0	1	1	0	0	11	6	18	8	2	25	32	6
Fail to Operate	0	0	0	0	1	5	6	3	5	2	0	0	12	2
IDCCS Not Applicable	17	50	57	54	5	25	42	21	44	21	0	0	165	28
Low p-value	1	3	3	3	1	5	5	3	7	3	0	0	17	3
Spurious Closing	1	3	0	0	0	0	2	1	0	0	0	0	3	1
Spurious Opening	0	0	14	13	0	0	9	5	31	15	1	13	55	9
Spurious Operation	0	0	1	1	2	10	8	4	7	3	0	0	18	3
UA (Maintenance)	2	6	12	11	4	20	34	17	34	16	3	38	89	15
UA (Other Comp)	2	6	2	2	0	0	1	1	1	0	0	0	6	1
Total	34	100	106	100	20	100	199	100	212	100	8	100	579	100

Table 7. Age of active circuit breakers of interest as of January 1, 2016

Age (years)	Component Subtype												Total	
	13.8		16kV		250		4160		480		DC			
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
<5	0	0	0	0	1	0	6	1	2	0	0	0	9	0
5-—10	2	2	5	3	9	2	7	1	10	0	1	0	34	1
10-–15	2	2	10	6	0	0	20	2	22	1	1	0	55	1
15-–20	4	4	78	48	19	4	137	12	180	7	12	4	430	9
20-–25	3	3	1	1	25	6	73	6	110	4	18	7	230	5
25-–30	63	57	9	6	186	44	185	16	286	11	133	49	862	18
30-–35	13	12	32	20	108	25	385	32	826	32	31	12	1395	29
35-–40	16	14	12	7	15	4	68	6	207	8	15	6	333	7
> 40	8	7	14	9	63	15	308	26	956	37	58	22	1407	30
Total	111	100	161	100	426	100	1189	100	2599	100	269	100	4755	100

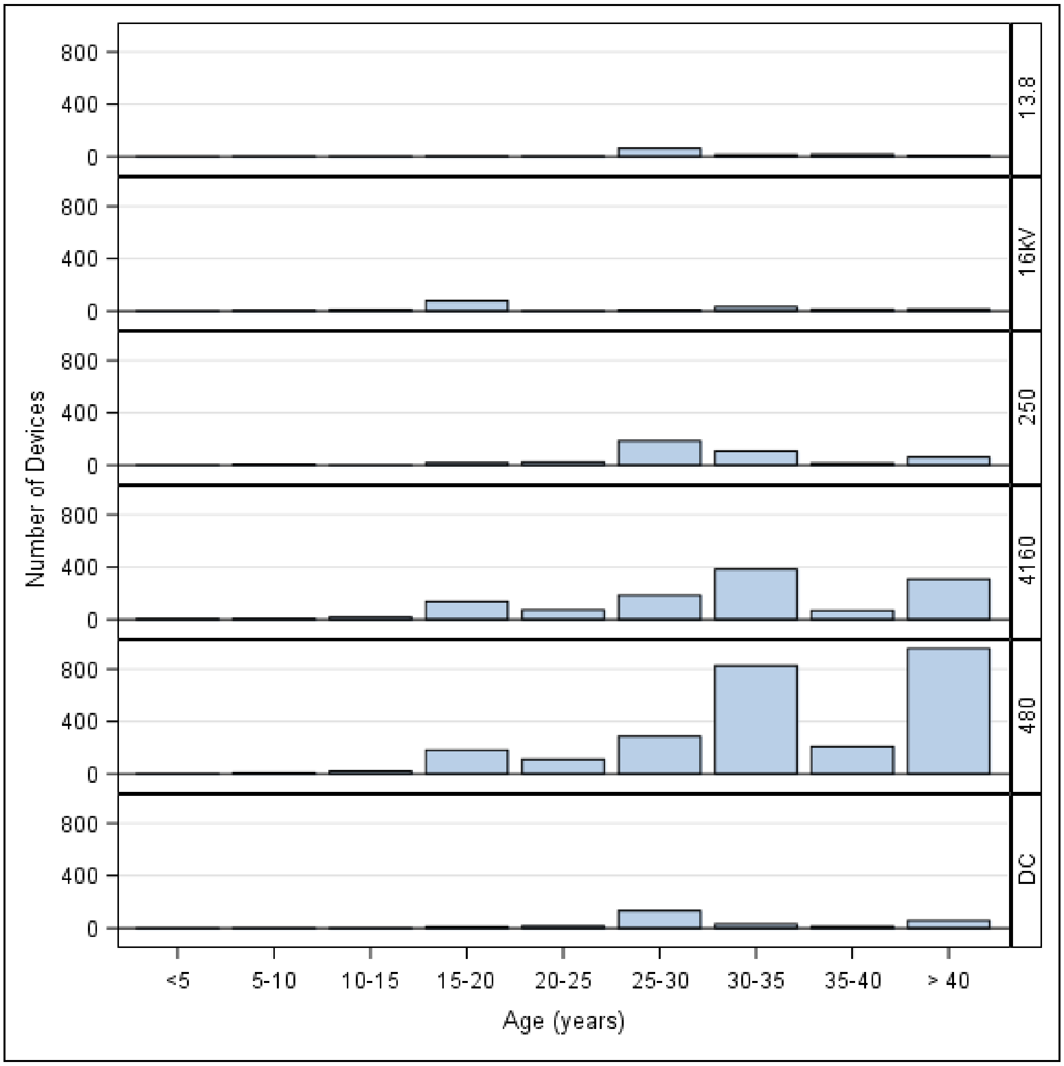


Figure 3. Age of active circuit breakers of interest

Table 8. Number of circuit breaker failures by age

Age (years)	Component Subtype												Total	
	13.8		16kV		250		4160		480		DC			
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
<5	0	0	0	0	1	5	2	1	0	0	0	0	3	1
5-–10	0	0	2	2	0	0	6	3	1	0	0	0	9	2
10-–15	2	6	6	6	0	0	7	4	4	2	0	0	19	3
15-–20	2	6	24	23	0	0	24	12	31	15	0	0	81	14
20-–25	0	0	1	1	2	10	23	12	23	11	1	13	50	9
25-–30	17	50	15	14	4	20	31	16	37	17	2	25	106	18
30-–35	4	12	26	25	4	20	34	17	31	15	2	25	101	17
35-–40	4	12	14	13	1	5	10	5	21	10	0	0	50	9
> 40	5	15	18	17	8	40	62	31	64	30	3	38	160	28
Total	34	100	106	100	20	100	199	100	212	100	8	100	579	100

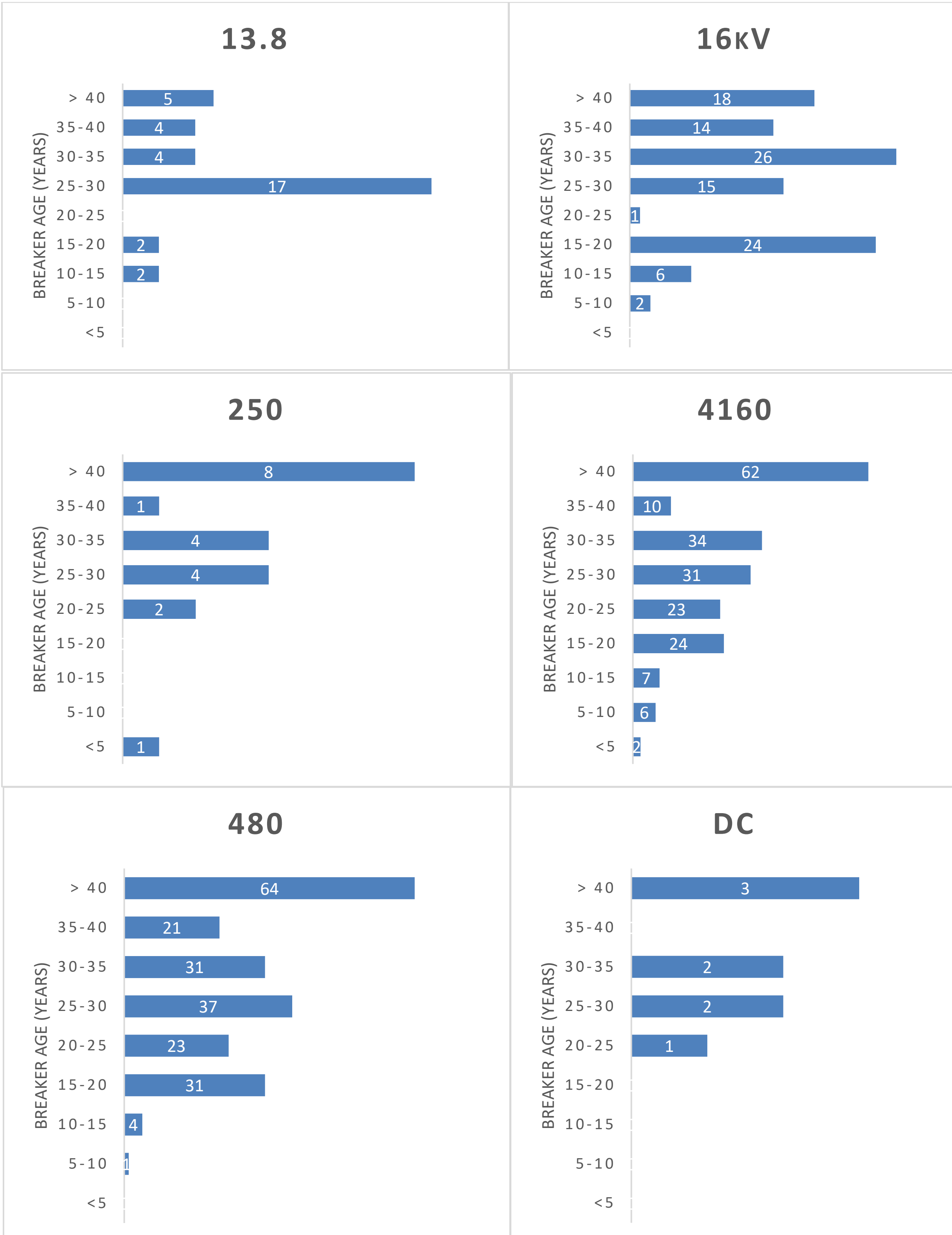


Figure 4. Failures of breakers by type of breaker and age

Table 9. Number of circuit breakers in this study by component subtype and by EIIS system code.

EIIS System Code	Component Subtype												Total	
	13.8		16kV		250		4160		480		DC			
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Missing	0	0	0	0	0	0	3	0	0	0	0	0	3	0
BI	0	0	0	0	0	0	0	0	7	0	0	0	7	0
EA	91	74	3	2	0	0	516	41	858	32	3	1	1471	30
EB	7	6	17	10	0	0	507	40	262	10	13	5	806	16
EC	12	10	3	2	0	0	61	5	554	21	3	1	633	13
ED	0	0	8	5	1	0	118	9	828	31	7	3	962	20
EI	0	0	0	0	220	50	0	0	7	0	162	60	389	8
EJ	0	0	0	0	215	49	0	0	107	4	82	30	404	8
EK	0	0	0	0	0	0	3	0	6	0	0	0	9	0
EL	13	11	3	2	0	0	51	4	10	0	0	0	77	2
FK	0	0	139	79	0	0	0	0	13	0	0	0	152	3
JC	0	0	0	0	0	0	0	0	0	0	1	0	1	0
UA	0	0	0	0	1	0	0	0	0	0	0	0	1	0
XG	0	0	2	1	0	0	0	0	0	0	0	0	2	0
Total	123	100	175	100	437	100	1259	100	2652	100	271	100	4917	100

Table 10. Circuit breaker failures by component subtype and by EIIS system code

	Component Subtype												Total	
	13.8		16kV		250		4160		480		DC			
EIIS System Code	N	%	N	%	N	%	N	%	N	%	N	%	N	%
EA	31	91	1	1	0	0	104	52	20	9	0	0	156	27
EB	0	0	4	4	0	0	80	40	29	14	0	0	113	20
EC	0	0	0	0	0	0	7	4	76	36	2	25	85	15
ED	0	0	6	6	1	5	2	1	79	37	0	0	88	15
EI	0	0	0	0	11	55	0	0	0	0	4	50	15	3
EJ	0	0	0	0	6	30	0	0	2	1	1	13	9	2
EK	0	0	0	0	0	0	1	1	2	1	0	0	3	1
EL	3	9	2	2	0	0	5	3	2	1	0	0	12	2
FK	0	0	90	85	0	0	0	0	2	1	0	0	92	16
JC	0	0	0	0	0	0	0	0	0	0	1	13	1	0
UA	0	0	0	0	2	10	0	0	0	0	0	0	2	0
XG	0	0	3	3	0	0	0	0	0	0	0	0	3	1
Total	34	100	106	100	20	100	199	100	212	100	8	100	579	100

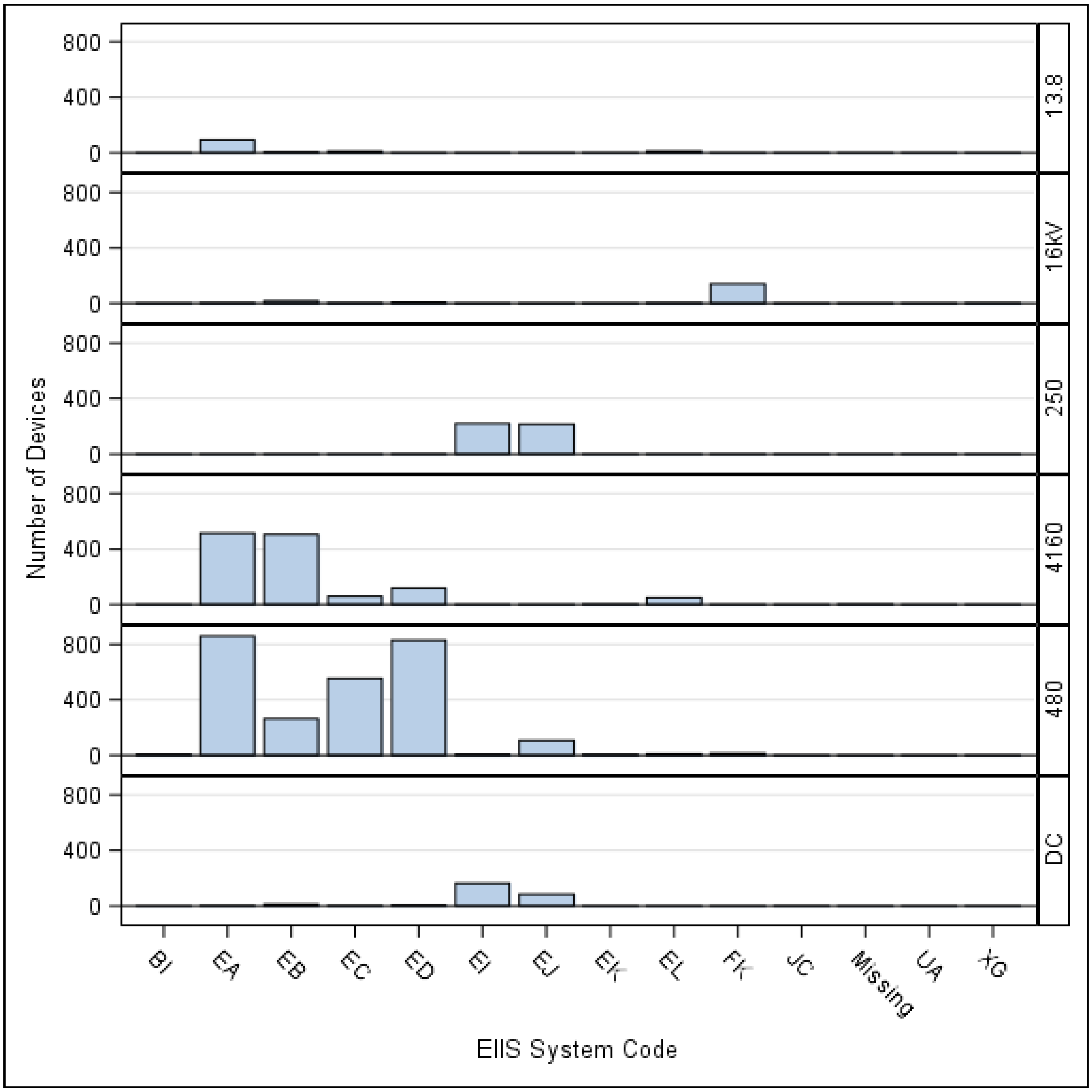


Figure 5. Number of circuit breakers of interest by component subtype and by EIIS system code

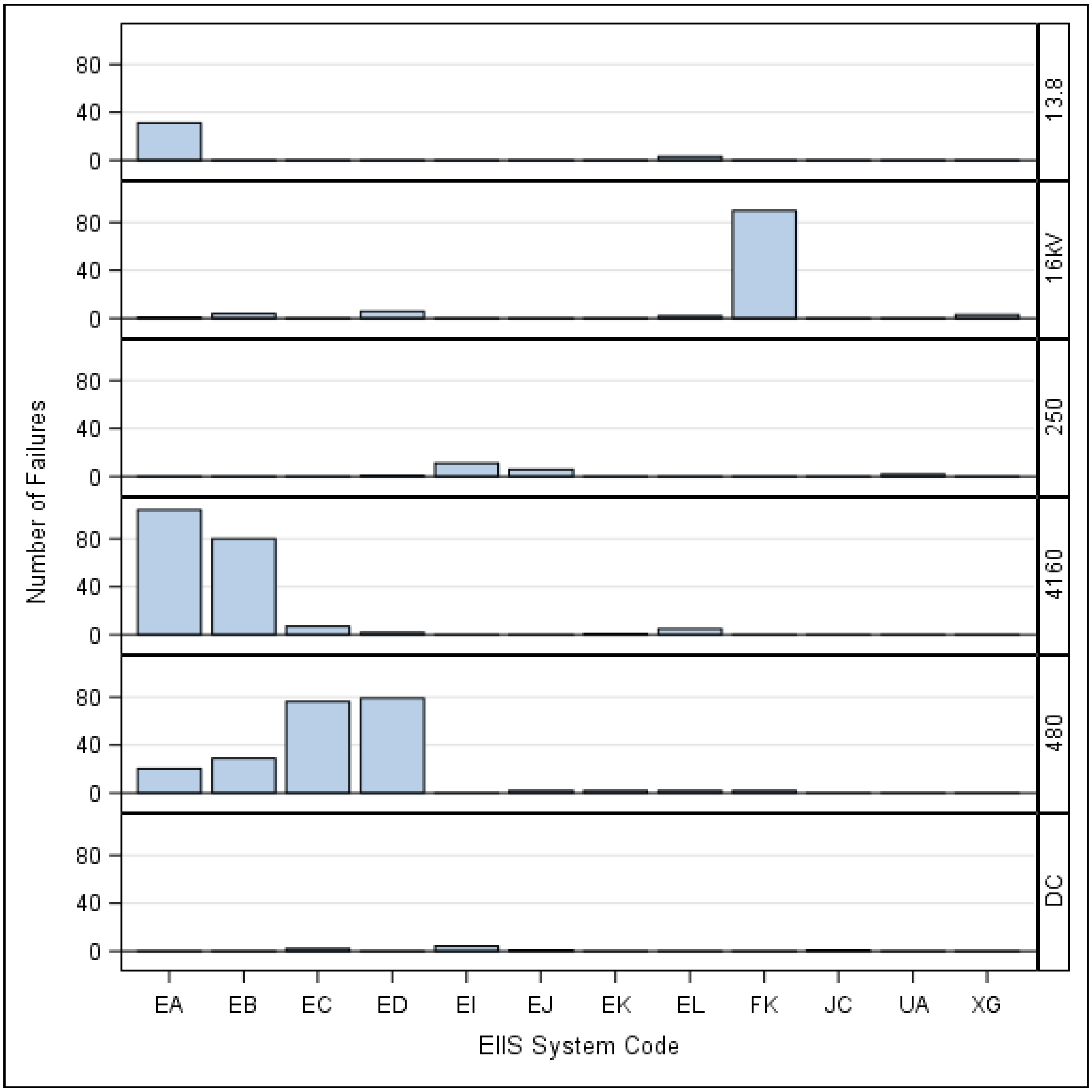


Figure 6. Circuit breaker failures by component subtype and EIIS system code

Table 11. Manufacturers of Breakers of Interest

Manufacturer	Component Subtype												Total	
	13.8		16kV		250		4160		480		DC			
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
ABB	16	13	26	15	56	13	480	38	574	22	16	6	1168	24
Eaton	1	1	4	2	7	2	1	0	48	2	0	0	61	1
GE	77	63	35	20	152	35	467	37	458	17	170	63	1359	28
Not Reported	0	0	32	18	103	24	61	5	443	17	0	0	639	13
Other	1	1	28	16	13	3	52	4	49	2	3	1	146	3
Siemens	0	0	10	6	0	0	27	2	4	0	0	0	41	1
Square D	0	0	0	0	2	0	12	1	440	17	15	6	469	10
Westinghouse	28	23	40	23	104	24	159	13	636	24	67	25	1034	21
Total	**123**	**100**	**175**	**100**	**437**	**100**	**1259**	**100**	**2652**	**100**	**271**	**100**	**4917**	**100**

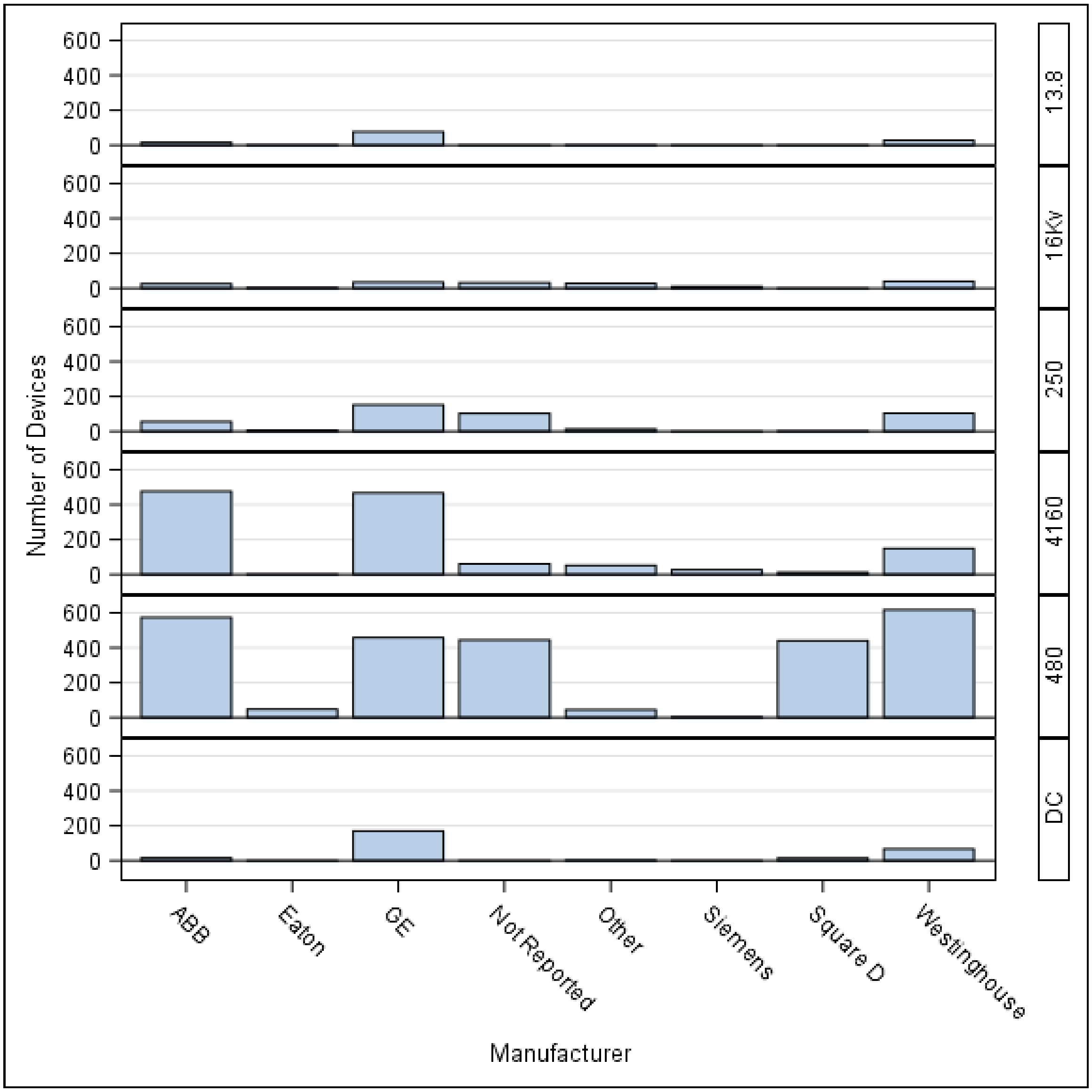


Figure 7. Circuit Breakers of Interest by Manufacturer.

Table 12. Circuit Breaker Failures by Manufacturer

Manufacturer	**Component Subtype**												**Total**	
	13.8		**16Kv**		**250**		**4160**		**480**		**DC**			
	N	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**
ABB	2	6	27	25	4	20	70	35	68	32	1	13	172	30
Eaton	2	6	4	4	2	10	4	2	3	1	0	0	15	3
GE	23	68	18	17	6	30	77	39	73	34	4	50	201	35
Not Reported	0	0	3	3	0	0	0	0	3	1	0	0	6	1
Other	1	3	28	26	1	5	9	5	12	6	1	13	52	9
Siemens	0	0	9	8	0	0	5	3	2	1	0	0	16	3
Square D	0	0	0	0	0	0	0	0	11	5	0	0	11	2
Westinghouse	6	18	17	16	7	35	34	17	40	19	2	25	106	18
Total	**34**	**100**	**106**	**100**	**20**	**100**	**199**	**100**	**212**	**100**	**8**	**100**	**579**	**100**

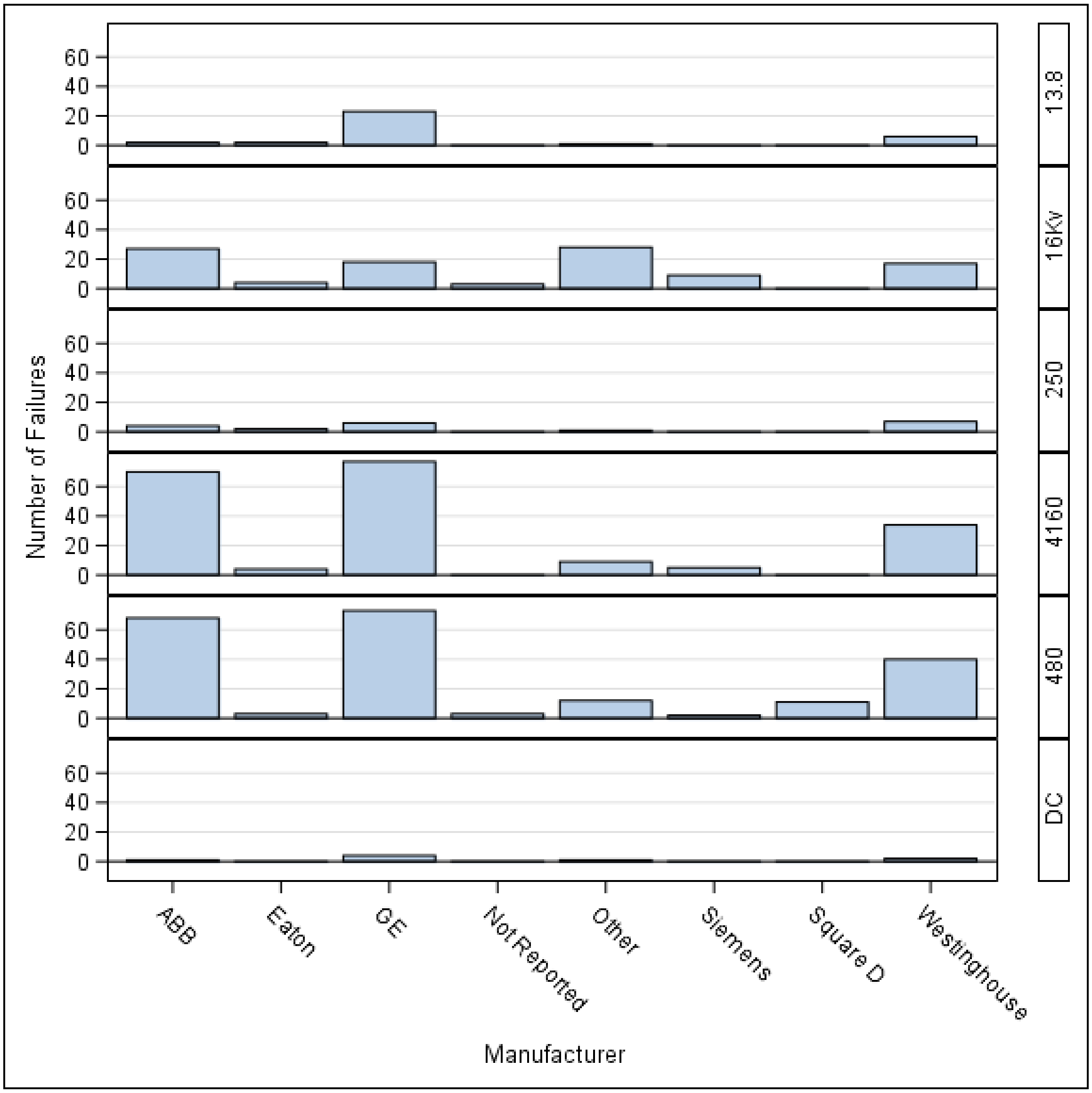


Figure 8. Circuit Breaker Failures by Manufacturer.

3.1.3 Analysis of Failure to Open/Close

The analysis for low-demand circuit breakers with failure modes of Fail to Open, Fail to Close, and Fail to Open/Close is based on the binomial model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates for each of the three groups of circuit breakers. The empirical Bayes method (Atwood et al., 2003) gives a model of the between-item variation that was found by the chi-squared test and includes a Kass-Steffey adjustment. Results are presented only for cases where the p-value for the Empirical Bayes Analysis indicates a statistically significant difference in plant rates.

Demand counts were queried from the RADS website, with 147,346 demands for all circuit breakers, 60,185 demands for medium voltage breakers, and 11,068 demands for high voltage breakers. The plants with the widest confidence intervals are generally associated with the lowest demand levels.

For each group of circuit breakers, multiple plants have significantly higher than average failure rates for Failure to Open/Close.

Trending analyses were performed on the failure rate data for each group of circuit breakers from the 10 year period from 2006 to 2015. Figure 9 to Figure 11 show the trends in the failure rate to open/close for the three groups of circuit breakers. Statistically significant decreasing trend was identified for the rate of high voltage circuit breakers failing to open/close, which has a p-value of 0.0417 (see Figure 11).

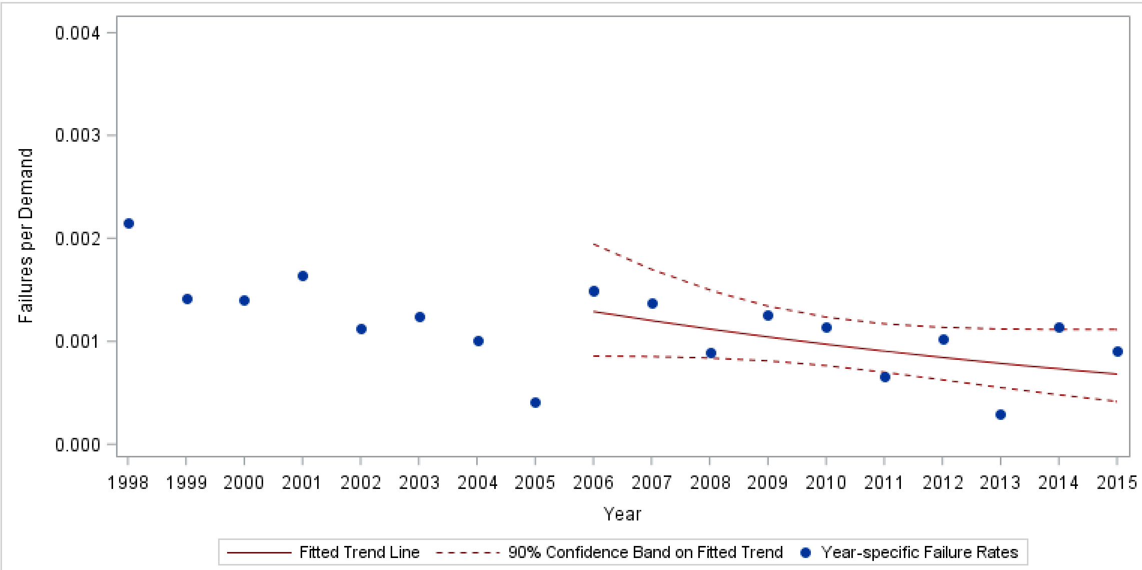


Figure 9. Ten year trend for rate of all circuit breakers failing to open/close (p=0.0707, no statistically significant trend)

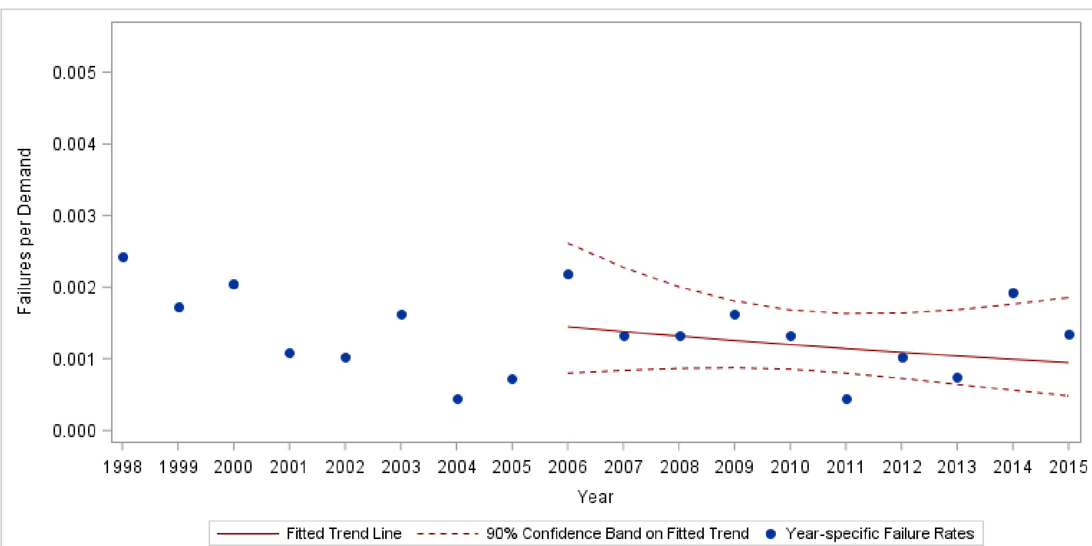


Figure 10. Ten year trend for rate of medium voltage circuit breakers failing to open/close (p=0.3936, no statistically significant trend)

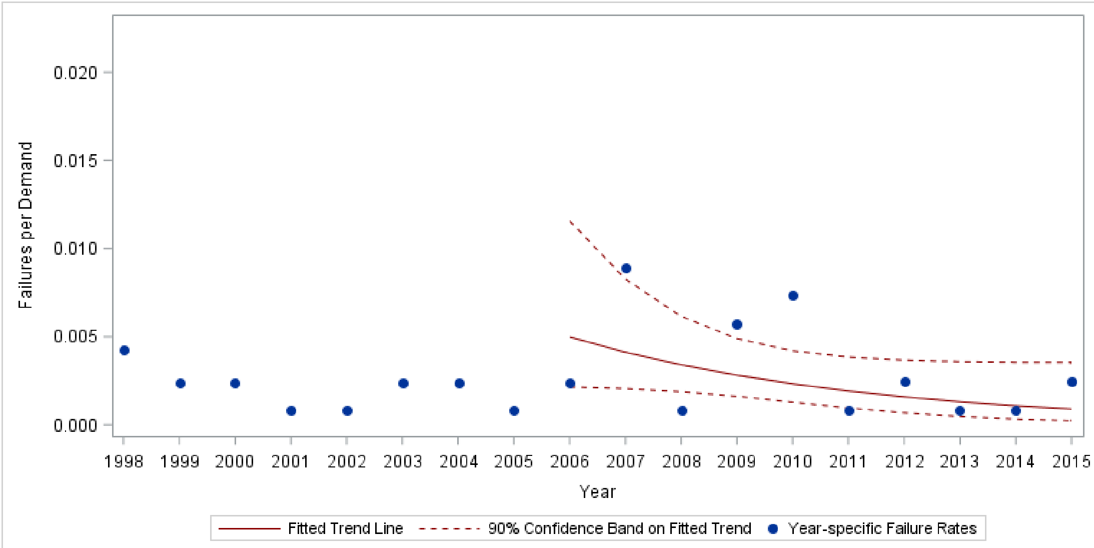


Figure 11. Ten year trend for rate of high voltage circuit breakers failing to open/close (p=0.0417, statistically significant decreasing trend)

3.1.4 Analysis of Spurious Operation

The analysis for circuit breakers with failure modes Spurious Opening, Spurious Closing, and Spurious Operation was based on the Poisson model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates for each of the three groups of circuit breakers. Exposure times were queried from the RADS website, with 738,957,543 hours for all circuit breakers, 184,876,076 hours for medium voltage breakers, and 43,105,711 hours for high voltage breakers. Multiple plants have significantly higher than average failure rates for Spurious Operation of all circuit breakers, and one plant has a significantly higher than average failure rate for Spurious Operation of high voltage circuit breakers. No plants have significantly higher than average failure rates for Spurious Operation of medium voltage circuit breakers.

Trending analyses were performed on the failure rate data for spurious operation for each group of circuit breakers for the 10 year period from 2006 to 2015. Figure 12 to Figure 14 show the trends in the rate of spurious operation for the three groups of circuit breakers. Statistically significant decreasing trend was identified for the rate of spurious operation for all circuit breakers, which has a p-value of 0.0446 (Figure 12).

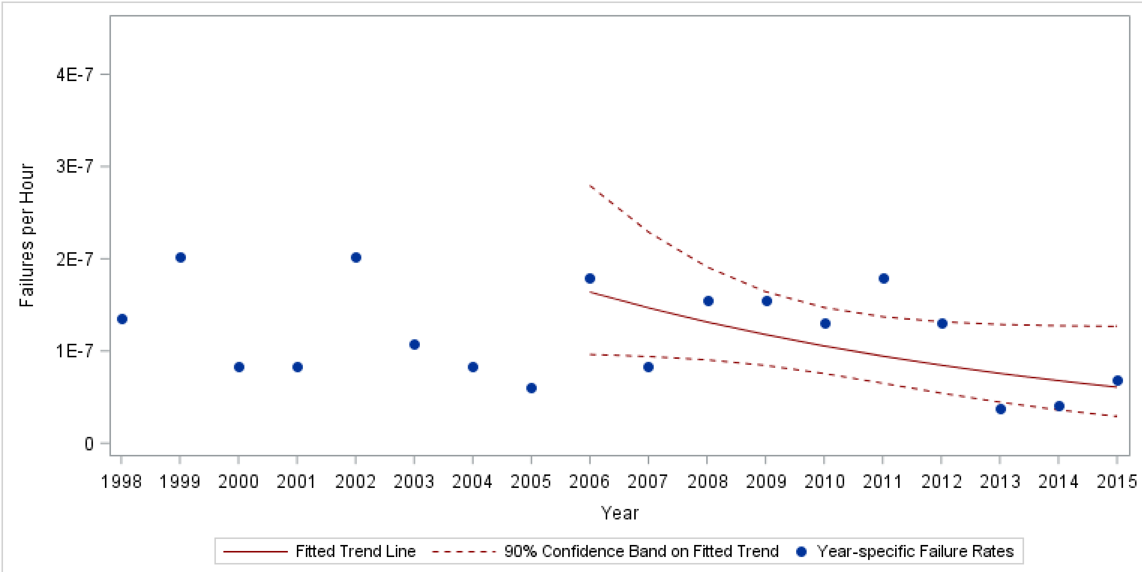


Figure 12. Ten year trend for rate of spurious operation of all circuit breakers (p=0.0446, statistically significant decreasing trend)

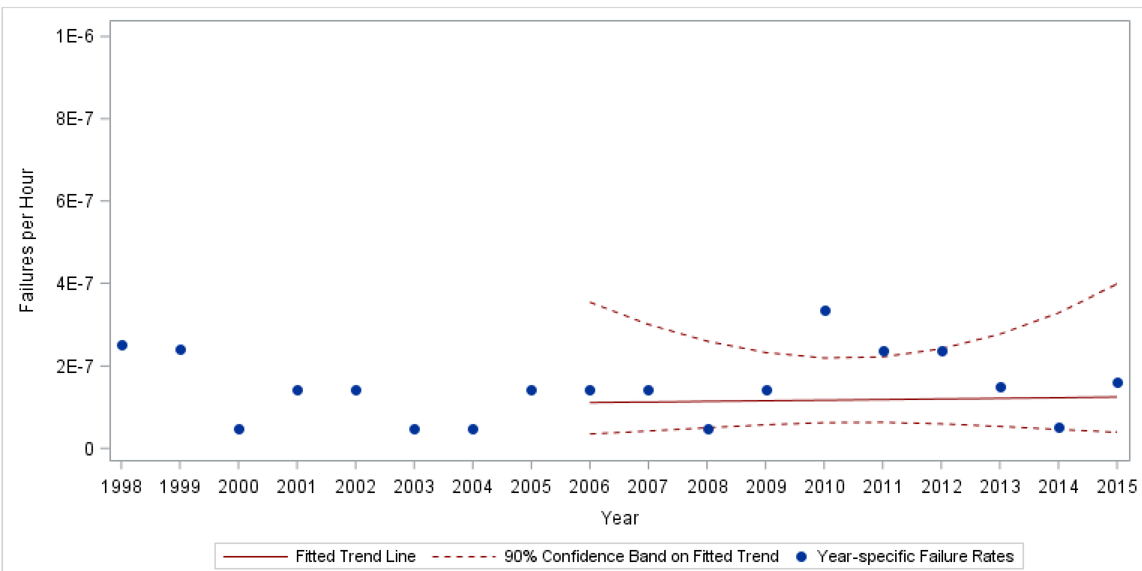


Figure 13. Ten year trend for rate of spurious operation of medium voltage circuit breakers (p=0.9003, no statistically significant trend)

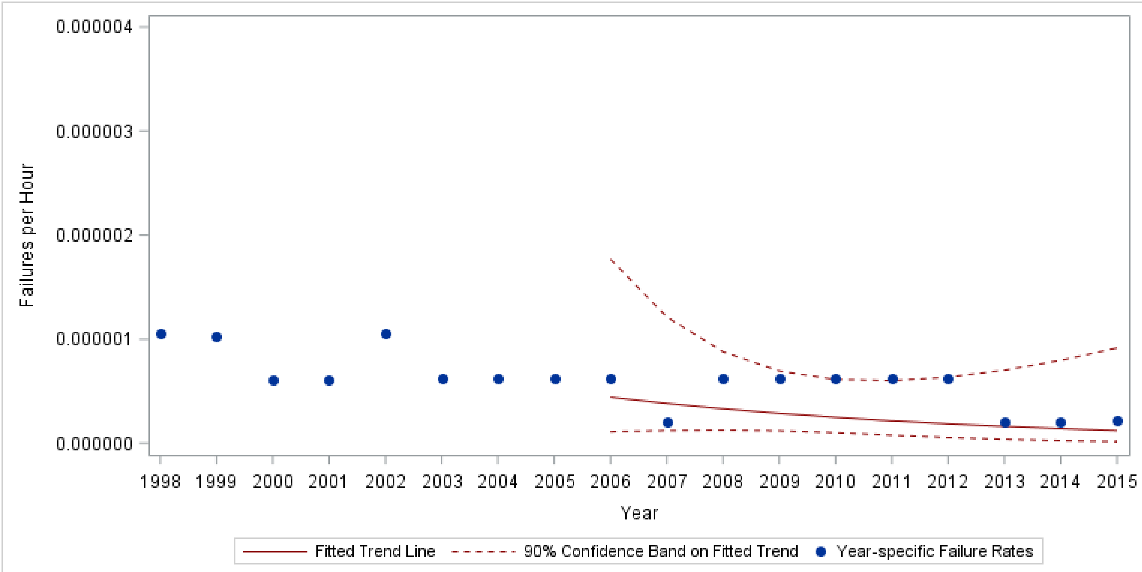


Figure 14. Ten year trend for rate of spurious operation of high voltage circuit breakers (p=0.3250, no statistically significant trend)

3.2 Battery Chargers

3.2.1 Scope

This section focuses on Class 1E battery charger failures reported during 1998-2015 at U.S. commercial nuclear power plants. All battery chargers monitored by RADS were included. The failure mode for battery chargers is failure to operate.

The data used in this study are associated with the failure records that have battery charger as the component type. Based on a search of proprietary information contained in NROD, there are 275 records from 1998 – June, 2016 where the subcomponent is Charger. There are no records identified with battery charger as a piecepart of a larger component. Only the data associated with the records that have battery charger as the component type are used in the following study.

3.2.2 Breakdown of Failure Counts

The total number of failures recorded in the database for battery chargers during the time frame under consideration is 156. Table 13 and Figure 15 show the age distribution of active battery chargers (relative to January 1, 2016) and the age of the battery chargers at failure. There is no way to identify or account for refurbishment. Assuming the out-of-service date field has been kept up-to-date, it appears there is a large population of very old battery chargers in use today.

Table 13. Current age and age at failure for monitored battery chargers

	Current Age		Age at Failure	
Age	**N**	**%**	**N**	**%**
<5	1	0	0	0
5–10	1	0	0	0
10–15	1	0	1	1
15–20	21	6	1	1
20–25	31	8	13	8

25–30	92	24	44	28
30–35	139	36	49	31
35–40	29	8	19	12
> 40	66	17	29	19
Total	381	100	156	100

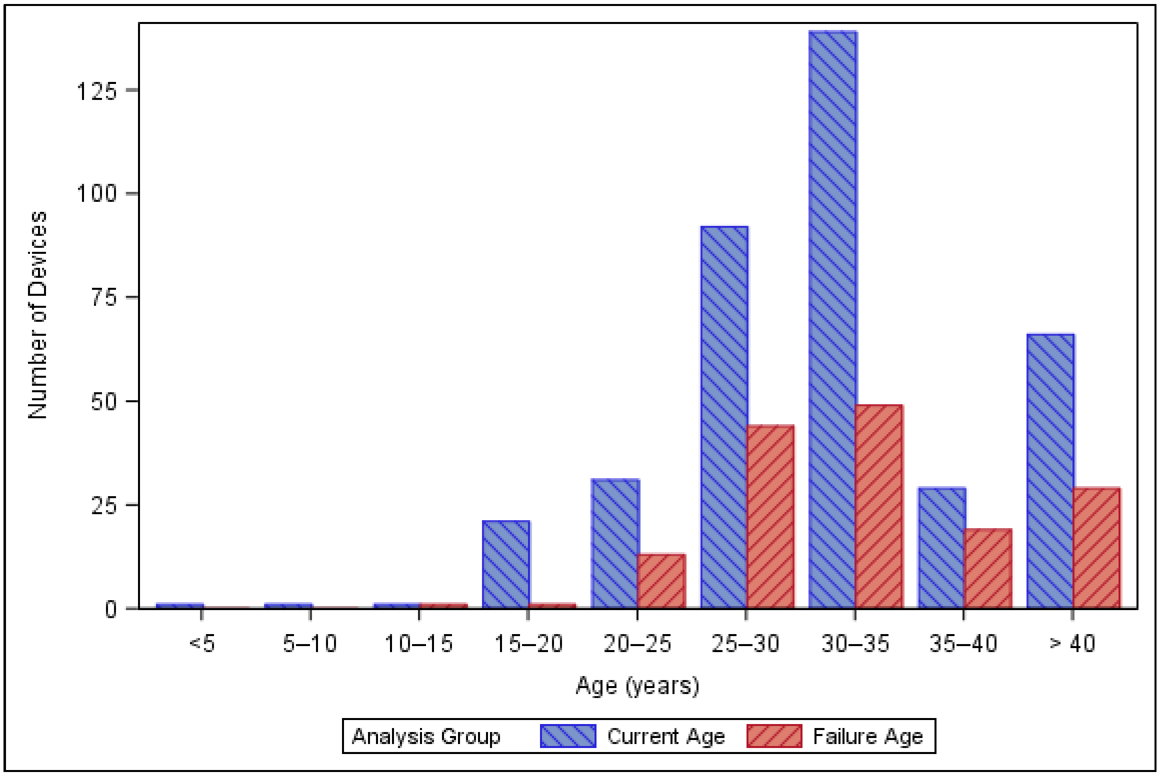


Figure 15. Current age and age at failure for monitored battery chargers

The manufacturers for all monitored battery charges and all failed battery chargers are tabulated in Table 14. Based on this tabulation, it appears the battery chargers by Power Conversion Products, Inc., fail at a higher than expected rate. A chi-square test confirms that hypothesis. The age distribution for Power Conversion Products, Inc. battery chargers currently in use is tabulated in Table 15 (3 devices manufactured by Power Conversion Products, Inc. are listed as having been removed from service, and hence are not included in this tabulation). Given the number of older devices in use that were manufactured by Power Conversion Products, Inc., it is not surprising to see a disproportionate number of failed devices.

Table 14. Manufacturer of all monitored and failed battery chargers

Manufacturer	Monitored Devices		Failed Devices	
	N	%	N	%
Power Conversion Products Inc.	141	36	77	49
C & D Batteries (Electra Corp.)	98	25	24	16
Solid State Controls Inc.	39	10	13	8
Exide Power Systems Div / INCO Electroenergy	35	9	13	8
Cyberex Inc	31	8	12	8
GNB Batteries	19	5	7	4

Eltra Corp	15	4	7	4
La Marche Manufacturing Co	5	1	1	1
Other	4	1	0	0
Not Reported	3	1	2	2
Total	390	100	156	100

Table 15. Age distribution of current battery chargers manufactured by Power Conversion Products, Inc.

Age Group	Number of Devices
15—20	8
20-–25	5
25-–30	39
30-–35	61
35-–40	5
> 40	20
Total	138

All Class 1E Battery chargers are part of the EIIS System DC Power System-Class 1E (code EJ).

3.2.3 Analysis of Failure to Operate

The analysis for battery chargers failing to operate is based on the Poisson model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates. Exposure times were queried from the RADS system. There are a total of 390 monitored battery chargers with 156 recorded failures. The total exposure time is calculated to be 59,652,354 hours. Two plants exhibited a statistically higher failure rate than the industry average. The ratio of the highest mean to the industry mean is 2.6.

Trending analysis was performed on the failure rate data for battery chargers from the 10 year period from 2006 to 2015. A statistically significant increasing trend was identified for the failure rate of battery chargers with a p-value of 0.0381 (Figure 16).

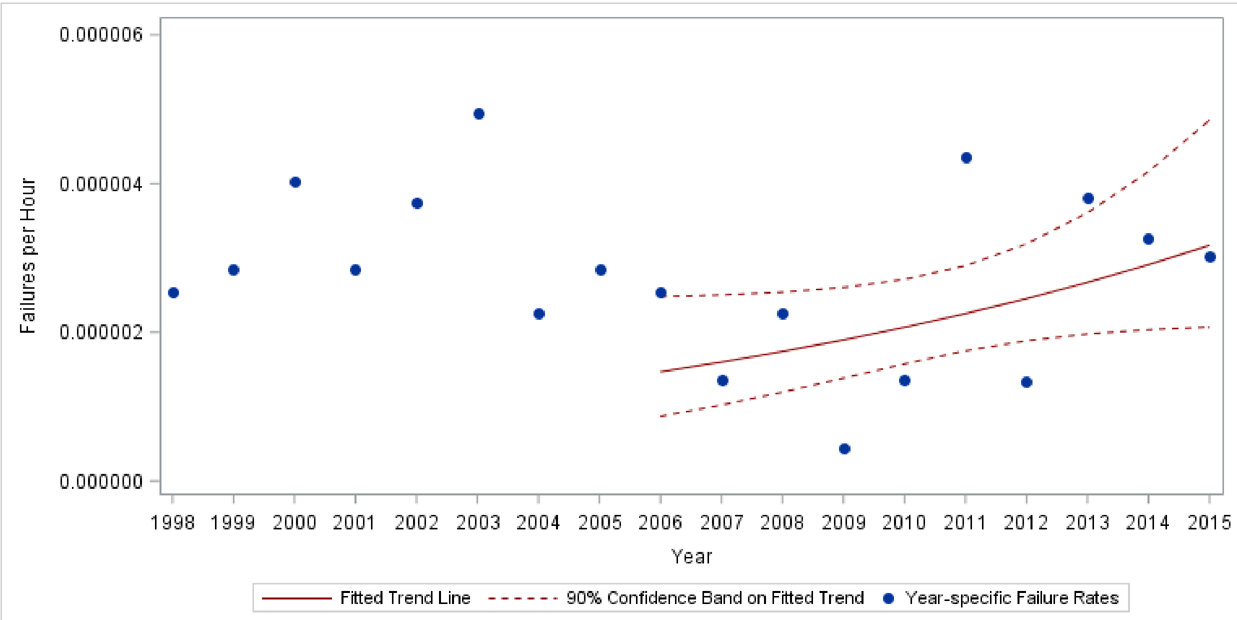


Figure 16. Ten year trend for failure rate of battery chargers (p=0.0381, statistically significant increasing trend)

3.3 Transformers

3.3.1 Scope

This section focuses on large power transformer (> 15 kV) failures reported during 2005-2015 at U.S. commercial nuclear power plants. All large power transformers in RADS were included. The failure mode for these transformers is failure to operate.

The data used in this study are associated with the failure records that have large power transformer coded as the component type. There are no records identified in the database with large power transformers as a subcomponent or piecepart of a large component.

3.3.2 Breakdown of Failure Counts

The total number of failures recorded in the database for large power transformers during the time frame under consideration is 185.

Table 16 and Figure 17 show the age distribution of actively operating large power transformers (relative to January 1, 2016) and the age of the transformers at failure. There is no way to identify or account for refurbishment. Assuming the out-of-service date field has been kept up-to-date, it appears there is a large population of old large power transformers currently in use.

Table 16. Age of current and failed large power transformers

Age	Current Devices N	Current Devices %	Failed Devices N	Failed Devices %
<5	9	2	2	1
5–10	19	4	4	2
10–15	17	4	13	7
15–20	27	6	18	10
20–25	22	5	21	11
25–30	71	16	33	18
30–35	108	24	34	18
35–40	80	17	18	10
> 40	105	23	42	23
Total	**458**	**100**	**185**	**100**

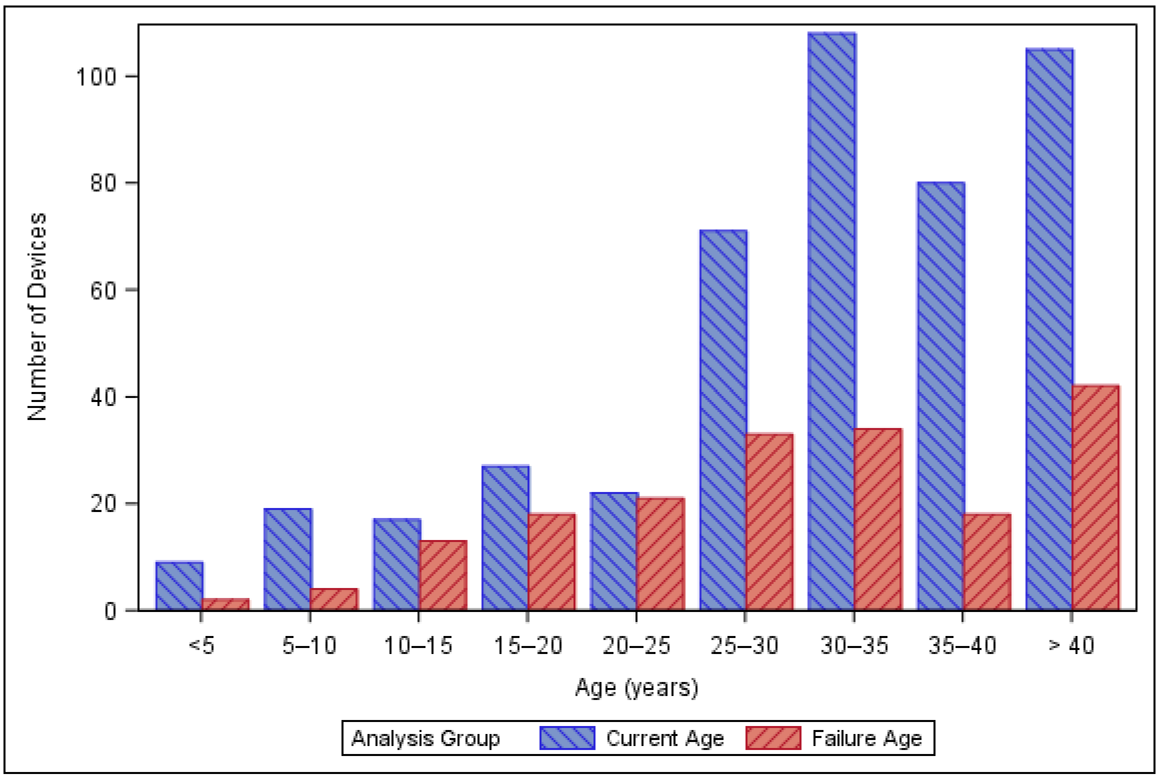


Figure 17. Age distribution for current and failed transformers

The distribution of monitored and failed large power transformers is tabulated in Table 17 by manufacturer. It should be noted that failure rates, especially for long-lived equipment in difficult working environments, are impacted significantly by the level of maintenance and repair received over the equipment's working life, so that care must be exercised in drawing conclusions based solely upon the manufacturer itself.

Table 17. Monitored and failed large power transformers by manufacturer

Manufacturer	Monitored Devices		Failures	
	N	%	N	%
Westinghouse Elec Corp. / Hagan	169	33	49	26
General Electric Company	152	30	58	31
McGraw Edison Co. (Power Systems)	47	9	11	6
ASEA Inc./Subsidiary of ABB Brown Boveri	24	5	19	10
Federal Pacific Electric	16	3	10	5
Not yet determined	12	2	2	1
ABB Brown Boveri	11	2	8	4
Westinghouse Elec Corp - Nuclear Energy Services	11	2	6	3
Mitsubishi International Corp.	10	2	1	1
ABB Power T&D Company Inc.	4	1	8	4
ELIN	7	1	4	2
Hyosung Corporation	6	1	0	0
ABB Power Distribution, Inc.	4	1	0	0
Moloney Elec Co.	4	1	1	1
Wagner Elec Corp., Tung Sol Division	4	1	0	0
Ferranti-Packard Limited	3	1	1	1
Siemens - Allis Inc.	3	1	1	1
U.S. Transformer	2	0	3	2
Kidde Fenwall, Inc.	2	0	0	0
SMIT	2	0	1	1
Siemens LTDA	2	0	0	0
VA TECH PEEBLES	2	0	0	0
Custom fabricated	2	0	0	0
ABB ATOM AB / ABB Sweden	1	0	1	1
Fortune Electric Company	1	0	0	0
General Electric Supply Co.	1	0	0	0
Hevi-Duti Elec Div / General Signal Corp	1	0	1	1
Penn Transformer Corp.	1	0	0	0
Smith, AO Corp.	1	0	0	0
Westinghouse-ABB	1	0	0	0
Total	**506**	**100**	**185**	**100**

The distribution of monitored and failed large power transformers is tabulated Table 18 and Figure 18 by EIIS System Code, and Table 19 by type of transformer. Table 20 lists the subcomponents of large power transformers identified as having failed.

Table 18. Monitored and failed large power transformers by EIIS System code

EIIS System	Monitored Devices		Failures	
	N	%	N	%
EA	209	41	71	38
EL	168	33	55	30
EB	66	13	30	16
EI	18	4	14	8
FK	18	4	2	1
EC	12	2	3	2
TL	8	2	1	1
ED	6	1	5	3
EK	1	0	4	2
Total	**506**	**100**	**185**	**100**

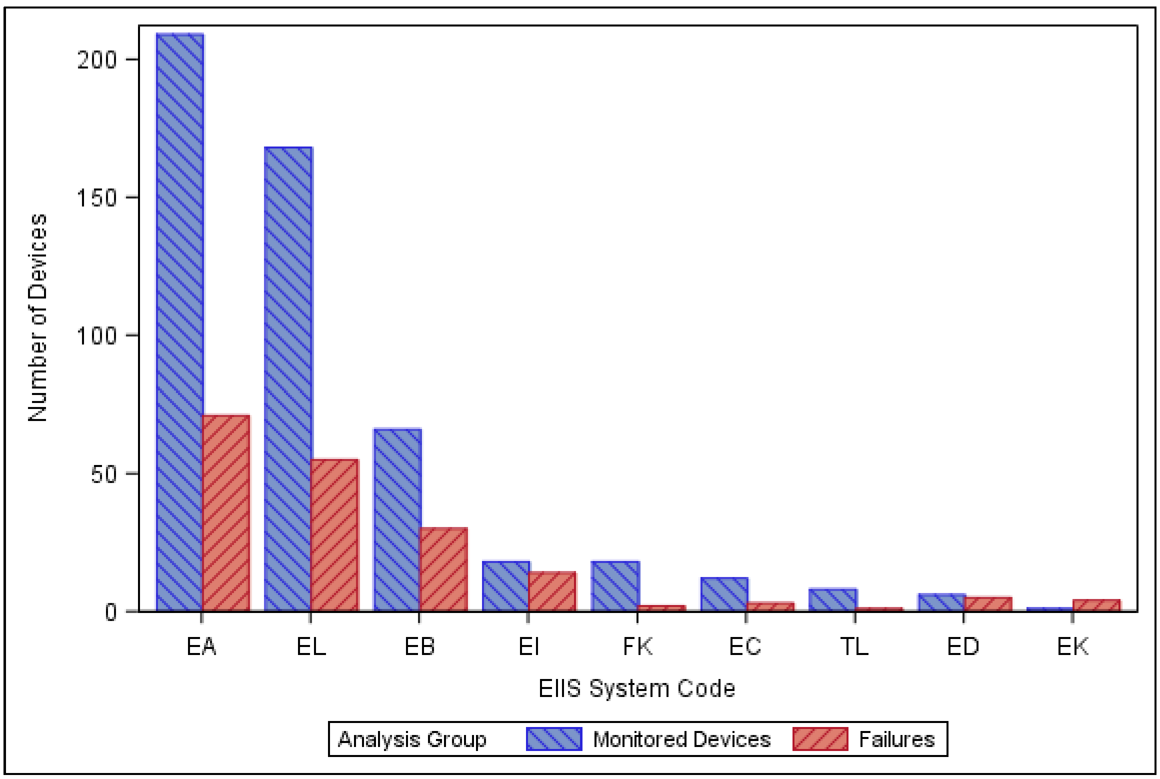


Figure 18. Monitored and failed large power transformers by EIIS System code

Table 19. Monitored and failed large power transformers by type of transformer.

Type of Transformer	Monitored Devices		Failed Devices	
	N	%	N	%
Power Step-Up Input: 15,000-35,999 VAC Output: 36,000 VAC or higher	109	22	37	20
Power Step-Down Input: 15,000-35,999 VAC Output: 3,000-5,999 VAC	104	21	43	23
Power Step-Down Input: 36,000 VAC or higher Output: 3,000-5,999 VAC	57	11	32	17
Power Step-Down Input: 15,000-35,999 VAC Output: 6,000-8,999 VAC	42	8	2	1
Power Step-Down Input: 36,000 VAC or higher Output: 9,000-14,999 VAC	40	8	27	15
Current Input: 15,000-35,999 VAC Output: 0-299 VAC	39	8	1	1
Power Step-Down Input: 36,000 VAC or higher Output: 6,000-8,999 VAC	23	5	13	7
Power Step-Down Input: 15,000-35,999 VAC Output: 9,000-14,999 VAC	17	3	4	2
Voltage Input: 15,000-35,999 VAC Output: 3,000-5,999 VAC	10	2	3	2
Voltage Input: 15,000-35,999 VAC Output: 36,000 VAC or higher	10	2	3	2
Voltage Input: 36,000 VAC or higher Output: 36,000 VAC or higher	7	1	0	0
Voltage Input: 15,000-35,999 VAC Output: 0-299 VAC	6	1	0	0
Voltage Input: 36,000 VAC or higher Output: 3,000-5,999 VAC	6	1	4	2
Voltage Input: 36,000 VAC or higher Output: 9,000-14,999 VAC	5	1	1	1
Power Step-Down Input: 36,000 VAC or higher Output: 36,000 VAC or higher	4	1	2	1
Power Step-Down Input: 15,000-35,999 VAC Output: 2,000-2,999 VAC	3	1	0	0
Power Step-Down Input: 36,000 VAC or higher Output: 15,000-35,999 VAC	3	1	2	1
Power Step-Up Input: 36,000 VAC or higher Output: 3,000-5,999 VAC	3	1	0	0
Current Input: 15,000-35,999 VAC Output: 36,000 VAC or higher	2	0	1	1
Differential Input: 36,000 VAC or higher Output: 36,000 VAC or higher	2	0	2	1
Power Step-Down Input: 36,000 VAC or higher Output: 2,000-2,999 VAC	2	0	2	1
Power Step-Up Input: 15,000-35,999 VAC Output: 300-699 VAC	2	0	1	1
Power Step-Up Input: 36,000 VAC or higher Output: 9,000-14,999 VAC	2	0	1	1
Voltage Input: 36,000 VAC or higher Output:	2	0	0	0
Differential Input: 15,000-35,999 VAC Output: 15,000-35,999 VAC	1	0	0	0
Other Input: 36,000 VAC or higher Output: 0-299 VAC	1	0	1	1
Other Input: 36,000 VAC or higher Output: 36,000 VAC or higher	1	0	1	1
Power Step-Up Input: 15,000-35,999 VAC Output: 9,000-14,999 VAC	1	0	0	0
Power Step-Up Input: 36,000 VAC or higher Output: 2,000-2,999 VAC	1	0	1	1
Transducer Input: 15,000-35,999 VAC Output: 9,000-14,999 VAC	1	0	1	1
Total	**506**	**100**	**185**	**100**

Table 20. Failed subcomponents within large power transformers

Subcomponent	N	%
Not Reported	111	60
Miscellaneous	31	17
Tap Changer	9	5
Surge Arrestor	7	4
Radiator Fan Motor	7	4
Bushing	7	4
Insulating Oil	3	2
Primary Winding	3	2
Linkage	2	1
Primary Winding Insulation	1	1
Fault Pressure Switch	1	1
Radiator	1	1
Tap Changer Drive Mechanism and Controls	1	1
Load Changer	1	1
Total	**185**	**100**

3.3.3 Analysis of Failure to Operate

The analysis for large power transformers failing to operate is based on the Poisson model. Empirical Bayes analysis was used to examine plant-to-plant variation in failure rates. Exposure times were queried from the RADS system. There are 506 monitored large power transformers with 185 recorded failures. The total exposure time is calculated to be 71,234,066 hours. The ratio of the highest mean to the industry mean was 2.7.

Trending analysis was performed on the failure rate data for large power transformers from the 10 year period from 2006 to 2015. No statistically significant trend was identified (Figure 19).

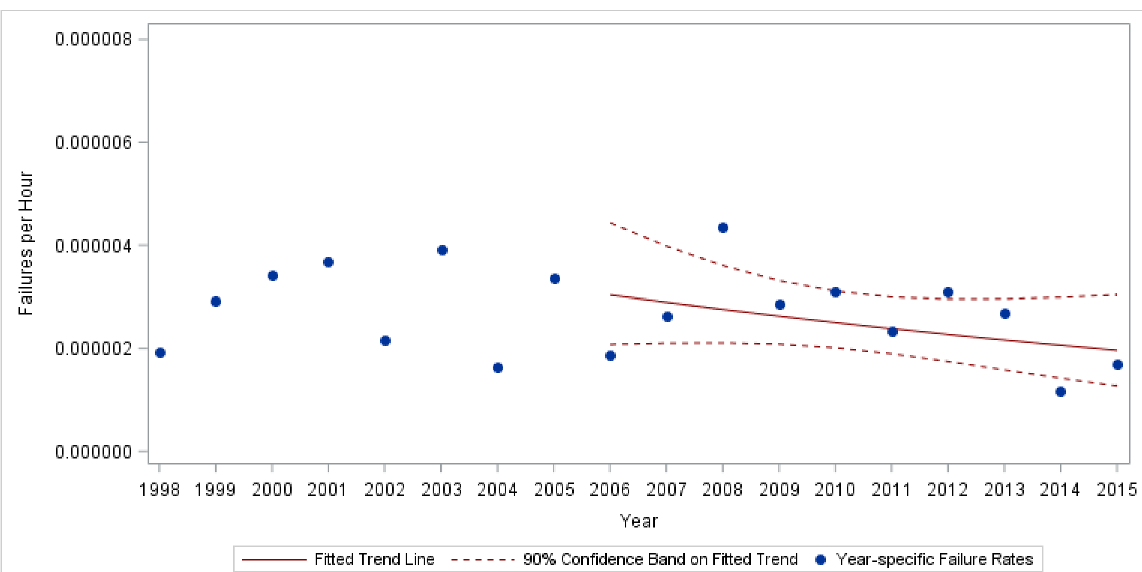


Figure 19. Ten year trend for failure rate of large power transformers (p=0.1738, no statistically significant trend)

3.4 Batteries

3.4.1 Scope

This section focuses on battery failures reported during 1998-2015 at U.S. commercial nuclear power plants. All batteries included in RADS were included. The failure mode for batteries is failure to operate.

The data used in this study are associated with the failure records that have battery coded as the component type. There are 13 failure records identified in the database with batteries as the subcomponent and 7 records identified with batteries as a piecepart of a larger component. As with the circuit breakers, only the data associated with the records that have battery as the component type are used in this study.

3.4.2 Breakdown of Failure Counts

The total number of failures recorded in the database for large power transformers during the time frame under consideration is 23. Table 21 and Figure 20 show the age distribution of actively operating batteries (relative to January 1, 2016) and the age of the batteries at failure. Failures are tabulated by EIIS system code in Table 22.

Failures were also tabulated by manufacturer in Table 23. As noted previously, failure rates, especially for long-lived equipment in difficult working environments, are impacted significantly by the level of maintenance and repair received over the equipment's working life, so that care must be exercised in drawing conclusions based solely upon the manufacturer itself.

Table 21. Age of current and failed batteries

	Current Age		Age at Failure	
Age (years)	N	%	N	%
5-–10	5	1	0	0
10-–15	5	1	0	0
15-–20	30	7	1	4
20-–25	82	20	6	26
25-–30	136	34	6	26
30-–35	92	23	5	22
35-–40	12	3	0	0
> 40	39	10	5	22
Total	401	100	23	100

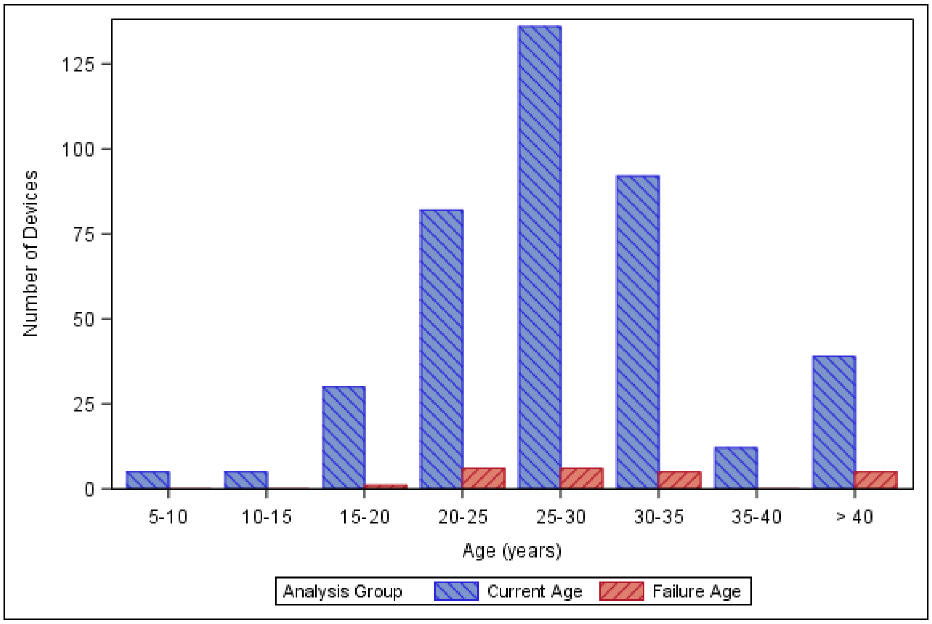


Figure 20. Age of current and failed batteries

Table 22. Monitored and failed batteries by EIIS system code

EIIS System Code	Current Devices		Failures	
	N	%	N	%
EJ	263	63	13	57
EI	146	35	10	43
EF	6	1	0	0
Total	415	100	23	100

Table 23. Monitored and failed batteries by manufacturer

Manufacturer	Monitored Devices		Failures	
	N	%	N	%
C & D Batteries (Electra Corp.)	168	40	11	48
GNB Batteries / formerly Gould Ind Bat Div.	116	28	3	13
Exide Indust Batry Div. / INCO Electroenergy	64	15	6	26
AT&T Energy Systems	20	5	0	0
Not yet determined	8	2	0	0
Charter Power Systems, Inc.	7	2	1	4
Gould Inc / formerly ITE Imperial	7	2	0	0
Exide Electronics Corp.	6	1	0	0
Exide Power Systems Div. / INCO Electroenergy	5	1	0	0
Saab Nife Inc.	5	1	0	0
Eltra Corp.	3	1	0	0
C & D Charter Power Systems (Batteries)	2	0	1	4
General Electric Company	2	0	1	4
Gould, Inc./Distribution Controls Division	1	0	0	0
Yuasa Exide Inc.	1	0	0	0
Total	**415**	**100**	**23**	**100**

3.4.3 Analysis of Failure to Operate

There are not enough battery failures to use an Empirical Bayes analysis to look the plant-to-plant variation in failure rates. There are 415 monitored batteries with 23 recorded failures. The total exposure time is calculated to be 63,157,736 hours.

Trending analysis was performed on the failure rate data for batteries for the 10 year period from 2006 to 2015. No statistically significant trend was identified (Figure 21).

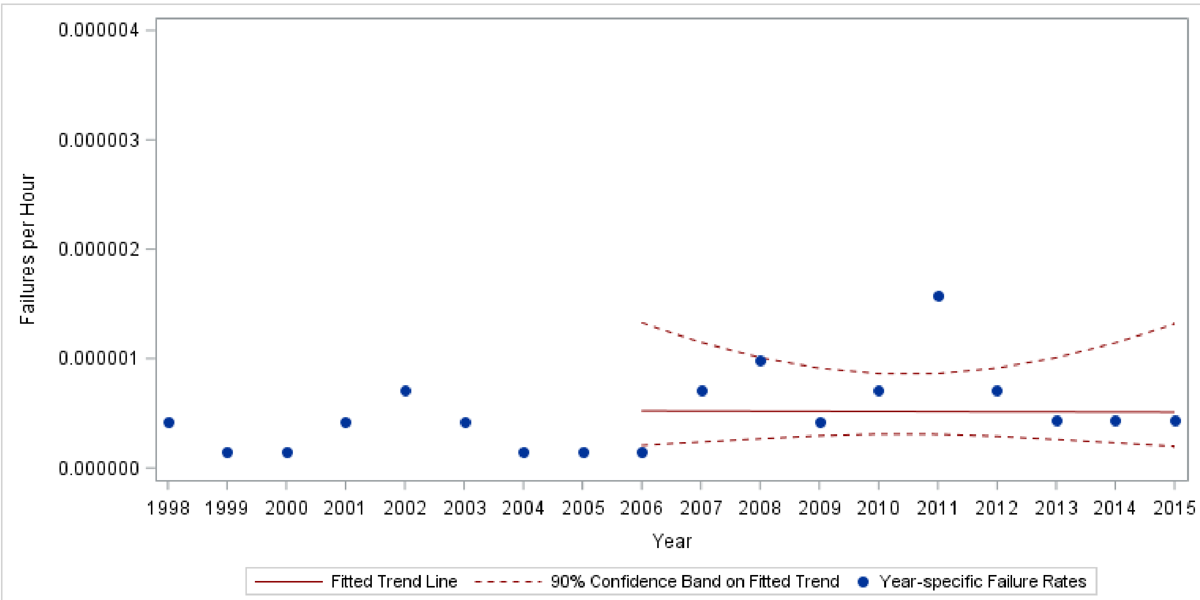


Figure 21. Ten year trend for failure rate of batteries (p=0.9740, no statistically significant trend)

3.5 Buses

3.5.1 Scope

This section focuses on bus failures reported during 2006-2015 at U.S. commercial nuclear power plants. The failure mode for buses is failure to operate.

The data used in this study are associated with the failure records that have AC bus coded as the component type. There are no records having DC bus coded as the component type. Based on a search of the database, there are 6 records from 1998 to June 2016 where the subcomponent is an AC bus and no records identified with an AC bus as a piecepart of a larger component. As with the circuit breakers, only the data associated with the records that have AC bus as the component type are used in this study.

3.5.2 Breakdown of Failure Counts

The total number of AC bus failures recorded in the database during the time of interest is 62. AC buses are categorized by their voltage rating. A breakdown of all monitored and failed AC buses by voltage rating tabulated in Table 24 and graphed in Figure 22. It shows that the 51-300 VAC buses group had fewer failures relative to its proportion of population, while the 2,001-5,000 VAC buses group had more failures relative to its proportion of population. Figure 23 shows a breakdown of failed AC breakers by subcomponent.

Table 24. Monitored and failed AC buses by voltage rating

Voltage Rating	Current Devices		Failures	
	N	%	N	%
301-600 Volts	539	43	32	52
Unknown	223	18	0	0
51-300 Volts	180	14	5	8
2,001-5,000 Volts	171	14	16	26
15,001-25,000 Volts	36	3	0	0
5,001-8,000 Volts	36	3	3	5
25,001 Volts and Over	27	2	0	0
8,001-15,000 Volts	19	2	3	5
601-2,000 Volts	13	1	1	2
300-699 Volts	7	1	2	3
0-50 Volts	4	0	0	0
Total	1255	100	62	100

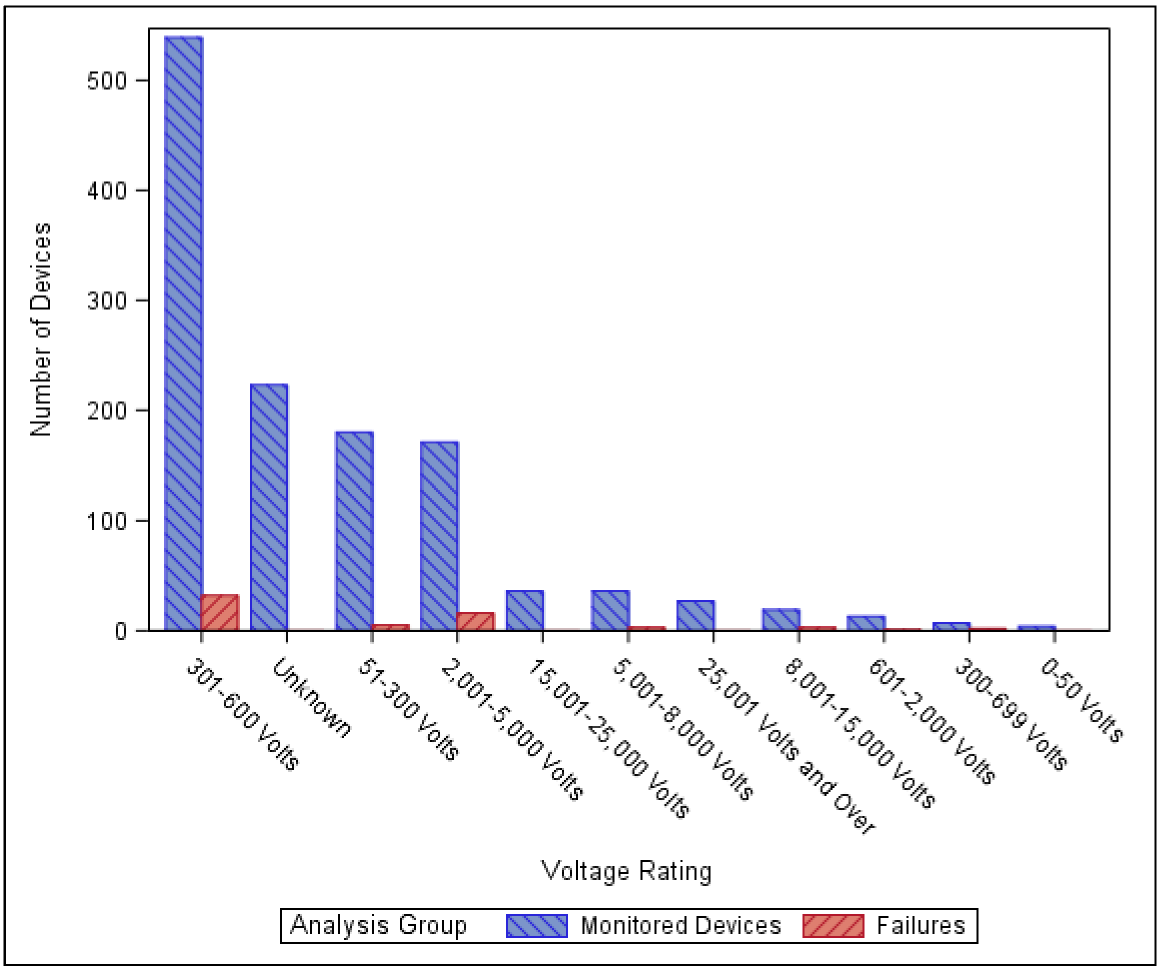


Figure 22. Monitored and failed AC buses by voltage rating.

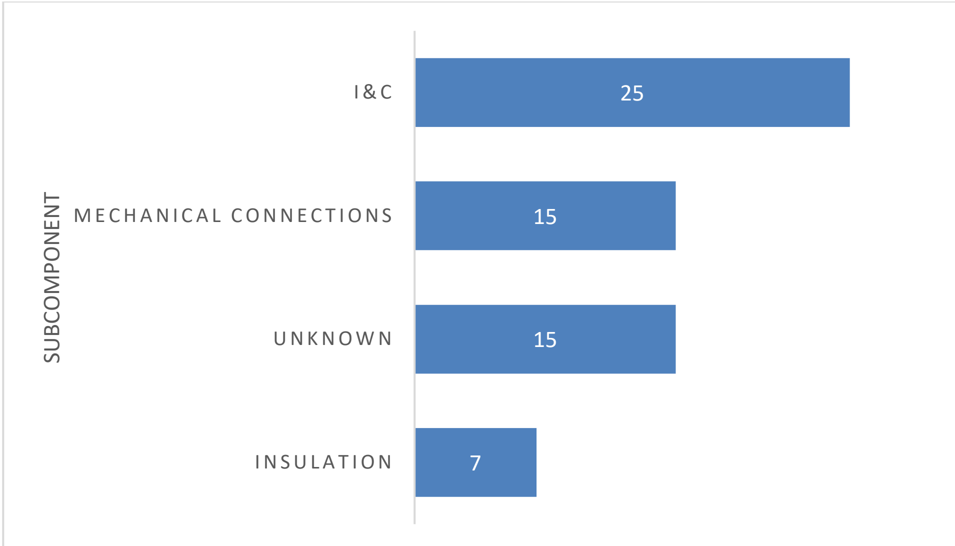


Figure 23. Failed subcomponents within AC breakers.

Table 25 and Figure 24 show the age distribution of actively operating large AC buses (relative to January 1, 2016) and the age of the bus at failure. There is no way to identify or account for refurbishment. The most failures occurred in the oldest AC buses, those older than 40 years. Approximately 25% of the current AC buses are older than 40 years.

Table 25. Age of current and failed AC buses.

Age (years)	Current Age		Age at Failure	
	N	%	N	%
5-10	3	0	0	0
10-15	14	1	0	0
15-20	221	18	5	8
20-25	98	8	5	8
25-30	271	22	6	10
30-35	185	15	14	23
35-40	112	9	6	10
> 40	305	25	26	42
Total	**1209**	**100**	**62**	**100**

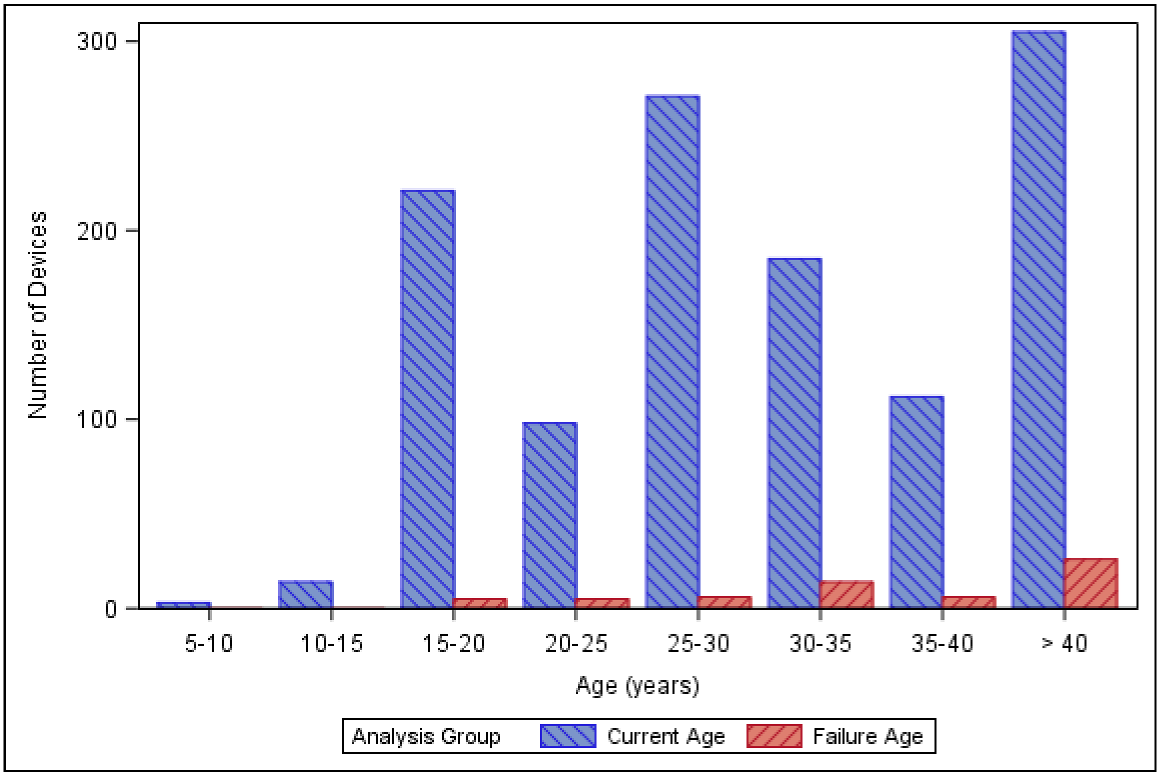


Figure 24. Age of current and failed AC buses

Failure were tabulated by EIIS system code in Table 26, and by manufacturer in Table 27. AC buses in the Medium Voltage Power System-Class 1E (EIIS code EB) appear to fail at a higher rate than might be expected by the population.

Bus failures were also tabulated by manufacturer. As indicated previously, failure rates, especially for long-lived equipment in difficult working environments, are impacted significantly by the level of maintenance and repair received over the equipment's working life, so that care must be exercised in drawing conclusions based solely upon the manufacturer itself.

Table 26. Current and failed AC buses by EIIS System Code

	Current Devices		Failures	
EIIS System Code	**N**	**%**	**N**	**%**
EC	385	32	17	27
EA	177	15	12	19
ED	173	14	6	10
EB	124	10	17	27
EJ	119	10	3	5
EF	47	4	1	2
EI	38	3	0	0
EK	32	3	1	2
TB	28	2	0	0
EL	20	2	2	3
FK	20	2	0	0
XT	12	1	1	2

AB	7	1	1	2
EE	6	0	0	0
BI	3	0	0	0
JC	3	0	0	0
AA	2	0	0	0
BB	2	0	0	0
BK	2	0	0	0
FH	1	0	0	0
FI	1	0	0	0
JA	1	0	0	0
JD	1	0	0	0
LD	1	0	0	0
NB	1	0	0	0
NC	1	0	1	2
VF	1	0	0	0
XG	1	0	0	0
Total	1209	100	62	100

Table 27. Current and failed AC buses by manufacturer

Manufacturer	Current Devices		Failures	
	N	%	N	%
Westinghouse Elec Corp. / Hagan	332	27	12	19
General Electric Company	225	19	8	13
Not yet determined	146	12	0	0
Custom fabricated	64	5	8	13
ITE Circuit Breaker Ltd.	53	4	8	13
Gould Inc. / formerly ITE Imperial	50	4	2	3
Square D Co.	32	3	0	0
Porter, HK Co. Inc.	29	2	0	0
Nelson Elec. Div. / Sola Basic Ind.	25	2	8	13
Cutler - Hammer Inc. (Eaton Corp)	20	2	0	0
ITE Imperial	19	2	1	2
ITE Gould	17	1	0	0
Brown Boveri Electric Co.	15	1	0	0
Westinghouse Elec Corp. - Nuclear Energy Services	15	1	0	0
ABB Brown Boveri	14	1	2	3
Gould Brown Boveri	13	1	0	0
Allis Chalmers Corp.	11	1	1	2
Delta Switchboard Co.	9	1	0	0
Gould Electronics / formerly Gould Shawmut	9	1	2	3
Exide Electronics Corp.	8	1	0	0
GTE Sylvania Inc.	8	1	0	0
Gould, Inc./Distribution Controls Division	7	1	0	0
ABB Power Distribution, Inc.	6	0	1	2
Empire Switchboard	6	0	3	5
SQUARE D CO.	6	0	0	0

Systems Control Corp.	6	0	0	0
HUSKY PRODUCTS	5	0	0	0
Cyberex Inc.	5	0	0	0
Sandvik Inc., Strip Steel Div.	4	0	0	0
Siemens Corp.	4	0	1	2
Calvert Company Inc.	3	0	1	2
Delta-Unibus Corp.	3	0	0	0
S & C Electric Co.	3	0	0	0
Siemens - Allis Inc.	3	0	0	0
ASEA Inc./Subsidiary of ABB Brown Boveri	2	0	1	2
Clark Electrical Controls and System	2	0	1	2
Combustion Engineering, Inc.	2	0	0	0
Golden Gate Switch Board Co.	2	0	0	0
Gould Industrial Battery	2	0	0	0
Harlo Corp.	2	0	0	0
Hoffman Engineering Co.	2	0	0	0
ITC Transmission	2	0	0	0
Power Conversion Prod Inc.	2	0	0	0
Telemecanique Inc.	2	0	0	0
Anaconda Co./Wire & Cable Div.	1	0	0	0
BBC Brown Boveri Inc.	1	0	0	0
CONDUCTIX, Inc.	1	0	1	2
Controlled Power Ltd Partnership	1	0	0	0
Control Associates Inc.	1	0	0	0
Eaton Corp.	1	0	0	0
Federal Pacific Electric	1	0	0	0
Goulds Mfg.	1	0	0	0
ITE/ABB	1	0	0	0
Kinney Electrical Mfg Co Inc.	1	0	0	0
Klockner – Moeller	1	0	1	2
N/A for subcomponent	1	0	0	0
RTE Corp.	1	0	0	0
Solid State Controls Inc.	1	0	0	0
Total	**1209**	**100**	**62**	**100**

3.5.3 Analysis of Failure to Operate

The analysis for AC buses failing to operate is based on the Poisson model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates. Exposure times were queried from the RADS system. There are 1255 monitored AC buses with 62 recorded failures. The total exposure time for AC buses is 105,426,621 hours. The ratio of the highest mean to the industry mean is 6.4.

Trending analysis was performed on the failure rate data for AC buses for the 10 year period from 2006 to 2015. No statistically significant trend was identified (Figure 25).

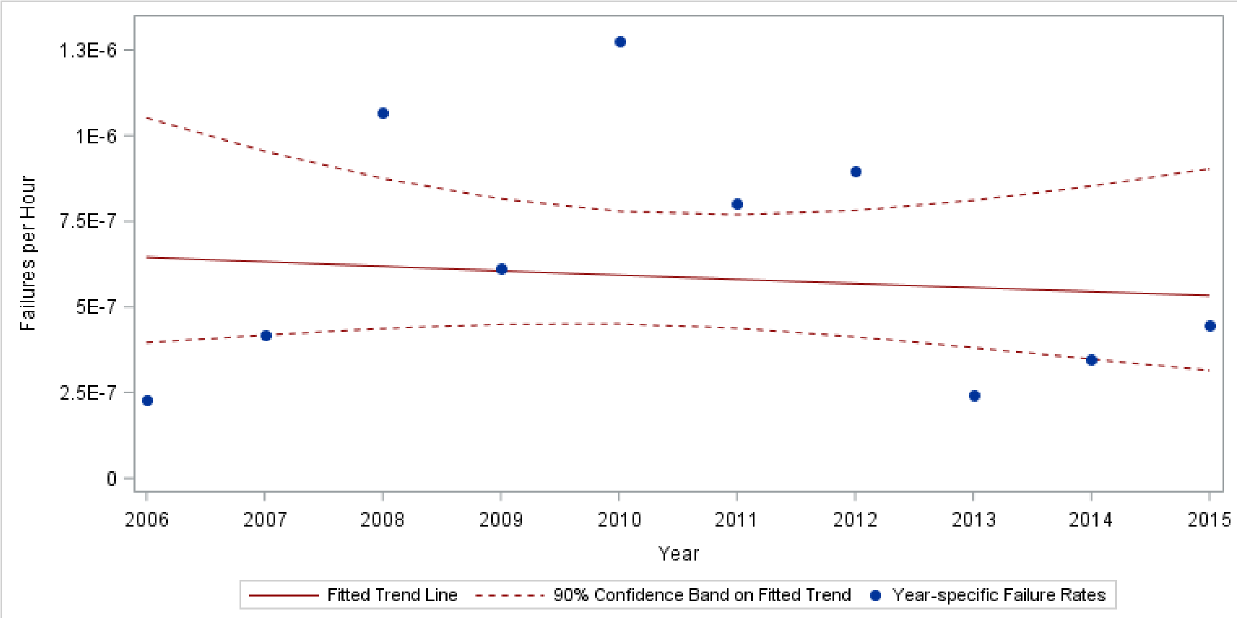


Figure 25. Ten year trend for failure rate of buses (p=0.6323, no statistically significant trend)

3.6 Proposed Failure Rates

Based on the data compiled for the analyses documented here, proposed failure rates for the components in this study were estimated and are provided in Table 28. The industry average value resulting from the Empirical Bayes analysis was used when the analysis converged, as denoted by Analysis Type EB/PL/KS (empirical Bayes/plant level/Kass Steffey). When the Empirical Bayes analysis did not converge, the rate was obtained from a Bayesian update of the Jeffreys noninformative prior, as denoted by Analysis Type JNID/IL (Jeffreys noninformative distribution/industry level). For demand-related events, the JNID/IL results in a mean of (n + 0.5)/(D + 1), where n is the number of failures and D is the number of demands. For time-related failures, the JNID/IL results in a mean of (n + 0.5)/T, where T is the number of hours.

Estimating a failure rate for battery chargers proved somewhat challenging. The data from 2006-2015 used to generate the average rate exhibits an upward trend, as seen in Figure 16, although the 3-year data (from 2013-2015) appears to exhibit a downward trend. For this reason, care is needed in estimating this failure rate for the purposes of PRA.

Table 28. Failure rate Estimates based upon ten years of data (2006-2015) included in this study

Component Failure Mode	Description	Data Source	Data				Industry-average Failure Probability or Rate Distribution				
			Failures	Demands or Hours	d or h	# Comps.	Distribution	Analysis Type	Mean	α	β
BAT FTOP	Battery fails to operate	RADS	18	34975050	h	415	Gamma	JNID/IL	5.29E-07	1.85E+01	3.50E+07
TFM FTOP	Large Power Transformer fails to operate	RADS	98	39641332	h	483	Gamma	EB/PL/KS	2.74E-06	1.12E+00	4.08E+05
BUS FTOP	BUS Fails to operate	RADS	62	105426616	h	1255	Gamma	EB/PL/KS	7.60E-07	6.64E-01	8.74E+05
CBK SOP	Circuit Breaker operates spuriously	RADS	42	401781824	h	4787	Gamma	EB/PL/KS	1.64E-07	4.03E-01	2.45E+06
CBKMV SOP	Medium voltage circuit breaker operates spuriously	RADS	12	101949500	h	1214	Gamma	JNID/IL	1.23E-07	1.25E+01	1.02E+08
CBKHV SOP	High voltage circuit breaker operates spuriously	RADS	6	23802900	h	279	Gamma	JNID/IL	2.73E-07	6.50E+00	2.38E+07
CBK FTOC	Circuit Breaker fails to open &/or close	RADS	78	82422.8	d	3649	Beta	EB/PL/KS	1.82E-03	5.79E-01	3.18E+02
CBKMV FTOC	Medium voltage circuit breaker fails to open &/or close	RADS	40	33893.4	d	1064	Beta	JNID/IL	1.19E-03	4.05E+01	3.39E+04
CBKHV FTOC	High voltage circuit breaker fails to open &/or close	RADS	15	6130.6	d	242	Beta	JNID/IL	2.53E-03	1.55E+01	6.12E+03
BCH FTOP	Class 1E Battery Charger fails to operate	RADS	73	32977438	h	382	Gamma	EB/PL/KS	2.22E-06	1.85E+00	8.33E+05

4. SYSTEM ANALYSIS

4.1 Study Overview

This study selected the designs that were representative of operating nuclear power plants in the United States based on the classification scheme provided below, which proposed three main categories to classify the design of offsite power systems and interconnecting power circuit paths. Category I deals with the independence of offsite power sources to the NPP. Category II classifies the power sources for the Class 1E buses during normal operation (i.e., main generator or offsite source). Category III classifies the automatic or manual transfer schemes for the Class 1E buses when both the normal and the backup sources of offsite AC power fail. Category III also has several subcategories. Category I and subcategories of Category III were not used in this classification of operating nuclear power sites due to their lesser importance to this study. The criteria for the three categories are presented below.

- Category I – Independence of offsite power sources to the nuclear power plant
  1. All offsite power sources are connected to the plant through one switchyard.
  2. All offsite power sources are connected to the plant through two or more switchyards, and the switchyards are electrically connected.
  3. All offsite power sources are connected to the plant through two or more switchyards or separate incoming transmission lines, but at least one of the AC sources is electrically independent of the others.
- Category II – Power sources for the Class 1E buses during normal plant operation
  1. During normal operation, the Class 1E buses are supplied by the main generator through a unit transformer.
  2. During normal operation, the Class 1E buses are supplied by a preferred offsite power source.
- Category III – Automatic and manual transfer schemes for the Class 1E buses when the normal source of AC power fails and when the backup sources of offsite power fail
  1. If the normal source of AC power fails, there are no automatic transfers and one or more manual transfers to preferred or alternate offsite power sources.
  2. If the normal source of AC power fails, there is one automatic transfer but no manual transfers to preferred or alternate offsite power sources.
  3. After loss of the normal AC power source, there is one automatic transfer. If this source fails, there may be one or more manual transfers of power sources to preferred or alternate offsite power sources.
  4. If the normal source of AC power fails, there is an automatic transfer to a preferred source of power. If this preferred source of power fails, there is an automatic transfer to another source of offsite power.

ESLDs were developed for the representative designs based on Updated Safety Analysis Reports. The equipment reliability was evaluated and detailed fault tree models were developed to calculate the frequency of loss of electrical supply to the Class 1E buses.

4.2 Study Process

There are seven designs with combinations of configurations from Categories II and III. For each design, one nuclear plant site was chosen as representative by considering the level of development of the Standardized Plant Analysis Risk (SPAR) model as well as the availability of plant PRA and related information. The existing SPAR model for selected sites or units (if separate SPAR models are developed for different units in a multi-unit site) is used as the base model which is then revised for reliability analysis. For example, Plant B is chosen to represent Plant Type 1, 2 which has the following configuration:

Category II, criterion 1:

During normal operation, the Class 1E buses are supplied by the main generator through a unit transformer.

Category III, criterion 2:

If the normal source of AC power fails, there is one automatic transfer but no manual transfers to preferred or alternate offsite power sources.

Plant E is selected to represent Plant Type 2, 1, which has the following configuration:

Category II, criterion 2:

During normal operation, the Class 1E buses are supplied by a preferred offsite power source.

Category III, criterion 1:

If the normal source of AC power fails, there are no automatic transfers and one or more manual transfers to preferred or alternate offsite power sources.

Table 29 lists the seven sites/units that were selected to represent the electrical distribution system designs and configurations for this electrical system reliability study. The SPAR models for these representing plants are obtained.

Table 29. Representative nuclear plant sites/units for electrical system reliability study.

Category II Normal Power Source	Category III Power Source Transfer Scheme	Selected Site/Unit Name	Reactor Type
1	1	Plant A	W (4-Loop)
1	2	Plant B	CE (2-Loop)
1	3	Plant C	B&W (L Loop)
1	4	Plant D	BWR/4
2	1	Plant E	W (4-Loop)
2	2	Plant F	BWR/4
2	3	Plant G	W (4-Loop)
2	4	N/A (Note)	N/A

Note: There was no nuclear plant that has the design of Plant Type 2, 4, i.e., criterion 2 of Category II and criterion 4 of Category III.

ESLDs were then developed with the available plant information. A Class 1E 4.16 kV AC system or single train AC bus failure is used as the top event of the fault tree model and as the surrogate for the electrical system unreliability. The associated fault trees in the base SPAR models were revised with the following changes:

1. Revise the fault tree logic as necessary based on the ESLDs developed.
2. Add new basic events for additional transformer, circuit breaker, bus failures, and operator actions for manual transfer and crossties into the logic.

   Model circuit breakers by the following failure modes: Fail to Open, Fail to Close, Fail to Remain Closed, CCF to Open or Close. (CCF of spurious operation is not modeled as it is estimated to be one or more orders of magnitude lower in risk than the CCF to open or close.)

   Transformers, buses, batteries, and battery chargers are modeled with Fail to Operate and common cause failure to operate.
3. Use the new equipment reliability data for transformers, buses, circuit breakers, batteries, and battery chargers in Section 3.6 to update the SPAR models.
4. Table 30 lists the updated failure probabilities of the template events that are applied to the related electrical equipment in the AC system models. Note that the templated event names may be slightly different from the models. For example, ZT-CBK-SOP may be named as ZT-CRB-CO, ZT-CBK-FTOC-HV be named as ZT-CRB-FTOC-13.6.

   Note that there are three groups of circuit breakers in the data analysis: all circuit breakers, medium voltage circuit breakers, and high voltage circuit breakers (refer to Section 3.1.1). The failure data for medium voltage circuit breaker are used for 4.16 kV and 6.9 kV breakers. The failure data for high voltage circuit breakers are used for 13.8 kV and above breakers. The failure data for all circuit breakers are used for all other breakers.

Table 30. Template events with updated failure probabilities for electrical equipment

Event	Description	Updated Failure Probability
ZT-BAC-LP	AC BUS FAILS TO OPERATE	1.82E-05
ZT-BAT-LP	BATTERY FAILS TO OPERATE	1.27E-05
ZT-BCH-LP	BATTERY CHARGER FAILS TO OPERATE	5.33E-05
ZT-CBK-FTOC	CIRCUIT BREAKER FAILS TO OPEN/CLOSE	1.82E-03
ZT-CBK-FTOC-HV	HIGH VOLTAGE (13.8 AND 16 KV) CIRCUIT BREAKER FAILS TO OPEN/CLOSE	2.53E-03
ZT-CBK-FTOC-MV	MEDIUM VOLTAGE (4160 V AND 6.9 KV) CIRCUIT BREAKER FAILS TO OPEN/CLOSE	1.19E-03
ZT-CBK-SOP	CIRCUIT BREAKER SPURIOUS OPERATION	3.94E-06
ZT-CBK-SOP-HV	HIGH VOLTAGE (13.8 AND 16 KV) CIRCUIT BREAKER SPURIOUS OPERATION	6.55E-06
ZT-CBK-SOP-MV	MEDIUM VOLTAGE (4160 V AND 6.9 KV) CIRCUIT BREAKER SPURIOUS OPERATION	2.95E-06
ZT-TFM-FC	TRANSFORMER FAIL TO OPERATE	6.58E-05

The Class 1E 4.16 kV AC system/single train fault tree models are quantified to represent the electrical system reliability. The reliabilities of offsite power sources are not evaluated. However, with the recognition that the loss of offsite power is a major risk contributor to the loss of electrical power and core damage, two scenarios are considered in the system reliability evaluation by use of the flag set feature in SAPHIRE: normal plant operation and LOOP condition. During the normal plant operation, the supply from all offsite sources is assumed to be reliable. For the LOOP condition, all “regular” offsite power sources (i.e., the normal offsite power supply to the Class 1E buses) are assumed to be unavailable.

The diesel generators (along with support systems), the support systems to the Class 1E AC buses such as the cooling systems and ventilating systems, and Class 1E DC system are included in the Class 1E 4.16 kV AC system fault tree models. Existing SPAR modeling of DGs, support systems, and DC systems are used in the study.

4.3 AC System Analysis

The AC system reliability models were built upon the existing SPAR models for each of the seven represented plants. ESLDs were developed based on the available plant information. The SPAR models were revised with new basic events and logic associated with the electrical system. Basic events were added for additional transformer, circuit breaker, bus failures, and operator actions for manual transfer and crossties. Circuit breakers were modeled with the following failure modes: Fail to Open, Fail to Close, Fail to Remain Closed, and CCF to Open or Close. CCF of spurious operation was not modeled as it is estimated to be one or more orders of magnitude lower in risk than the CCF to open or close. DC power to the circuit breakers was modeled. An assumption was applied to the models that the DC supplies are the same ones that supply the Class 1E buses. Diesel generators were modeled, along with support systems. There was some variability across models in the details for these systems. Additionally, the modeling of HVAC systems is not consistent between plants. All transformers were modeled as well as the CCF of similar transformers. Operator actions were placed for manual transfers, crossties, etc. The Sequencer logic was updated with the latest data. LOOP logic was modeled with its associated house events.

4.3.1 Plant Type 1, 1 – Plant A

Plant A has the following configuration:

Category II, criterion 1:

During normal operation, the Class 1E buses are supplied by the main generator through a unit transformer.

Category III, criterion 1:

If the normal source of AC power fails, there are no automatic transfers and one or more manual transfers to preferred or alternate offsite power sources.

4.3.2 Plant Type 1, 2 – Plant B

Plant B has the following configuration:

Category II, criterion 1:

During normal operation, the Class 1E buses are supplied by the main generator through a unit transformer.

Category III, criterion 2:

If the normal source of AC power fails, there is one automatic transfer but no manual transfers to preferred or alternate offsite power sources.

4.3.3 Plant Type 1, 3 – Plant C

Plant C is selected as the representative of Plant Type 1, 3, which has the following configuration:

Category II, criterion 1:

During normal operation, the Class 1E buses are supplied by the main generator through a unit transformer.

Category III, criterion 3:

After loss of the normal AC power source, there is one automatic transfer. If this source fails, there may be one or more manual transfers of power sources to preferred or alternate offsite power sources.

4.3.4 Plant Type 1, 4 – Plant D

Plant D is selected as the representative of Plant Type 1, 4, which has the following configuration:

Category II, criterion 1:

During normal operation, the Class 1E buses are supplied by the main generator through a unit transformer.

Category III, criterion 4:

If the normal source of AC power fails, there is an automatic transfer to a preferred source of power. If this preferred source of power fails, there is an automatic transfer to another source of offsite power.

4.3.5 Plant Type 2, 1 – Plant E

Plant E is selected as the representative of Plant Type 2, 1, which has the following configuration:

Category II, criterion 2:

During normal operation, the Class 1E buses are supplied by a preferred offsite power source.

Category III, criterion 1:

If the normal source of AC power fails, there are no automatic transfers and one or more manual transfers to preferred or alternate offsite power sources.

4.3.6 Plant Type 2, 2 – Plant F

Plant F is selected as the representative of Plant Type 2, 2, which has the following configuration:

Category II, criterion 2:

During normal operation, the Class 1E buses are supplied by a preferred offsite power source.

Category III, criterion 2:

If the normal source of AC power fails, there is one automatic transfer but no manual transfers to preferred or alternate offsite power sources.

4.3.7 Plant Type 2, 3 – Plant G

Plant G is selected as the representative of Plant Type 2, 3, which has the following configuration:

Category II, criterion 2:

During normal operation, the Class 1E buses are supplied by a preferred offsite power source.

Category III, criterion 3:

After loss of the normal AC power source, there is one automatic transfer. If this source fails, there may be one or more manual transfers of power sources to preferred or alternate offsite power sources.

4.3.8 Summary of AC System Analysis Results

Table 31 provides a summary of the electrical system reliability analysis results (for both single 4.16 kV ESF bus and system, under either normal plant operation or LOOP condition) conducted for the seven representing plants. Other than Plant A, all plants have almost the same failure probability of the single 4.16 kV ESF bus, about 1.9E-5, under normal plant operation, which is dominated by the failure of the associated ESF bus with a probability of 1.82E-5. The failure probabilities of the 4.16 kV ESF bus system are mostly around 5.6E-7 under normal plant operation. The failure probabilities of 4.16 kV ESF bus and system have much wider ranges under LOOP condition (from 1E-3 to 6E-2 for single 4.16 kV ESF bus, and from 1E-4 to 7E-4 for 4.16 kV ESF bus system) due to the various plant design features on standby AC power sources such as cross-tie EDGs between different units in multiple-unit plants and availability of SBO EDG or SBO lines.

Plant A has much higher failure probabilities of single 4.16 kV ESF bus and system under normal plant operation due to its unique inclusion of the related 480 V ESF bus failures in the corresponding 4.16 kV ESF bus fault tree in the plant SPAR model, i.e., the failures of the associated 4.16kV/480V transformer, 480 V buses, and the circuit breakers would lead to 4.16 kV ESF bus failure. Even so, the plant still has a very reliable onsite AC electrical system with a failure probability of less than 5E-4 for single 4.16 kV ESF bus and about 5E-6 for 4.16 kV ESF bus system under normal plant operation.

Table 31. Summary of AC system unreliability results.

Plant Type (Electrical System Category II, III)	Plant/Unit	AC System Unreliability			
		Normal Plant Operation		LOOP Condition	
		Single Bus	System	Single Bus	System
1, 1	Plant A	3.63E-04	5.12E-06	6.84E-02	6.13E-04
1, 2	Plant B	1.89E-05	5.59E-07	1.36E-03	2.52E-04
1, 3	Plant C	1.90E-05	5.59E-07	9.64E-03	5.41E-04
1, 4	Plant D	1.88E-05	5.63E-07	4.64E-03	1.08E-04
2, 1	Plant E	1.95E-05	5.60E-07	9.46E-03	7.33E-04
2, 2	Plant F	1.84E-05	1.00E-07	3.70E-03	2.37E-04
2, 3	Plant G	1.88E-05	5.59E-07	1.85E-03	1.16E-04

Other insights that are gained from the above AC system reliability study are presented below:

- Different plant configurations of offsite power systems and interconnecting power circuit paths appear to have relatively small impacts on the reliability of onsite AC electrical system.
- Under normal plant operation, AC bus failures are the most significant contributors to the single train unreliability, while the CCF of the buses is the dominant contributor to the Class 1E 4.16 kV system unreliability.
- The onsite electrical system reliability for the LOOP condition depends on the plant design and performance of the standby AC power sources (for example, EDGs, SBO EDG, cross-tie features, SBO lines, etc.) and their support systems.

- EDG failures and unavailability and the SBO crosstie-related failures are the most significant contributors to single train unreliability during the LOOP condition.
- CCF of EDGs to run or the combinations of individual failures or unavailability of the EDGs are the most significant contributors to Class 1E 4.16 kV AC system unreliability during the LOOP condition. Other risk significant basic events include the operator actions, the random failures of the Class 1E buses, DC buses and batteries, and related circuit breakers.

4.4 DC System Analysis

While the DC power distribution model is similar across SPAR models, some variations do exist. This report first used a typical DC model in existing SPAR Models to conduct DC system reliability analysis, then reviewed the modeling variances and their impacts on the results.

4.4.1 DC Success Requires Both Battery and Charger

Figure 26 shows the top-level fault tree logic for a single division of the DC power system in the Plant F SPAR model. In this fault tree logic, success requires both the battery and 1-of-2 battery chargers to provide 125V DC power to the DC bus. The requirement for both battery and battery chargers to operate in order to provide DC power may appear conservative (by comparison, in other SPAR models, the success of DC power requires only the battery or the battery charger) but it is not; DC power must support AC switchgear operation at any point in the mission, and battery life is usually two to four hours. Furthermore, chargers may momentarily be unavailable during the startup of EDGs on failure of offsite power supply, so the model requires both battery and chargers to be available for the entire mission. CCFs of DC buses, batteries, and battery chargers are included in the logic.

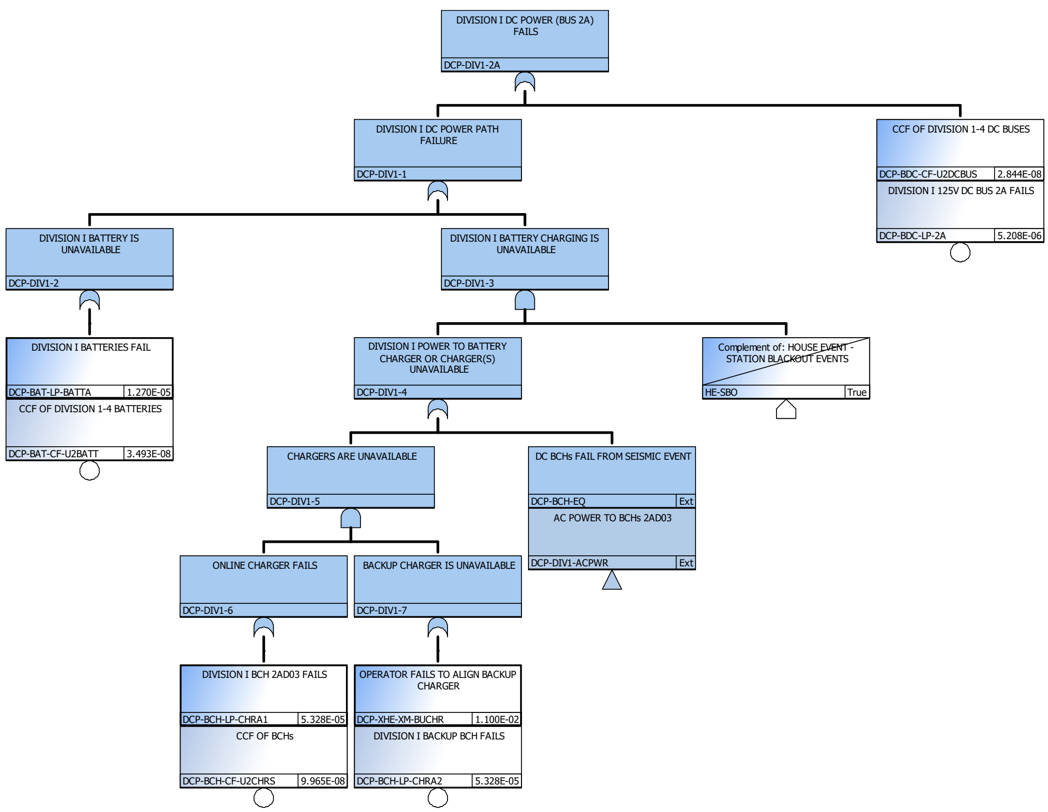


Figure 26. 125V DC Division 2A fault tree logic.

The failure probability of the above single division of DC power is solved to be 1.86E-5. The results are dominated by the failure of battery (DCP-BAT-LP-BATTA) and DC bus (DCP-BDC-LP-2A), which contribute about 68% and 28%, respectively, to the total failure probability. The dominant cut set results and importance measure results are provided in Table 32 and Table 33, respectively.

Table 32. 125V DC fault tree dominant cut sets – with DC success criteria of both battery and charger.

#	Probability	Total %	Cut Set
Total	1.863E-5	100	
1	1.270E-5	68.14	DCP-BAT-LP-BATTA
2	5.208E-6	27.95	DCP-BDC-LP-2A
3	5.861E-7	3.15	DCP-BCH-LP-CHRA1,DCP-XHE-XM-BUCHR
4	3.491E-8	0.19	DCP-BAT-CF-U2BATT
5	2.844E-8	0.15	DCP-BDC-CF-U2DCBUS

Table 33. 125V DC fault tree basic event importance measures (ordered by FV with FV >= 1E-5).

Name	Prob.	FV	RIR	Birnbaum	Description
DCP-BAT-LP-BATTA	1.27E-05	6.81E-01	5.37E+04	1.00E+00	DIVISION I BATTERIES FAIL
DCP-BDC-LP-2A	5.21E-06	2.80E-01	5.37E+04	1.00E+00	DIVISION I 125V DC BUS 2A FAILS
DCP-BCH-LP-CHRA1	5.33E-05	3.16E-02	5.94E+02	1.11E-02	DIVISION I BCH 2AD03 FAILS
DCP-XHE-XM-BUCHR	1.10E-02	3.15E-02	3.83E+00	5.34E-05	OPERATOR FAILS TO ALIGN BACKUP CHARGER
ACP-XHE-XM-ALTPWRCHA	1.00E-03	2.94E-03	3.93E+00	5.47E-05	OPERATOR FAILS TO ALIGN ALT POWER TO BCH 2ADD03
DCP-BAT-CF-U2BATT	3.49E-08	1.87E-03	5.37E+04	1.00E+00	CCF OF DIVISION 1-4 BATTERIES
DCP-BDC-CF-U2DCBUS	2.84E-08	1.53E-03	5.37E+04	1.00E+00	CCF OF DIVISION 1-4 DC BUSES
ACP-BAC-LP-E12	1.82E-05	1.32E-03	7.35E+01	1.35E-03	4160 VAC BUS E12 (20A15) IS UNAVAILABLE
ACP-BAC-LP-E124	1.82E-05	1.32E-03	7.35E+01	1.35E-03	FAULT ON 480VAC BUS E124
ACP-BAC-LP-E124TB	1.82E-05	1.32E-03	7.35E+01	1.35E-03	480V MCC E124-T-B FAILS TO OPERATE
OEP-VCF-LP-CLOPT	5.30E-03	9.01E-04	1.17E+00	3.17E-06	CONSEQUENTIAL LOSS OF OFFSITE POWER - TRANSIENT
EPS-DGN-FR-DGA	3.75E-02	5.99E-04	1.02E+00	2.98E-07	DIESEL GENERATOR A FAILS TO RUN
EPS-DGN-TM-DGA	1.48E-02	2.36E-04	1.02E+00	2.98E-07	DG A IS UNAVAILABLE DUE TO T&M
DCP-BCH-LP-CHRA2	5.33E-05	1.53E-04	3.87E+00	5.34E-05	DIVISION I BACKUP BCH FAILS
DCP-BCH-CF-U2CHRS	9.97E-08	5.91E-05	5.94E+02	1.11E-02	CCF OF BCHs
ACP-BAC-LP-E13	1.82E-05	5.36E-05	3.94E+00	5.47E-05	4.16KV BUS E13 (30A15) IS UNAVAILABLE
ACP-BAC-LP-E134	1.82E-05	5.36E-05	3.94E+00	5.47E-05	FAULT ON 480VAC BUS E134 (30B10)
EPS-DGN-FS-DGA	2.86E-03	4.56E-05	1.02E+00	2.97E-07	DIESEL GENERATOR A FAILS TO START
ACP-CRB-CC-E212	1.19E-03	1.90E-05	1.02E+00	2.97E-07	AC BUS E12 CRB E212 (152-1508) FROM AC BUS OOA19 FAILS TO OPEN
ACP-TFM-FC-0BX04	6.58E-05	1.82E-05	1.28E+00	5.16E-06	OFFSITE POWER EMERGENCY AUX XFMER 0BX04 FAILS
ACP-TFM-FC-SAT3	6.58E-05	1.82E-05	1.28E+00	5.16E-06	STARTUP/AUX XFMER 3 IS UNAVAILABLE
ESW-AOV-CC-F241A	9.51E-04	1.52E-05	1.02E+00	2.97E-07	COOLING WATER CONTROL VALVE FAILS TO OPEN

4.4.2 DC Success Requires either Battery or Charger

In other SPAR models (e.g., models for Plant A and Plant G), the success of DC power requires only either the battery or battery charger but not both. For these models, the failure of battery alone will not cause the top event (i.e., single division 125V DC power fails) to fail, but needs to be combined with the failure of the corresponding battery charger(s) to fail the top event. As a result, the failure probability of the single division is 5.21E-6, with 99.9% of the contribution coming from the failure of DC bus.

4.4.3 CCF of DC Buses

Although CCFs of batteries and battery chargers are included in 125V DC models, CCF of DC buses is often not modeled. Table 32 lists the CCF of DC buses (DCP-BDC-CF-U2DCBUS) as the #5 highest cut set, contributing just 0.15% of the single division failure. However, its significance increases dramatically when evaluating the reliability of a 125V DC power system with 4 divisions and 1-of-4 divisions is required for success. The 125V DC power system failure probability is 6.34E-8. CCF of DC bus failures contributes 45% of the system failure (Table 34).

Table 34. 125V DC power system fault tree cut sets.

#	Probability	Total %	Cut Set
Total	6.340E-8	100	
1	3.491E-8	55.07	DCP-BAT-CF-U2BATT
2	2.844E-8	44.85	DCP-BDC-CF-U2DCBUS

4.4.4 DC Room Cooling

Some DC models include the failure of battery room cooling. In solving the fault tree without the DC room cooling logic, DC success only requires either battery or battery charger and yields similar results as in Table 34, i.e., 5.21E-6 with dominant contribution from the failure of DC bus. However, if DC room cooling is required for DC success the failure probability of the DC system increases significantly from 5.21E-6 to 1.04E-4, with the cut sets dominant by the failures of battery room cooling and operation actions (Table 35).

Table 35. 125V DC single division fault tree cut sets (top 10) – with DC room cooling

#	Probability	Total %	Cut Set
Total	1.04E-4	100	
1	3.75E-5	36.06	DCP-XHE-XM-DOORS,EPS-DGN-FR-DGA
2	2.00E-5	19.24	CWS-CHL-TM-001,DCP-XHE-XM-DOORS
3	1.48E-5	14.23	DCP-XHE-XM-DOORS,EPS-DGN-TM-DGA
4	1.32E-5	12.73	CWS-MDP-TM-001,DCP-XHE-XM-DOORS
5	5.21E-6	5.01	DCP-BDC-LP-1AD1
6	2.86E-6	2.75	DCP-XHE-XM-DOORS,EPS-DGN-FS-DGA
7	1.66E-6	1.60	CWS-CHL-FR-001,DCP-XHE-XM-DOORS
8	1.39E-6	1.34	DCP-XHE-XM-DOORS,NSW-MDP-TM-TRNA
9	1.09E-6	1.05	CWS-MDP-FS-001,DCP-XHE-XM-DOORS
10	1.00E-6	0.96	CWS-XHE-XL-LOOP,DCP-XHE-XM-DOORS

5. CONCLUSIONS

This report presents a new engineering study of the on-site electrical system performance in commercial nuclear power plants during the period 1998-2015. The study contains both individual electrical component studies and electrical system (AC and DC) studies. This section presents the main results from the study.

5.1 Electrical Component Study

The electric components included in this study are circuit breakers, battery chargers, buses, batteries, and transformers. The data for circuit breakers, battery chargers, and batteries were already available in IDCCS for calendar years 1998 through 2015. The data for buses (for calendar years 2006 through 2015) and transformers (for calendar years 2005 through 2015) were obtained from ICES, then reviewed and coded. These data are statistically evaluated for impacts on reliability as a function of relevant parameters: manufacturer, system, operating environment, inspection/testing regimen, operating range (voltages, amperes), setpoints, and other factors.

Note that the data used in the electrical component study are associated with records having the component coded as the “component” type in the database. For circuit breakers, battery chargers, and batteries, there are significant numbers of records available in which these electrical components are coded as “subcomponent” or “piecepart” of other component types. Since the component type, not the subcomponent or piecepart, describes the equipment that fails and reflects operational system components that are normally modeled in PRA, only the data associated with the records that have the component coded as “component” are used in the study. This is consistent with prior studies of non-electrical components, whereby the “main” component performance is the one of interest, not the individual piecepart.

Trend analyses were performed on the component data from the 10 year period from 2006 to 2015 using a general linear model based on a Poisson distribution with a log link function and an offset. This methodology is most applicable to failure rates associated with hours of usage but can also be used for failure rates that are associated with demands.

Circuit Breakers

The study was limited within the power distribution system so that the reactor trip breakers and EDG output breakers were not considered. There were a total of 579 failures for the population of 4880 circuit breakers during the time frame under consideration.

Three groups of circuit breakers were used in the analysis: all circuit breakers, medium voltage circuit breakers (from 4.16 to 6.9 kV), and high voltage circuit breakers (13.8 kV and above). Data shows that the higher voltage breakers seem to have higher failure counts than might be expected.

The analysis for low-demand circuit breakers with failure modes Fail to Open, Fail to Close, and Fail to Open/Close was performed based on the binomial model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates for each of the three groups of circuit breakers. Trend analyses identified a statistically significant decreasing trend for the rate of high voltage circuit breakers (13.8 kV and above) failing to open/close.

The analysis for circuit breakers with failure modes Spurious Opening, Spurious Closing, and Spurious Operation was performed based on the Poisson model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates for each of the three groups of circuit breakers. Trend analyses identified a statistically significant decreasing trend for the spurious operation rate for all circuit breakers.

Battery Chargers

There were a total of 390 monitored battery chargers with 156 recorded failures during the time frame under consideration. Data shows that a large population of very old battery chargers are currently in use.

The analysis for battery chargers failing to operate was performed based on the Poisson model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates. Trend analyses identified a statistically significant increasing trend for the failure rate of battery charger.

Transformers

The study focuses on large power transformers (> 15 kV). There were a total of 506 monitored large power transformers with 185 recorded failures during the time frame under consideration. Data indicated that a large population of old large power transformers are currently in use.

The analysis for large power transformers failing to operate was performed based on the Poisson model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates. No statistically significant trends were identified in the trending analysis.

Batteries

There were a total of 415 monitored batteries with 23 recorded failures during the time frame under consideration.

There are not enough battery failures to use an Empirical Bayes analysis to look at the plant-to-plant variation in failure rates. No statistically significant trends were identified in the trending analysis.

Buses

There were a total of 1255 monitored AC buses with 62 recorded failures and no recorded DC bus failures during the time frame under consideration. It is noted that the 51-300 VAC buses group had fewer failures relative to its proportion of population, while the 2,001-5,000 VAC buses group had more failures relative to its proportion of population. Also, the most failures occurred in the oldest AC buses, those older than 40 years. Approximately 25% of the current AC buses are older than 40 years.

The analysis for AC buses failing to operate was performed based on the Poisson model. Empirical Bayes analysis was used to look at the plant-to-plant variation in failure rates. No statistically significant trends were identified in the trending analysis.

Component Failure Rates

The proposed failure rates for the above electrical components were estimated (see Table 28) by applying Empirical Bayes analysis or a Bayesian update to the Jeffreys noninformative prior with the 10 years of data (2006-2015).

5.2 Electrical System Study - AC System

The AC system study used the same categorization scheme discussed previously. There were three main categories that classified the design of offsite power systems and interconnecting power circuit paths: Category I deals with the independence of offsite power sources to the NPP; Category II classifies the power sources for the Class 1E buses during normal operation; and Category III classifies the automatic or manual transfer schemes for the Class 1E buses when both the normal and the backup sources of offsite AC power fail. The seven designs, which use the combinations of subcategories within Categories II and III (while Category I is not used due to lesser importance to the study), were used in this study. For each design, one nuclear plant site was chosen as representative by considering the level of development of the SPAR model as well as the availability of plant PRA and related information. Existing SPAR models for each selected site or unit were used as the base model that were then revised for this reliability analysis. The latest available Updated Safety Analysis Reports were used to confirm that the electrical distribution designs of the representing plants remained in the same categories as defined previously. ESLDs were developed with the available plant information. Class 1E 4.16 kV AC bus system or single train failures were used as the top event of fault tree models and as a surrogate of the electrical system unreliability. The associated fault trees in the base SPAR models were revised with the following changes:

- Revised the fault tree logic as necessary based on the ESLDs developed.
- Added new basic events for additional transformer, circuit breaker, bus failures, and operator actions for manual transfer and crossties into the logic.
- Circuit breakers were modeled for the following failure modes: Fail to Open, Fail to Close, Fail to Remain Closed, CCF to Open or Close. CCF of spurious operation was not modeled as it is lower in risk than CCF to open or close.
- Transformers, buses, batteries, and battery chargers were all modeled as Failure to Operate and common cause failure to operate.
- Used the newly developed or updated failure rates of transformers, buses, circuit breakers, batteries, and battery chargers in this study to update the SPAR models.
- Note that there are three groups of circuit breakers in the data analysis: all circuit breakers, medium voltage circuit breakers, and high voltage circuit breakers (refer to Section 3.1.1). The failure data for medium voltage circuit breaker were used for 4.16 kV and 6.9 kV breakers. The failure data for high voltage circuit breakers were used for 13.8 kV and above breakers. The failure data for all circuit breakers were used for all other breakers.
- Diesel generators (including their support systems) and the support systems to the Class 1E AC buses (such as the cooling systems, ventilating systems, and Class 1E DC system) were included in the electrical system fault tree models using the existing SPAR models for them.
- Operator actions were modeled for manual transfers and crossties as necessary. The Sequencer logic was updated with the latest data. LOOP logic was modeled with its associated house events.
- The reliability of offsite power sources were not evaluated. However, with the recognition that LOOP is a major risk contributor to the loss of electrical power and core damage, two scenarios were considered in the system reliability evaluation: Normal and LOOP. In the Normal scenario, the supply from all offsite sources was assumed to be reliable. In the LOOP scenario, all "regular" offsite power sources (i.e., the normal offsite power supply to the Class 1E buses) was assumed to be unavailable.

The electrical system reliability analyses for single train and a system of Class 1E 4.16 kV AC buses, under either normal plant operation or LOOP condition were conducted for the seven representing plants. All but one plant have almost the same failure probability for the single train under normal plant operation, about 2E-5, which is dominated by the failure of the associated Class 1E bus. The failure probabilities of the system are approximately 6E-7 under normal plant operation, except for two plants. The failure probabilities of a single train and a system have much wider ranges under LOOP condition (from 1E-3 to 6E-2 for single train, and from 1E-4 to 7E-4 for the system) due to the various plant design features related to standby AC power sources such as cross-tie EDGs between different units in multiple-unit plants and availability of SBO EDG or SBO lines.

One of the representing plants (Plant A) has higher failure probabilities of a single bus and the system under normal plant operation than other plants. This is due to its inclusion of the 480 V AC bus failures in the associated Class 1E 4.16 kV AC bus fault tree in the SPAR model. Even so, the plant still has a reliable onsite AC electrical system with a failure probability of about 4E-4 for single bus and about 5E-6 for the system under normal plant operation.

Other insights that are gained from the AC system reliability study are:

- Different plant configurations of offsite power systems and interconnecting power circuit paths have relatively small impacts on the reliability of onsite AC electrical system.
- Under normal plant operation, AC bus failures are the most significant contributors to the single train unreliability, while the CCF of the buses is the dominant contributor to the Class 1E 4.16 kV system unreliability.
- The onsite electrical system reliability for LOOP condition depends on the plant design and performance of the standby AC power sources (for example, EDGs, SBO EDG, cross-tie features, SBO lines, etc.) and their support systems.
- EDG failures and unavailability and the SBO crosstie-related failures are the most significant contributors to single train unreliability during the LOOP condition.
- CCF of EDGs to run or the combinations of individual failures or unavailability of the EDGs are the most significant contributors to Class 1E 4.16 kV AC system unreliability during the LOOP condition. Other risk significant basic events include the operator actions, the random failures of the Class 1E buses, DC buses and batteries, and related circuit breakers.

5.3 Electrical System Study - DC System

While the DC power distribution models are generally similar to each other in the SPAR models, some variations exist. This report first used a typical DC model in an existing SPAR Models to conduct DC system reliability analysis, then reviewed the modeling variances and their impacts on the results.

The failure probability of a single division of DC power in a typical SPAR model is about 2E-5. The results are dominant by the failure of battery and DC bus, which contribute about 68% and 28%, respectively, to the total failure probability. Some DC system modeling variances in SPAR and their impacts are presented below:

- DC Success Requires either Batter or Charger

  In the typical SPAR model, the success of DC power requires both battery and battery charger. For some SPAR models, however, the success of DC power only requires either the battery or battery charger, but not both. For these models, the failure probability of single division of DC power is decreased to 5E-6, with 99.9% of the contribution coming from the failure of DC bus.

- CCF of DC Buses

  Although CCFs of batteries and battery chargers are always included in 125V DC models, CCF of DC buses is often not modeled. The CCF of DC buses may contributes as little as 0.1% towards the single division failure. However, its significance increases dramatically when evaluating the reliability of a 125V DC power system with 4 divisions and 1-of-4 divisions is required for success. The failure probability for such DC power system is about 6E-8, with the CCF of DC bus failures contributes 45% of the system failure.

- DC Room Cooling

  Some SPAR models include the failure of battery room cooling in DC fault tree. If DC room cooling is required for DC success, the failure probability of the DC system could increase significantly, from 5E-6 (with no room cooling requirement) to 1E-4, while the cut sets are dominant by the failures of battery room cooling and operation actions.

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2. TITLE AND SUBTITLE

3. DATE REPORT PUBLISHED

MONTH	YEAR

4. FIN OR GRANT NUMBER

5. AUTHOR(S)

6. TYPE OF REPORT

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

13. AVAILABILITY STATEMENT

14. SECURITY CLASSIFICATION
(This Page)
(This Report)

15. NUMBER OF PAGES

16. PRICE