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Analysis of Loss-of-Offsite-Power Events

1987–2018

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ABSTRACT

Loss of offsite power (LOOP) can have a negative impact on a nuclear power plant's ability to achieve and maintain safe shutdown conditions. LOOP event frequencies and times required for subsequent restoration of offsite power are important inputs to plant probabilistic risk assessments. This report presents a statistical and engineering analysis of LOOP frequencies and durations at U.S. commercial nuclear power plants. The data used in this study were based on the operating experience during calendar years 1987 through 2018. LOOP events during critical operations that do not result in a reactor trip are not included. Frequencies and durations were determined for four event categories: plant-centered, switchyard-centered, grid-related, and weather-related. No significant trends in critical operation LOOP frequencies over the most recent 10-year period were identified. However, adverse trends in LOOP durations were identified for switchyard-centered and grid-related LOOPs, as well as overall LOOPs during critical operation and overall LOOPs during shutdown operation. Both grid-related and weather-related LOOP events were found to show statistically significant seasonality. The engineering analysis of LOOP data showed that human errors have been much less frequent since 1997 than in the 1987–1996 time period.

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EXECUTIVE SUMMARY

Loss of offsite power (LOOP) can have a negative impact on a plant's ability to achieve and maintain safe shutdown conditions. Risk analyses have shown that LOOP can represent a majority of the internal event risk at some plants.

The objectives of this study are (1) to summarize the frequency, duration, and other aspects of LOOP events at commercial nuclear plants in the U.S. through calendar years 2018 and (2) to provide operational experience insights and trend information. Since this study includes the most recent annual data, it provides a basis for input to Standardized Plant Analysis Risk (SPAR) and industry probabilistic risk assessments (PRAs).

As in previous studies, the LOOP data were studied for four categories: plant-centered, switchyard-centered, grid-related, and weather-related. There were two new LOOP events in 2018, both during shutdown operation (one plant-centered, one weather-related).

Occurrence Rates. An investigation of possible trends in the LOOP occurrence rates for the most recent 10 years shows no significant trends in critical operation LOOP frequencies for all LOOP categories as well as for each of the four LOOP categories over the most recent 10-year period (2009–2018).

To characterize the variation in LOOP frequencies in each category, for plant critical operation and shutdown operation, statistical tests were performed for each of the categories to see if there were significant differences across plant units and between regions as defined by the North American Electric Reliability Corporation (NERC). For the data that are not homogeneous (i.e., there are significant differences among the data groupings), Empirical Bayes (EB) gamma distributions were sought to describe any identified variation. The results show that the critical operation grid-related, shutdown operation grid-related, and shutdown operation weather-related LOOPs can be described by EB distributions as reflecting variation when the data are pooled by reliability councils. Also, the critical operation weather-related, shutdown operation plant-centered, and the combined shutdown data can be modeled using EB distributions showing variation between plants. For the remaining data groupings, the data appear homogeneous. In those cases, the Jeffreys prior was updated with industry-level data to obtain a posterior distribution. These distributions could be used in risk assessments as prior distributions to be updated with plant-specific data.

Recovery Times. A trend analysis of the sustained (greater than 2 minute) LOOP recovery times at the site level showed an extremely statistically significant increasing trend for switchyard-centered LOOPs (p-value = 2.22E-4). A significant increasing trend is present for grid-related LOOPs (p-value = 0.012). These two categories represent over half of the data, and the trend carries over into the results for total LOOP recovery times. With the higher sample size, the increasing trend in total LOOP recovery time is the most significant (p-value = 1.09E-5). Highly statistically significant increasing trends are also identified for both overall data during critical operation (p-value = 4.21E-3) and overall data during shutdown operation (p-value = 1.66E-3). The above statistically significant increasing trends indicate they take longer to recover from the associated LOOP categories exist. There is no trend in the recovery times for plant-centered or weather-related events.

To develop estimates of the probability of exceeding specified recovery time limits, the recovery times for each category were fit to lognormal distributions by matching moments for the underlying normal distributions. The results show that switchyard-related LOOPs have the shortest (on average) recovery times while the weather-related LOOPs have the longest recovery times.

Seasonal Effects. To study seasonal patterns in the LOOP occurrences, the 1997–2018 data were grouped by months and evaluated to see if the counts could be uniformly distributed. The statistical test shows that the counts are not uniformly distributed across the 12 months, therefore seasonal effects on

LOOP frequency do exist, for critical operation grid-related LOOPs (highly statistically significant, with p-value = 0.008) and for critical operations weather-related LOOPs (statistically significant, with p-value = 0.017).

Multi-Unit LOOPs. Data for LOOP events that affected multiple units at multi-unit sites was reviewed. No 2018 LOOP events affected multiple units. There were seven occasions during 1987-1996 and 13 occasions during 1997–2018 when more than one unit at a site was affected by the same incident. The 13 occasions contributed 28 of the 98 unit events during 1997–2018. When multiple units at a site experience a LOOP on the same day, the LOOP events may not be independent. While the analyses in this report treat the events independently for the most part, we also present an investigation of different approaches to address multi-unit LOOP events.

Consequential LOOPs. NUREG/CR-6890 provided an estimate of conditional probabilities of a consequential LOOP (CLOOP) given a reactor trip, 5.3E-3 for the period 1997–2004 and 3.0E-3 for the period 1986–1996. The estimated conditional probability of 5.3E-3 is currently used in the SPAR models. This study presents an update of the conditional probability using data from 1997–2018. The updated conditional probabilities of CLOOP given a reactor trip are found to be 2.3E-3, which represents a reduction of about 56% versus the value of 5.3E-3 from NUREG/CR-6890.

Engineering Analysis of LOOP Data. The engineering review of the LOOP data found that for the period of 1997–2018, equipment failures are dominated by failures of circuits, relays, and transformers. One new LOOP qualified as a failure of relays in 2018. Human errors associated with the events occurred primarily in maintenance and testing. The weather events were dominated by tornadoes, high winds, and hurricanes. This review shows that human errors have been much less frequent during the current period, 1997–2018, than in the 1987–1996 time period.

ACRONYMS

ac	alternating current
CLOOP	consequential loss of offsite power
EDG	emergency diesel generator
EB	empirical Bayes
GR	grid-related
IE	initiating event
INL	Idaho National Laboratory
LER	licensee event report
LOCA	loss of coolant accident
LOOP	loss of offsite power
MLE	maximum likelihood estimator
NERC	North American Electric Reliability Council
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PC	plant-centered
PLOOP	partial loss of offsite power
PRA	probabilistic risk assessment
rcry	reactor critical year
rsy	reactor shutdown year
SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SBO	station blackout
SC	switchyard-centered
SPAR	Standardized Plant Analysis Risk
WR	weather-related

GLOSSARY[1]

Loss of offsite power (LOOP) event—the simultaneous loss of electrical power to all unit safety buses (also referred to as emergency buses, Class 1E buses, and vital buses) requiring all emergency power generators to start and supply power to the safety buses. The nonessential buses may also be de-energized as a result of this situation. *Note that while this definition includes "requiring all emergency power generators to start and supply power to the safety buses," an event in which all emergency power generators started but did not load in response to a loss of offsite power to all safety buses is still classified as a LOOP event in this report.*

An alternate definition of a LOOP event based on NUREG-2122 and NUREG/CR-6890 is "the loss of all AC power from the electrical grid to the plant safety buses."

Partial LOOP (PLOOP) event—the loss of electrical power to at least one but not all unit safety buses that requires at least one emergency power generator to start and supply power to the safety bus(es).

Station blackout (SBO)—the complete loss of ac power to safety buses in a nuclear power plant unit. Station blackout involves the LOOP concurrent with the failure of the onsite emergency ac power system. It does not *require* the loss of available ac power to safety buses fed by station batteries through inverters or successful high-pressure core spray operation *or station blackout power supplies (e.g. non-safety related SBO diesel generators or alternate offsite SBO feeds). For example, a LOOP concurrent with the failure of the onsite emergency ac power system is a SBO, even if SBO diesel generators are functional.*

*We have noted the slight differences between the above SBO definition (based upon NUREG/CR-6890) and that in 10 CFR 50.2 and ASME/ANS RA-Sb-2013. For example, 10CFR 50.2 states that "Station blackout means the complete loss of alternating current (ac) electric power to the **essential and nonessential switchgear buses** in a nuclear power plant (i.e., loss of offsite electric power system concurrent with turbine trip and unavailability of the onsite emergency ac power system)." The SBO definition in NUREG/CR-6890 and the following annual LOOP analyses do not include non-essential buses (also referred to as non-safety buses, non-1E buses) for a number of reasons, for instance, non-essential buses are usually not modeled in probabilistic risk assessment (PRA), they are not used as a criterion in the state-of-the-practice identifying/classifying LOOP and SBO events, and the performance of non-essential buses is generally not considered sufficient in leading PRA sequences to the safe and stable state.*

Terms Related to LOOP Categories

Grid-related LOOP—a LOOP event in which the initial failure occurs in the interconnected transmission grid that is outside the direct control of plant personnel. Failures that involve transmission lines *within* the site switchyard are usually classified as switchyard-centered events if plant personnel can take actions to restore power when the fault is cleared. However, the event should be classified as grid related if the transmission lines fail from voltage or frequency instabilities, overload, or other causes that require restoration efforts or corrective action by the transmission operator.

Plant-centered LOOP—a LOOP event in which the design and operational characteristics of the nuclear power plant unit itself play the major role in the cause and duration of the LOOP. Plant-centered failures typically involve hardware failures, design deficiencies, human errors, and localized weather-induced faults such as lightning. The line of demarcation between plant-centered and

[1] This Glossary section uses the same definitions as those in NUREG/CR-6890. Additional notes or revisions are in *Italic font* for clarification as needed.

switchyard-centered events is the nuclear power plant main and station power transformers' high-voltage terminals.

Switchyard-centered LOOP—a LOOP event in which the equipment, or human-induced failures of equipment, in the switchyard play the major role in the loss of offsite power. Switchyard-centered failures typically involve hardware failures, design deficiencies, human errors, and localized weather-induced faults such as lightning. The line of demarcation between switchyard-related events and grid-related events *is the point where the transmission lines leave the switchyard*.

Weather-related LOOP—a LOOP event caused by severe or extreme weather. There are two subcategories:

Extreme-weather-related LOOP—a LOOP event caused by extreme weather. Examples of extreme weather are hurricanes, strong winds greater than 125 miles per hour, and tornadoes. Extreme-weather-related LOOP events are also distinguished from severe weather-related LOOP events by their potential to cause significant damage to the electrical transmission system and long offsite power restoration times. Extreme-weather-related events are included in the weather-related events category in this volume.

Severe-weather-related LOOP—a LOOP event caused by severe weather, in which the weather was widespread, not just centered on the site, and capable of major disruption. Severe weather is defined to be weather with forceful and broad (beyond local) effects. A LOOP is classified as a severe-weather event if it was judged that the weather was widespread, not just centered at the power plant site, and capable of major disruption. An example is storm damage to transmission lines instead of just debris blown into a transformer. This does not mean that the event had to actually result in widespread damage, as long as the potential *existed*. Examples of severe weather include thunderstorms, snow, and ice storms. Lightning strikes, though forceful, are normally localized to one unit, and so are coded as plant centered or switchyard centered. LOOP events involving hurricanes, strong winds greater than 125 miles per hour, and tornadoes are included in a separate category—extreme-weather-related LOOPs. Severe-weather-related events are included in the weather-related category in this volume.

Terms Related to Time Needed to Restore Offsite Power

Actual bus restoration time—the duration, in minutes, from event initiation until offsite electrical power is restored to a safety bus. This is the actual time taken*, from the onset of the LOOP (time zero), until offsite power is restored* from the first available source to a safety bus.

Potential bus recovery time—the duration, in minutes, from the event initiation until offsite electrical power could have been recovered to a safety bus. This estimated time is less than or equal to the actual bus restoration time. *The determination of potential bus recovery time is based on engineering judgement (refer to Section 6.7 of NUREG/CR-6890).*

Switchyard restoration time—the duration, in minutes, from event initiation until offsite electrical power is actually restored (or could have been restored, whichever time is shorter) to the switchyard. Such items as no further interruptions to the switchyard, adequacy of the frequency and voltage levels to the switchyard, and no transients that could be disruptive to plant electrical equipment, should be considered in determining the time.

Terms Related to LOOP Classifications

LOOP initiating event (LOOP-IE), or Functional LOOP IE—a LOOP occurring while a plant is at power and also involving a reactor trip. The LOOP can cause the reactor to trip or both the LOOP event and the reactor trip can be part of the same transient. Note that this is the NUREG/CR-5750 definition of a functional impact LOOP initiating event (as opposed to an initial plant fault LOOP initiating event). *LOOP-IE events are further subdivided into LOOP-IE-I, LOOP-IE-C, and LOOP-IE-NC (see below).*

Initial plant fault LOOP IE (LOOP-IE-I)—a LOOP-IE in which the LOOP event causes the reactor to trip. LOOP-IE-I is a subset of LOOP-IE events. NUREG/CR-5750 uses the term "initial plant fault" to distinguish these events from other "functional impact" events (LOOP-IE-C and LOOP-IE-NC).

Consequential LOOP IE (LOOP-IE-C)—a LOOP-IE in which the LOOP is the direct or indirect result of a plant trip. For example, the event is consequential if the LOOP occurred during a switching transient (*e.g.*, main generator tripping) after a unit trip from an unrelated cause. In this case, the LOOP would not have occurred if the unit remained operating. LOOP-IE-C is a subset of LOOP-IE events.

Nonconsequential LOOP IE (LOOP-IE-NC)—a LOOP-IE in which the LOOP occurs following, but is not related to, the reactor trip. LOOP-IE-NC is a subset of LOOP-IE events.

LOOP no trip event (LOOP-NT)—a LOOP occurring while a plant is at power but not involving a reactor trip. (Depending upon plant design, the plant status at the time of the LOOP, and the specific characteristics of the LOOP event, some plants have been able to remain at power given a LOOP.)

LOOP shutdown event (LOOP-SD)—a LOOP occurring while a plant is shutdown.

Additional Terms Related to LOOP Conditions

Sustained LOOP event—a LOOP event in which the potential bus recovery time is equal to or greater than 2 minutes.

Momentary LOOP event—a LOOP event in which the potential bus recovery time is less than 2 minutes.

Analysis of Loss-of-Offsite-Power Events 1987 - 2018

1. INTRODUCTION

United States commercial nuclear power plants (NPPs) rely on alternating current (ac) power supplied through the electric grid for both routine operation and accident recovery. While emergency generating equipment is always available onsite, a loss of offsite power (LOOP) can have a major negative impact on a plant's ability to achieve and maintain safe shutdown conditions. Risk analyses have shown that LOOP can represent a majority of the internal events risk at many plants. Therefore, LOOP events and subsequent restoration of offsite power are important inputs to plant probabilistic risk assessments (PRAs). These inputs must reflect current industry performance so PRAs accurately estimate the risk from LOOP-initiated scenarios.

The objectives of this study are (1) to summarize the frequency, duration, and other aspects of LOOP events at commercial nuclear plants in the U.S. through calendar year 2018 and (2) to provide operational experience insights and trend information. Since this study includes the most recent annual data, it provides a basis for input to Standardized Plant Analysis Risk (SPAR) and industry PRAs.[2]

NUREG/CR-6890, *Reevaluation of Station Blackout Risk at Nuclear Power Plants: Analysis of Loss of Offsite Power Events* (Eide, Gentillon, and Wierman, 2005) was completed in 2005. Annual update studies similar to the present document have been issued since (see https://nrcoe.inl.gov/resultsdb/LOSP/). This study continues the work by covering data through 2018. As in the previous studies, the events are studied based on four LOOP categories: plant-centered (PC), switchyard-centered (SC), grid-related (GR), and weather-related (WR). See the Glossary for definitions of these and other related terms.

The starting period of the data for most analyses in this report is January 1, 1997.[3] In previous reports in this series, this date is regarded as the start of deregulation of the U.S. electrical industry. The actual deregulation process has been piecemeal among states, but most states with deregulation had implemented the changes in the 1996–1997 time period. In the update reports prior to 2014, data from fiscal year 1988 (which includes some of calendar year 1987) were included for critical operations weather-related LOOPs and for shutdown operations LOOPs other than switchyard-centered. However, as more time and data have accrued, the older data are no longer displayed in the graphs or used in the frequency analyses. Frequency data from 1987 to the current update year are summarized in section 2.3. Appendix A lists the licensee event reports (LERs) associated with the LOOP events supporting this study.

This report contains trending information as well as distributions that describe variation in the data. Since the 2014 update, the frequency trends have been analyzed for the most recent 10 years (2008-2018 for this study).

The other aspect of LOOP events that is a main focus of this report is their duration. Three durations are explained in the Glossary, but the one that is analyzed herein is the potential recovery time. Because

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[2] The LOOP frequency distribution results in this report include more recent LOOP data and could therefore be used to update the LOOP initiating event frequency in PRA model in place of those from the less-frequent data update for industry average parameter estimates (e.g., 2015 Updates in https://nrcoe.inl.gov/resultsdb/AvgPerf/) or the baseline frequencies in the NRC initiating event update study (e.g., INL/EXT-18-45524 for 2017 IE report).
[3] Different starting years of the data have been used for specific analysis in the study. As such, the counts of LOOP events in various sections and tables of the report will vary. The ranges of data are included in the associated table titles.

the data are limited, the data from 1988 to 2018 are still used here. In the trend analysis of the recovery times, the time span is 1997–2018.

NUREG/CR-6890 also classifies LOOP events into LOOP-IE which occurs during critical operation and involve a plant trip, LOOP-NT which occurs during critical operation, but the plant is able to continue operation without a plant trip, and LOOP-SD, which occurs during shut down. The LOOP-IE events are further divided into LOOP-IE-I in which a LOOP event causes the reactor trip, LOOP-IE-C in which an unrelated reactor trip causes a LOOP to occur, and LOOP-IE-NC in which a reactor trip and LOOP occur during the same transient but are unrelated. Partial LOOP (PLOOP) events occur when some but not all offsite power is lost to unit safety buses. See the Glossary for definitions and Figure 1 for the classification.

The data covered in the annual update analysis includes LOOP initiating events (LOOP-IE) and LOOP shutdown events (LOOP-SD), but not LOOP no-trip events (LOOP-NT) or partial LOOP events (PLOOP).

Since 2009, the annual LOOP updates have included a discussion of emergency diesel generator (EDG) repair times. Such analysis has been moved to the EDG component study report since 2018 (Schroeder, 2018) and can be accessed from https://nrcoe.inl.gov/resultsdb/CompPerf/.

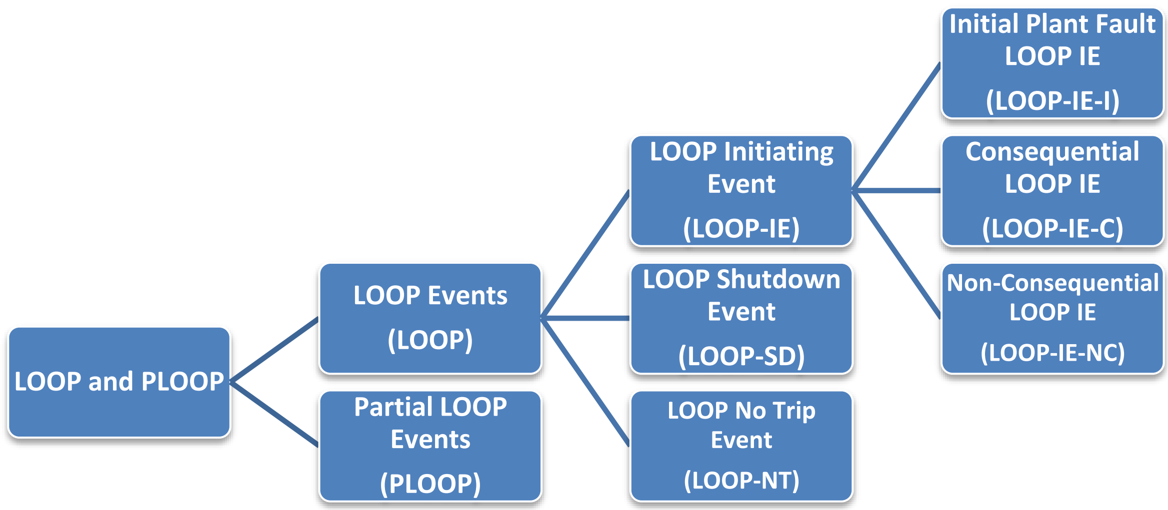


Figure 1. LOOP classification

1.1 Main Changes in this Study

Main changes in this study include:

(1) Two new LOOP events occurred in 2018;

- Oconee 3 on May 10, 2018, (LER 2872018002) as shutdown operation plant-centered
- Pilgrim on March 13, 2018, (LER 2932018004) as shutdown operation weather-related

(2) The North American Reliability Corporation (NERC) reliability council regions used in NUREG/CR-6890 and previous LOOP annual update analyses have changed on both the NERC reliability council names and territories. The latest NERC reliability council regions are incorporated into this study (see Section 2.2).

(3) More discussions on multi-unit LOOP events are provided in this study (see Section 4.2).

(4) Conditional probabilities of consequential LOOP given a reactor trip is updated in this study (see Section 4.3).

2. INDUSTRY-WIDE LOOP FREQUENCIES

Industry-average LOOP frequencies were determined for calendar years 1997–2018. The 1997 start date for the data reflects the period since implementation of deregulation of the electrical supplier system. The values include critical and shutdown operations in four event categories: plant-centered, switchyard-centered, grid-related, and weather-related. Section 2.1 provides frequentist analysis of LOOP frequencies for 1997–2018. Annual data and trending analysis for the most recent 10 years are presented. Section 2.2 provides Bayesian analysis of LOOP frequencies, which are more often used in PRA applications, for 1997–2018. The section discusses variation in the frequencies between plants. It also provides an update of the NERC names and territories, and the uncertainty distributions for critical operation grid-related LOOPs for plants grouped in NERC regions. Section 2.3 presents a summary of LOOP data for 1987–2018.

2.1 Frequentist Analysis of LOOP Frequencies and Trend

2.1.1 LOOP Frequencies

Table 1 reports the observed event counts and reactor years, with the latter one from the Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases website Operating Time webpage, https://nrcoe.inl.gov/resultsdb/ReactorYears. The simplest statistic that comes from the counts and exposure time is the maximum likelihood estimate (MLE) of the occurrence rate. This estimate is the value that maximizes the probability of seeing the observed data, assuming a constant LOOP occurrence rate across the industry for each LOOP category/reactor mode. It is computed as *event count/exposure time*.

Table 1. Average LOOP frequencies for 1997–2018.

Mode	LOOP Category	Events	Reactor Critical or Shutdown Years	Maximum Likelihood Estimate (MLE) (Events/Years)	Percent
Critical Operation[a]	Plant-centered	6	2027.68	2.96E-03	10.53
	Switchyard-centered	19	2027.68	9.37E-03	33.33
	Grid-related	20	2027.68	9.86E-03	35.09
	Weather-related	12	2027.68	5.92E-03	21.05
	All LOOPs	57	2027.68	2.81E-02	100.00
Shutdown Operation[b]	Plant-centered	9	234.11	3.84E-02	21.95
	Switchyard-centered	17	234.11	7.26E-02	41.46
	Grid-related	4	234.11	1.71E-02	9.76
	Weather-related	11	234.11	4.70E-02	26.83
	All LOOPs	41	234.11	1.75E-01	100.00

a. The frequency units for critical operation are events per reactor critical year (/rcry).
b. The frequency units for shutdown operation are events per reactor shutdown year (/rsy)

For critical operation, switchyard-centered LOOPs contribute 33% to the total critical operation LOOP frequency, while grid-related LOOPs contribute 35% of the total. For shutdown operation, switchyard-centered events contribute about 42% of the total shutdown operation LOOP frequency. It is interesting to note that grid-related is the most common type of LOOP category during critical operation, but is the least common LOOP category during shutdown.

2.1.2 Plots of Annual Data and 10-year Trends

The performance trends provided in this section are intended to be representative of current operating conditions. The amount of historical data to be included in the trend period requires judgement on what constitutes current trend, which is considered to be the most recent 10 years in the study. To provide perspective, the plots include data since 1997 when implementation of deregulation of the electrical system was well underway.

Figure 2 shows the annual estimated overall LOOP frequencies from 1997 through 2018 and the trend for the most recent 10 years (from 2009 through 2018) during critical operation for all LOOP categories. The 90% confidence intervals of the LOOP frequency (plotted vertically) are confidence intervals for the estimated rate associated with each individual year's data. The 90% confidence band of the trend for the most recent 10 years is a simultaneous band, intended to cover 90% of the possible trend lines that might underlie the data. Each regression itself is analyzed as a generalized linear model, with Poisson data in each year and a trend from year to year postulated for the logarithm of the occurrence rate.

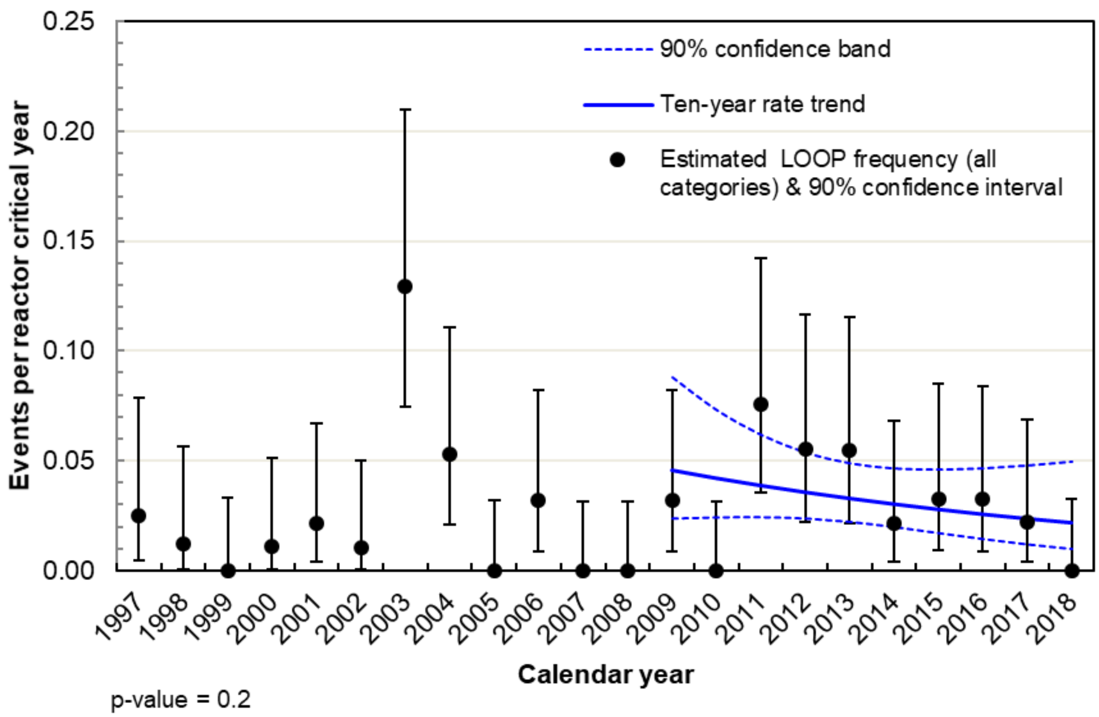


Figure 2. Estimated LOOP frequencies (all categories) and 10-year trend during critical operations.

Figures 3-6 show the annual frequencies and 10-year trends for critical operations for each of the four LOOP categories. The LERs for the events supporting the plots are listed in Appendix A.

None of the p-values in Figures 2–6 are less than or equal to 0.05, therefore there are no statistically significant[4] 10-year trends identified in critical operation LOOP frequencies for overall LOOP (Figure 2) as well as for the four LOOP categories covering the 2009–2018 period (Figures. 3-6).

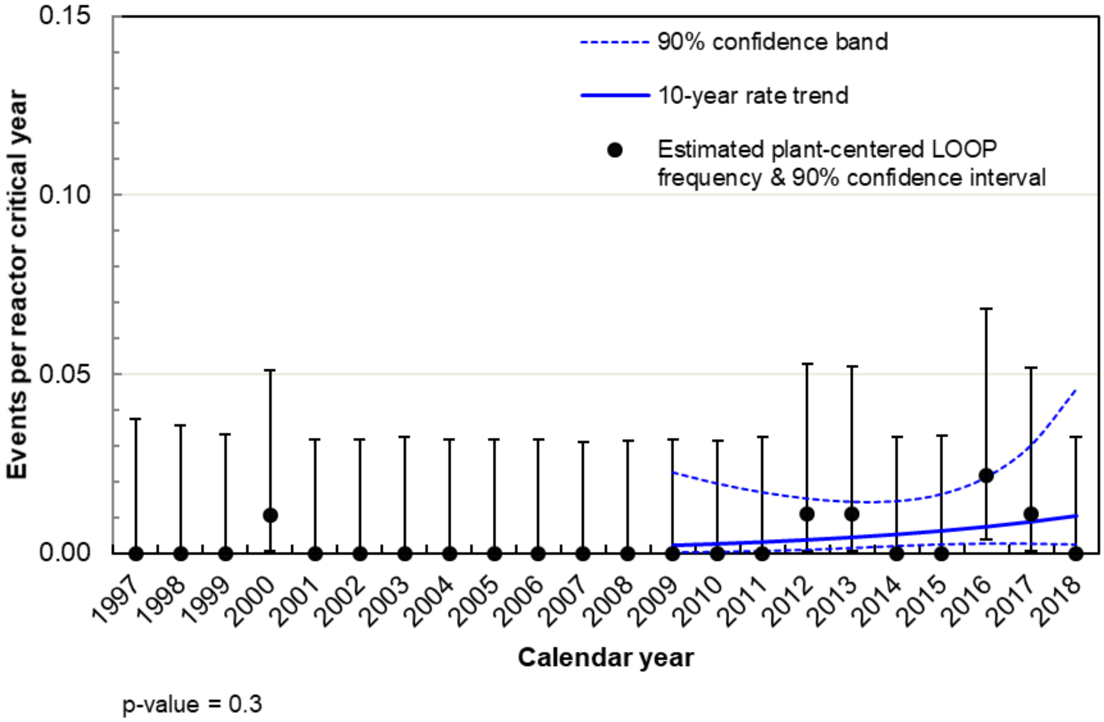


Figure 3. Estimated plant-centered LOOP frequency and 10-year trend during critical operation.

[4] Statistical significance is defined in terms of the 'p-value.' A p-value is a probability indicating whether to accept or reject the null hypothesis that there is no trend in the data. P-values of less than or equal to 0.05 indicate that we are 95% confident there is a trend in the data (reject the null hypothesis of no trend.) By convention, we use the "Michelin Guide" scale: p-value < 0.05 (statistically significant), p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant).

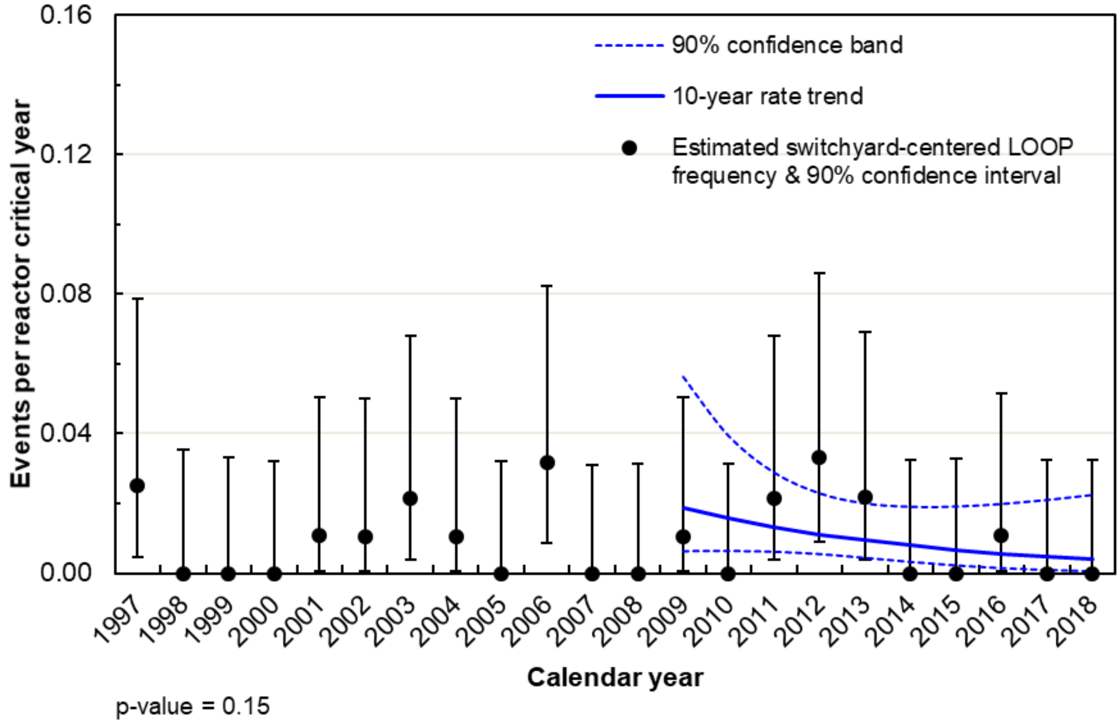


Figure 4. Estimated switchyard-centered LOOP frequency and 10-year trend during critical operation.

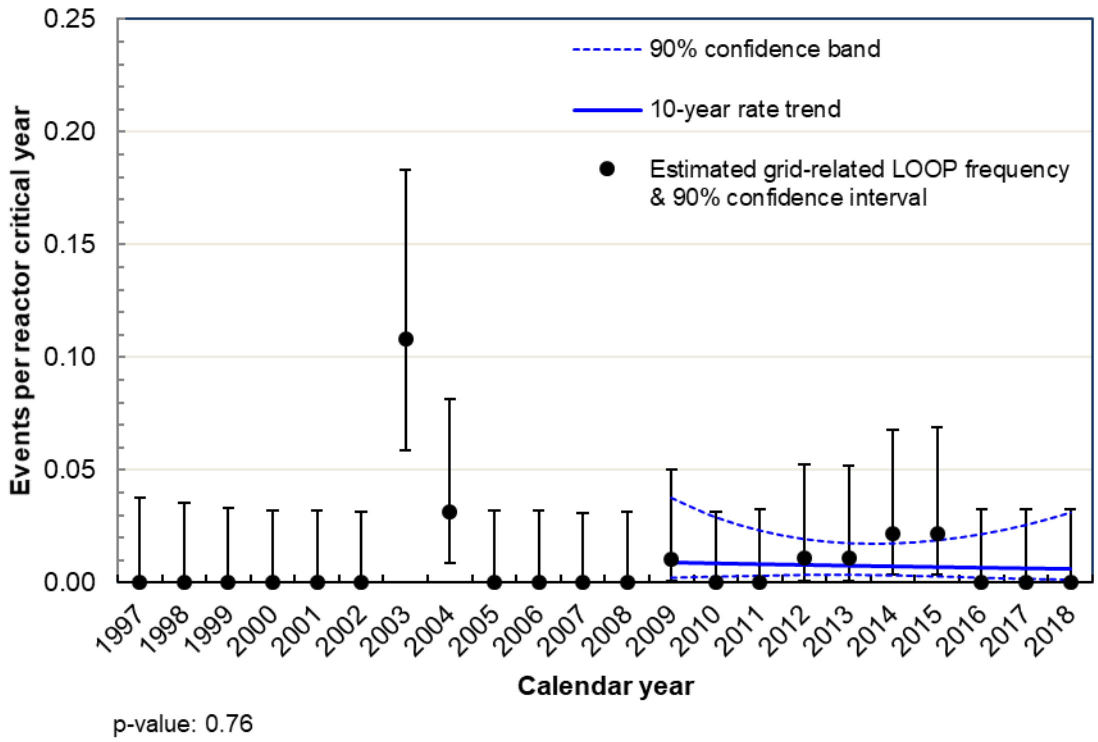


Figure 5. Estimated grid-related LOOP frequency and 10-year trend during critical operation.

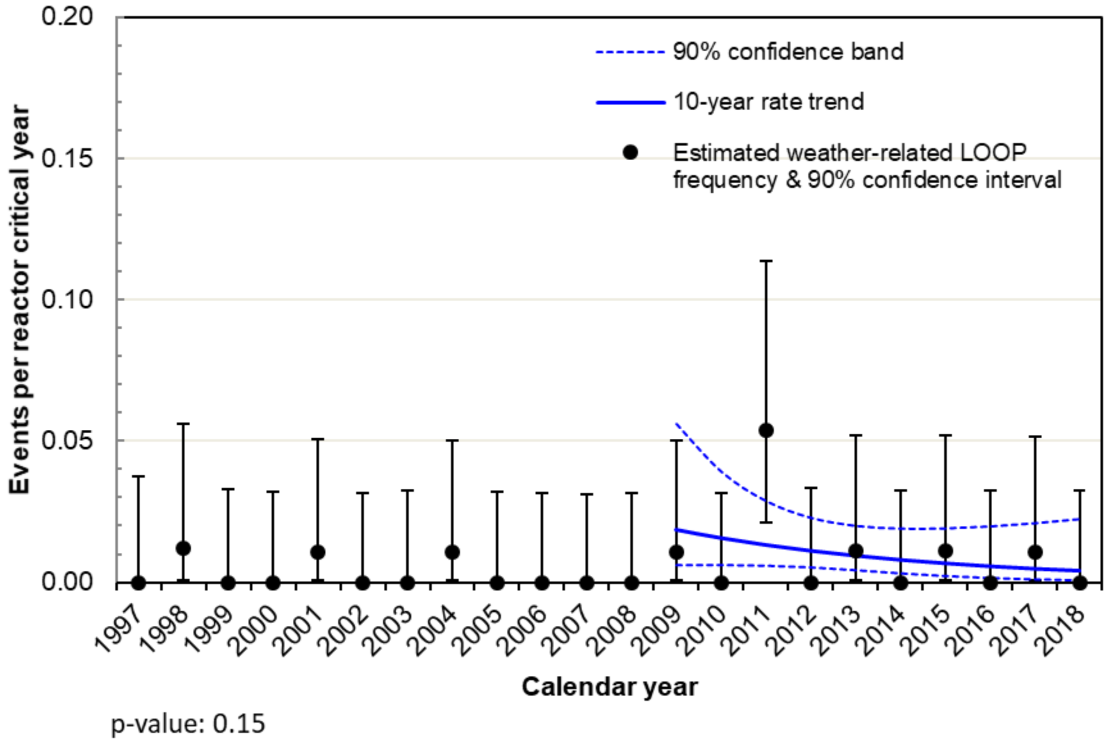


Figure 6. Estimated weather-related LOOPs frequency and 10-year trend during critical operation.

2.2 Bayesian Analysis of LOOP Frequencies

2.2.1 LOOP Frequencies

When developing parameter estimates for use in PRA applications, the question arises as to whether all plants are comparable, or whether there is significant plant-to-plant variation in performance. Other factors might also account for differences in performance, such as electrical grid, power pool, plant operating mode, and time (calendar years). In this section, Bayesian methods are used to derive distributions describing industry-level occurrence rates for use in PRAs. The methods account for uncertainties coming from the random nature of the data and from between-group variation. The methods start by searching for variability in the data after grouping (pooling) the data based on a particular factor. The variability is sought for each LOOP frequency estimate using chi-squared tests and empirical Bayes analyses (Atwood, C. L. et al., 2003).

When the statistical tests detect variation, we can obtain an empirical Bayes (EB) distribution representing that variation, then the empirical Bayes distribution result is reported in Table 2. If the tests for variation indicate the data appear homogeneous for each grouping, we then use a Jeffreys noninformative prior to construct the industry estimate. The Jeffreys prior results in a distribution with the event count plus 0.5, divided by the exposure time, as the mean (compared with the simple MLE, which is the count divided by the exposure time). For each distribution, we tabulated the 5th, 50th, 95th percentiles, and mean.

Past data support separating data by plant mode of operation, namely critical operations and shutdown operations, for grid and weather-related LOOPs, but recent data has shown fewer differences. The decision has been made to retain the split in the data for all LOOP categories because of the different plant operating conditions and the different demands on the emergency power system associated with the two operational modes even when evidence for variability is weak.

Table 2. Gamma distributions describing variation in LOOP frequencies across the U. S. NPP industry (1997–2018).

Mode	LOOP Category	Shape (α)	Scale (β)	5%	Median	95%	Gamma Mean	Simple MLE	Notes
Critical Operation	Plant-centered	6.5	2027.7	1.45E-03	3.04E-03	5.51E-03	3.21E-03	2.96E-03	a
	Switchyard-centered	19.5	2027.7	6.34E-03	9.45E-03	1.35E-02	9.62E-03	9.37E-03	a
	Grid-related	20.5	2027.7	6.74E-03	9.95E-03	1.40E-02	1.01E-02	9.86E-03	b
	Weather-related	1.54	259.00	7.22E-04	4.72E-03	1.53E-02	5.93E-03	5.92E-03	c
	All	57.5	2027.7	2.25E-02	2.82E-02	3.48E-02	2.84E-02	2.81E-02	a
Shutdown Operation	Plant-centered	9.5	234.3	2.16E-02	3.91E-02	6.43E-02	4.06E-02	3.84E-02	a
	Switchyard-centered	17.5	234.3	4.79E-02	7.33E-02	1.06E-01	7.47E-02	7.26E-02	a
	Grid-related	4.5	234.3	7.10E-03	1.78E-02	3.61E-02	1.92E-02	1.71E-02	b
	Weather-related	0.5	10.1	1.85E-04	2.22E-02	1.89E-01	4.91E-02	4.69E-02	c
	All	2.3	13.1	3.71E-02	1.52E-01	3.99E-01	1.76E-01	1.75E-01	c

a. Homogeneous. The data rule out the possibility of wide variations among plants or within the other data groupings that were considered. The Jeffreys prior is used.

b. Homogeneous. With the new NERC regions (see Section 2.2.2), Empirical Bayes did not provide results to be used. Jeffreys prior was used to provide a homogenous posterior distribution.

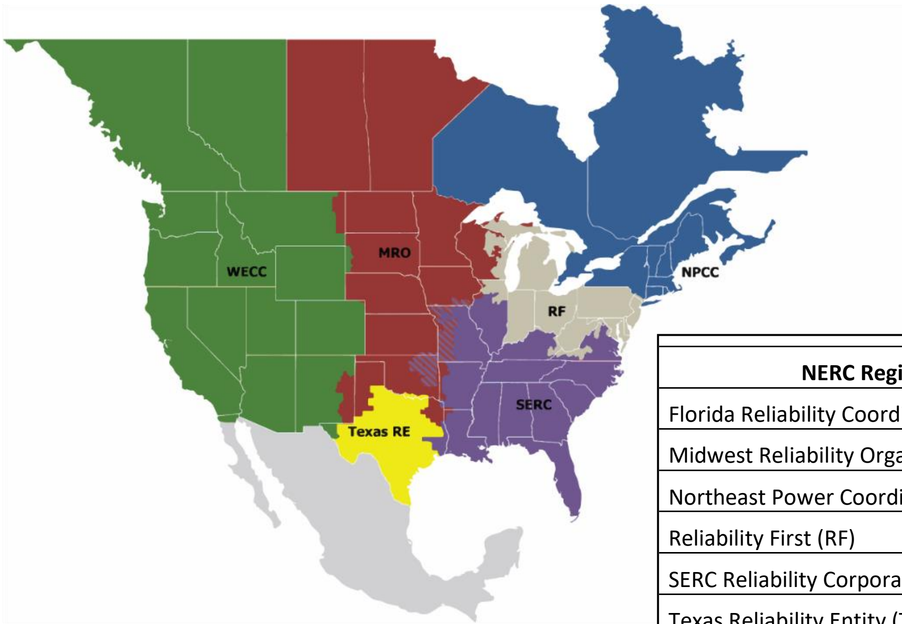
c. Empirical Bayes. There appears to be variability between plants.

The results show that the critical operation weather-related, shutdown operation weather-related, and the combined shutdown data can be modeled using EB distributions showing variation between plants. For the remaining data groupings, the data appear homogeneous, i.e., the variations among the data groupings are small. In those cases, the Jeffreys prior was updated with industry-level data to obtain a distribution. These distributions could be used in risk assessments as prior distributions to be updated with plant-specific data.

2.2.2 Variations over NERC Regions

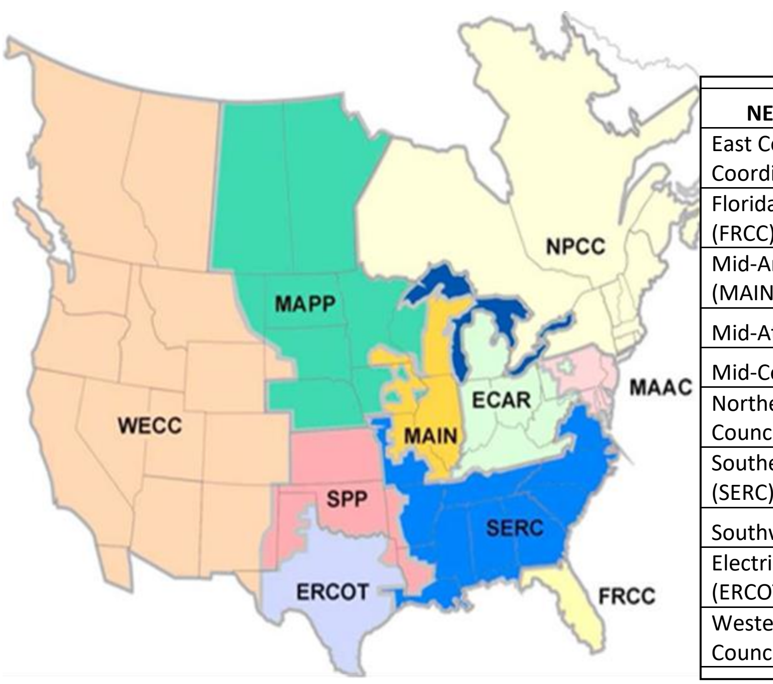
It is, in principle, possible to group the data in any number of ways (by season, year, site, state, proximity to the coast, NERC regional entities or reliability council regions) and characterize how much variation exists among the subgroups. Such variations may exist—rolling blackouts in California, hurricanes along the Gulf Coast, and ice storms in the Northeast have occurred in recent years. Attempting to detect and model all such variations is beyond the scope of this report. But because of the significance of grid events, which may even affect multiple units in different sites, the critical operations grid-related LOOP data have been grouped according to the NERC region containing each plant to examine the variation (refer to NUREG/CR-6890 and INL/EXT-18-45359). However, the NERC reliability council regions used in previous studies are no longer current. Both the NERC regional council names and territories have changed. This study incorporates the latest NERC regions (called Regional Entities) obtained from https://www.nerc.com/AboutNERC/keyplayers/Pages/default.aspx for regional variation analysis. Figure 7 presents the map showing these new NERC regional entities. As a reference, Figure 8 contains the older grouping of geographical regions which were also called power pools or reliability councils.

With the new NERC regions, the analysis results derived from the empirical Bayesian method result in the 5th percentile more than 3 orders of magnitude lower than the mean of the distribution and so are not recommended for use. Instead, a Bayesian Update with Jeffreys noninformative prior was performed to provide a homogenous posterior distribution, as provided in Table 2. For reference purpose only, Table 3 presents the variation analysis results with the old NERC reliability councils.



NERC Regional Entity	Short Name
Florida Reliability Coordinating Council (FRCC)	Florida
Midwest Reliability Organization (MRO)	Midwest
Northeast Power Coordinating Council (NPCC)	North East
Reliability First (RF)	Central East
SERC Reliability Corporation (SERC)	South East
Texas Reliability Entity (Texas RE)	Texas
Western Electricity Coordinating Council (WECC)	West

Figure 7. NERC Regional Entities.



NERC Reliability Council Regions	Short Name
East Central Area Reliability Coordination Agreement (ECAR)	East Central
Florida Reliability Coordinating Council (FRCC)	Florida
Mid-America Interconnected Network (MAIN)	Mid-America
Mid-Atlantic Area Council (MAAC)	Mid-Atlantic
Mid-Continent Area Power Pool (MAPP)	Mid-Continent
Northeastern Power Coordinating Council (NPCC)	North East
Southeastern Electric Reliability Council (SERC)	South East
Southwest Power Pool (SPP)	South West
Electric Reliability Council of Texas (ERCOT)	Texas
Western Electricity Coordinating Council (WECC)	Western

Figure 8. NERC Reliability Council regions.

Table 3. Estimated grid-related LOOP frequencies by the older reliability council during critical operation (1997–2018).

NERC Regional Entities	LOOP Events	Critical Years	Shape (α)	Scale (β)	5%	Median	95%	Gamma Mean	Simple MLE
East Central	2	148.1	2.46	194	2.86E-03	1.10E-02	2.82E-02	1.27E-02	1.35E-02
Florida	0	89.7	0.50	125	1.63E-05	1.84E-03	1.54E-02	4.01E-03	0.00E+00
Mid-America	2	335.9	2.52	382	1.53E-03	5.75E-03	1.46E-02	6.60E-03	5.95E-03
Mid-Atlantic	4	223.9	4.34	264	5.92E-03	1.52E-02	3.11E-02	1.64E-02	1.79E-02
Mid-Continent	0	114.5	0.49	144	1.27E-05	1.54E-03	1.32E-02	3.42E-03	0.00E+00
North East	9	214.6	7.88	222	1.76E-02	3.40E-02	5.85E-02	3.55E-02	4.19E-02
South East	0	557.5	0.45	473	2.04E-06	3.90E-04	3.79E-03	9.49E-04	0.00E+00
South West	0	118	0.49	147	1.23E-05	1.51E-03	1.29E-02	3.35E-03	0.00E+00
Texas	0	80.6	0.51	118	1.80E-05	1.98E-03	1.64E-02	4.28E-03	0.00E+00
Western	3	145	3.28	183	5.26E-03	1.61E-02	3.66E-02	1.79E-02	2.07E-02

2.3 Summary of LOOP Event Count Data

Table 4 shows a summary of LOOP data for 1987–2018, including reactor years and LOOP counts by plant status and LOOP category. The table shows the industry's improvement in avoiding shutdown operation LOOP events[5] and shortening of shutdown periods over the years. No grid-related shutdown LOOP events have occurred since 2008; no (or at most one) plant-centered shutdown LOOP events have occurred yearly since 1999; and no switchyard-centered shutdown LOOP events have occurred over the previous four years. Also, there were no critical operation LOOP events in 2018, a situation which has not been seen since 2010.

[5] Assuming each LOOP is an independent event—an assumption that is not quite true (see Section 4.2).

Table 4. Summary of all U.S. NPP LOOP frequency data, 1987–2018[a]

Calendar	Reactor Years			Critical Operations				Shutdown Operations				Total by Status		Total by Type				
Year	Critical	Shutdown	Total	PC	SC	GR	WR	PC	SC	GR	WR	Up	Down	PC	SC	GR	WR	Total
1987	70.56	30.23	100.80	0	5	0	0	2	5	1	2	5	10	2	10	1	2	15
1988	76.19	30.77	106.96	1	3	0	0	1	4	0	1	4	6	2	7	0	1	10
1989	76.42	33.08	109.50	1	4	0	0	0	4	1	0	5	5	1	8	1	0	10
1990	80.66	29.23	109.88	0	0	0	0	0	4	0	0	0	4	0	4	0	0	4
1991	83.94	25.67	109.61	3	3	0	0	4	3	0	1	6	8	7	6	0	1	14
1992	83.61	24.64	108.25	2	3	1	0	4	1	0	2	6	7	6	4	1	2	13
1993	82.90	24.26	107.16	0	4	0	1	3	2	0	4	5	9	3	6	0	5	14
1994	85.80	21.20	107.00	0	0	0	0	2	1	0	0	0	3	2	1	0	0	3
1995	88.84	18.42	107.26	0	0	0	0	0	2	0	0	0	2	0	2	0	0	2
1996	87.09	21.91	109.00	0	1	0	2	0	2	0	0	3	2	0	3	0	2	5
1997	79.93	28.15	108.08	0	2	0	0	1	2	1	1	2	5	1	4	1	1	7
1998	84.39	21.61	106.00	0	0	0	1	2	1	0	1	1	4	2	1	0	2	5
1999	90.73	15.10	105.83	0	0	0	0	1	2	0	0	0	3	1	2	0	0	3
2000	92.92	10.08	103.00	1	0	0	0	1	3	0	0	1	4	2	3	0	0	5
2001	93.96	9.04	103.00	0	1	0	1	0	0	0	0	2	0	0	1	0	1	2
2002	94.88	8.12	103.00	0	1	0	0	0	0	0	0	1	0	0	1	0	0	1
2003	92.61	10.39	103.00	0	2	10	0	1	0	1	0	12	2	1	2	11	0	14
2004	94.94	8.06	103.00	0	1	3	1	0	0	0	2	5	2	0	1	3	3	7
2005	93.92	9.08	103.00	0	0	0	0	0	0	0	2	0	2	0	0	0	2	2
2006	94.34	8.66	103.00	0	3	0	0	1	0	0	0	3	1	1	3	0	0	4
2007	96.16	7.45	103.61	0	0	0	0	0	0	2	1	0	3	0	0	2	1	3
2008	95.43	8.57	104.00	0	0	0	0	0	4	0	0	0	4	0	4	0	0	4
2009	94.34	9.66	104.00	0	1	1	1	0	0	0	0	3	0	0	1	1	1	3
2010	95.44	8.56	104.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2011	92.61	11.39	104.00	0	2	0	5	0	1	0	0	7	1	0	3	0	5	8
2012	90.02	13.98	104.00	1	3	1	0	0	2	0	1	5	3	1	5	1	1	8
2013	91.23	10.34	101.57	1	2	1	1	1	1	0	0	5	2	2	3	1	1	7
2014	92.44	7.56	100.00	0	0	2	0	0	1	0	0	2	1	0	1	2	0	3
2015	91.44	7.56	99.00	0	0	2	1	0	0	0	0	3	0	0	0	2	1	3
2016	92.18	6.77	98.95	2	1	0	0	0	0	0	1	3	1	2	1	0	1	4
2017	91.87	7.13	99.00	1	0	0	1	0	0	0	1	2	1	1	0	0	2	3
2018	91.89	6.86	98.75	0	0	0	0	1	0	0	1	0	2	1	0	0	1	2

a. Abbreviations: PC—plant-centered, SC—switchyard-centered, GR—grid-related, and WR—weather-related, SD—shut down.

3. LOOP DURATION/RECOVERY

Sustained LOOP recovery times were selected as the parameter for modeling the duration of recovery times from LOOP. The recovery time is the duration, in minutes, from the event initiation until offsite electrical power could have been recovered to a safety bus. It is less than or equal to the actual bus restoration time (refer to the Glossary of this report and NUREG/CR-6890 for the discussions of the three LOOP recovery times). Sustained recovery times are defined as times that are at least 2 minutes long.

When a LOOP event affects more than one unit at a site with multiple units, the duration of the event is defined as the time needed for all the affected units to be on off-site power. Thus, the duration associated with the plant unit with the longest duration time is the duration selected for the event, so that individual unit duration times are not used in this study. This choice is based upon the assumption that the plant unit-level LOOP events on a single day are not independent, therefore the time to recovery at each plant unit should not be treated as independent.

Two analyses were performed in conjunction with these times. First, the data were analyzed to see if trends in the recovery times exist. Then distributions characterizing the times were estimated.

3.1 Trends in Recovery Times

As in previous LOOP update studies, the recovery time data were evaluated for trends using the period since deregulation (1997–2018).

The recovery times for each LOOP category were trended using log linear regression. The recovery time trend data are shown in Figure 9. Table 5 provides the trend equations for each of the data subsets.

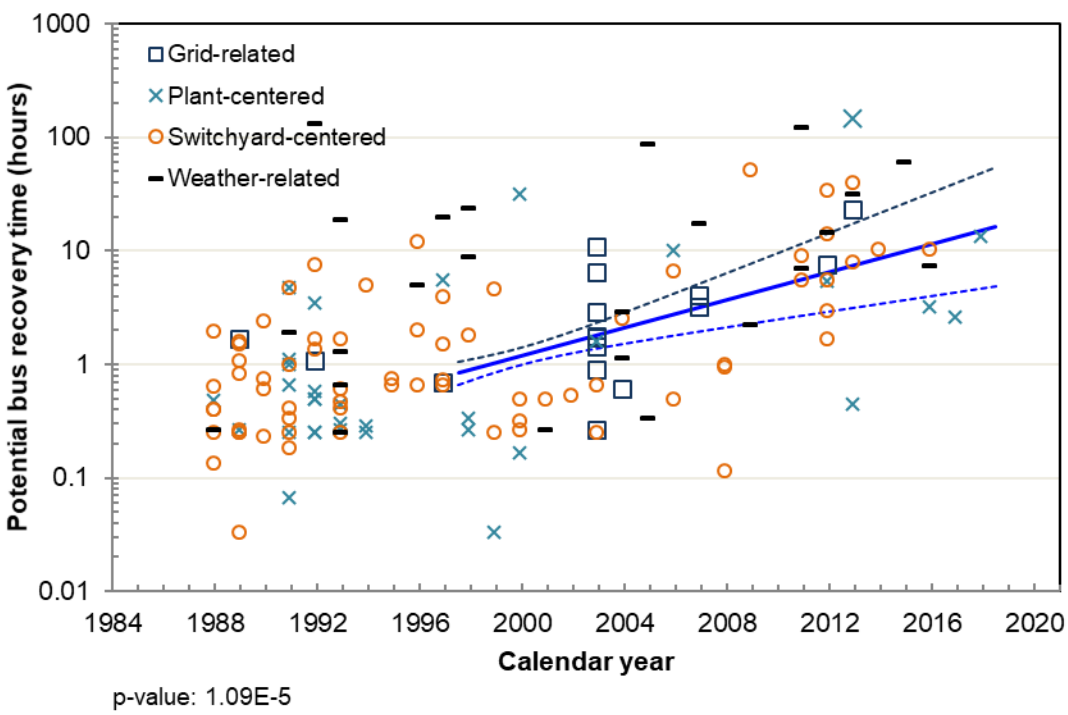


Figure 9. Extremely statistically significant increasing trend on LOOP recovery times (all event types) from 1997–2018.

Table 5. Results of log linear regression of LOOP recovery times for the post-deregulation period (1997–2018).

Subset	# of LOOP Events[b]	Trend Line Equation[a]	Standard Error of Slope	p-value for significance of trend
Plant-centered	14	Exp(0.125 x (year-2018) +2.232)	0.073	1.13E-01
Switchyard-centered	32	Exp(0.161 x (year-2018) +2.724)	0.038	2.22E-04
Grid-related	14	Exp(0.196 x (year-2018) +3.508)	0.066	1.22E-02
Weather-related	16	Exp(0.081 x (year-2018) +3.067)	0.077	3.07E-01
All LOOPs	76	Exp(0.141 x (year-2018) +2.785)	0.030	1.09E-05
Critical Operations	39	Exp(0.129 x (year-2018) +2.623)	0.042	4.21E-03
Shutdown Operations	37	Exp(0.154 x (year-2018) +2.989)	0.045	1.66E-03

a. The best fitting regression line defined by exp(intercept + slope*(year difference)). The (year–2018) terms goes from -21 to 0.
b. Multi-Unit LOOPs are counted as a single LOOP.

Extremely statistically significant increasing trends in recovery times are identified for the category, all LOOPs (p-value = 1.09E-05), and switchyard-centered LOOPs (p-value = 2.22E-4). Highly statistically significant increasing trends are identified for all LOOPs during critical operations (p-value = 4.21E-3) and all LOOPs during shutdown operations (p-value = 1.66E-03). A statistically significant increasing trend is identified for grid-related LOOPs (p-value = 1.22E-02). These statistically significant increasing trends highlight the possibility that there may be underlying causes for the longer LOOP recoveries in the associated categories.

There is no trend in recovery times for plant-centered or weather-related LOOPs.

3.2 LOOP Recovery Times

This section presents the analysis on LOOP recovery times, or the probability of exceedance versus duration. For the study of LOOP duration, the largest possible data set was sought that could be considered representative of current operations. The presence of an adverse increasing trend in the duration data complicated the selection of a starting date. Using too much of the older data weights the durations in a non-conservative direction that cannot be considered representative of current industry conditions. Therefore the largest homogeneous population was sought with an end date in the most recent year. This resulted in using data from calendar years 1988 through 2018. Also, in accordance with NUREG-6890, the data for shutdown and critical operations were combined.

As in previous LOOP update studies, the lognormal family of distributions was selected to model variation in the recovery times. The exceedance probabilities (1 minus the cumulative distribution function value) that come from these distributions are useful in PRAs where a failure event involves recovery times exceeding a specified number of hours.

For the LOOP recovery times in each category, lognormal distributions were fitted using a method that matches moments. More specifically, since the logarithms of lognormal data follow a normal distribution, the first step in identifying the best lognormal distribution for each set of data is to find the best underlying normal distribution. All the recovery times are greater than zero, so the natural logarithms of the data were computed. The underlying normal distribution mean (μ) is estimated by the average of these data, and the standard deviation (σ) is estimated by the sample standard deviation. For use in PRA analyses using SAPHIRE, the standard deviation of μ is computed as $\sigma/\sqrt{n}$, where n is the sample size. The standard deviation of σ is estimated by noting that, for normally-distributed data, the sum of the squared deviations that form the numerator of the sample variance estimate, divided by the actual variance, has a chi-square distribution with $(n - 1)$ degrees of freedom. The variance of this distribution is $2(n - 1)$. For any random variable X and constant, k, the variance of kX is k^2 times the variance of X. Therefore the variance of the numerator sum is $2(n-1)$ times the square of the actual variance. After some algebraic manipulations, the estimate of the standard deviation of σ turns out to be $\sigma\sqrt{2(n-1)}$.

The parameters of the fitted lognormal distributions are provided in Table 6. The fitted lognormal density and cumulative distribution functions for the recovery times are as follows:

$$f(t) = \frac{1}{t\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left[\frac{\ln(t)-\mu}{\sigma}\right]^2}$$ [6]

$$F(t) = \Phi\left[\frac{\ln(t)-\mu}{\sigma}\right]$$ = Prob[potential recovery time <= t]

Where

t = offsite power potential bus recovery time

μ = mean of natural logarithms of data

σ = standard deviation of natural logarithms of data

Φ = cumulative distribution function[7].

Note that the values for μ and σ completely define the distribution; the lognormal median, mean, and 95th percentile of these distributions can then be found by direct calculation: exp(μ), exp($\mu + \sigma^2/2$), and exp(μ + 1.645σ), respectively.

Table 6. Fitted lognormal recovery time distributions (1988-2018).

Parameter	Plant-centered	Switchyard-centered	Grid-related	Weather-related
LOOP event count	33	70	16	24
Mu (μ)	-0.10	0.15	0.80	1.73
Standard error of μ	0.31	0.18	0.29	0.41
Sigma (σ)	1.80	1.49	1.17	1.99
Standard error of σ	0.22	0.13	0.21	0.29
Fitted median, hour	0.90	1.16	2.23	5.62
Fitted mean, hour	4.53	3.53	4.40	40.98
Fitted 95th percentile, hour	17.31	13.48	15.18	149.21
Error Factor	19.18	11.65	6.81	26.56

[6] This equation is a correction of the one in previous studies such as NUREG/CR-6890 and INL/EXT-18-45359.
[7] This term is a correction of the one in previous studies such as NUREG/CR-6890 and INL/EXT-18-45359, in which "error function" was used.

The distributions in Table 6 are plotted as probability-of-exceedance versus duration curve (1-F(t)) in Figure 10. The probability of LOOP duration exceeding T hours can be obtained either by calculating the distribution function of 1-F(t) or by drawing a vertical line at t = T hours in the plot and reading the intersect point values for non-recovery probabilities (within T hours) for different LOOP categories. Figure 10 shows visually that weather-related LOOPs have the longest recovery times.

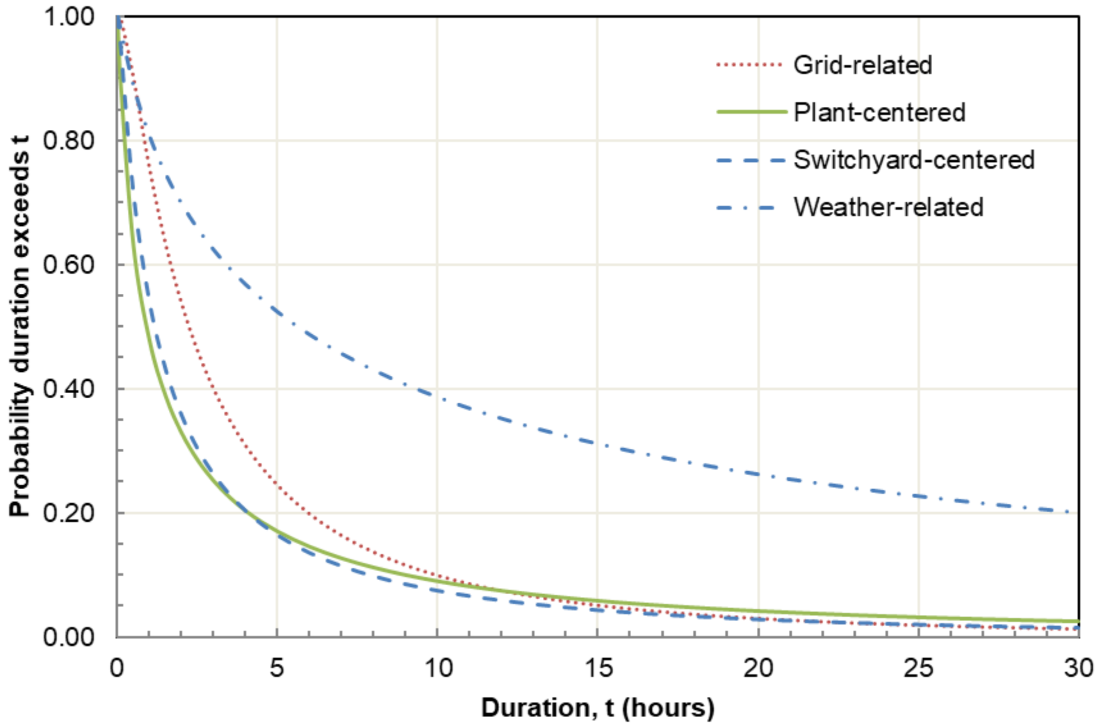


Figure 10. Probability of exceedance (non-recovery probability) vs. duration curves for all event types and operating modes (1988–2018).

4. SPECIAL TOPICS IN LOOP FREQUENCY

Two issues are considered in this section: seasonal variation in LOOP frequency, and the effect of multi-unit LOOP events.

4.1 Seasonal Effects on LOOP Frequency

In 2003, Raughley and Lanik called attention to an emerging tendency for grid-related LOOPs to occur during the summer:

> *This assessment noted that seven of the eight LOOPs (87%) involving a reactor trip since 1997 occurred in the summer – May to September – in contrast to 23 of 54 (44%) of LOOPs in the summers of 1985–1996.* (Raughley and Lanik, 2003)

The authors did not perform a formal statistical test, but readers of their report found this early evidence compelling.

Such events have continued to occur, as displayed in Table 7 below (particularly for critical operations). The table shows LOOP counts from 1997 based on the month of occurrence, plant mode, and LOOP category.

The Rayleigh Test is a standard test for whether points are distributed uniformly around a circle (wind directions, fracture orientations) and adapts readily to testing whether a set of events are scattered uniformly through the year (Mardia and Jupp, 2000). The test is applied separately for each column of Table 7.

Table 7. LOOP event counts by month and LOOP category (1997–2018).

	Critical Operations				Shutdown Operations			
Month	Grid	Plant	Switchyard	Weather	Grid	Plant	Switchyard	Weather
Jan	0	0	2	1	0	0	1	0
Feb	0	1	1	1	0	0	1	1
Mar	0	0	0	1	0	2	4	1
Apr	2	2	3	6	1	2	3	2
May	2	1	4	0	1	2	2	0
Jun	3	0	1	1	1	0	0	0
Jul	2	1	2	0	0	0	0	0
Aug	8[a]	1	4	2	1	0	1	1
Sep	2	0	0	0	0	1	1	3
Oct	1	0	1	0	0	1	2	3
Nov	0	0	1	0	0	0	1	0
Dec	0	0	0	0	0	1	1	0

a. The northeast blackout of August 14, 2003, affected eight plants simultaneously.

The counts in Table 7 differ from those in the 2017 report (Johnson, Ma, and Schroeder, 2018) with the two new shutdown LOOP events occurred in 2018 (see Section 1.1). Also, prior to evaluating the statistical test, the blackout of August 14, 2003, was treated as one critical grid-related LOOP event rather than counting it eight times for this analysis.

Applying the Rayleigh Test to the counts in Table 7 shows the following statistically significant results:

- The counts for critical operation grid-related LOOPs are not uniformly distributed across the 12 months. The variation is highly statistically significant (p-value = 8.05E-03).
- The counts for critical operation weather-related LOOPs are not uniformly distributed across the 12 months. The variation is statistically significant (p-value = 1.67E-02).

4.2 Multi-Unit LOOP Events

Similar to NUREG/CR-6890 and previous annual LOOP updates, the analysis of LOOP events in this study is at the plant level (or unit level), in contrast to the site level or regional level. For example, if a single weather event causes both units at a site to experience a LOOP, it is counted as two unit-level LOOP events instead of one site-level LOOP event. This approach assumes that the unit LOOP events are independent events. This is not quite true, however, as demonstrated in the above example that the weather caused two unit LOOP events at the same site, as well as in the 2003 northeast blackout that affected nine units (eight in critical and one in shutdown) at seven sites. There were seven occasions during 1987–1996 and 13 occasions during 1997–2018 when more than one unit at a site was affected by the same incident. The 13 occasions contributed 28 of the 98 unit events (from 1997–2018) counted in Table 1 (≈28%). This calls the simplifying assumption of treating each LOOP as independent into serious question. This section presents an overview of multi-unit LOOP issues. Section 4.2.1 categorizes LOOP events by unit and site. Section 4.2.2 estimates the conditional probability of all units at a multi-unit site experiencing a LOOP if a LOOP occurs at one of the units. Section 4.2.3 investigates other approaches that treat multi-unit LOOP issues.

4.2.1 LOOP Events by Unit and Site

From 1987 to 2018, there were 188 unit-level LOOP events, including 146 single-unit LOOP occurrences and 20 multi-unit occurrences that involved more than one unit at a site for the same occurrence. Eighteen multi-unit occurrences involved both units at two-unit sites. Two involved all three units at three-unit sites. Of the single-unit LOOPs, 72 occurred at single-unit site, 60 occurred at two-unit sites, and 14 occurred at three-unit sites. Table 8 shows the matrix of LOOP occurrences and unit-level LOOP events from 1987–2018. In general, offsite power events affect multiple units and, as such, unit-based LOOP events are not independent.

Table 8. LOOP occurrences and unit-level LOOP events from 1987–2018.

	LOOP Occurrence			Unit-Level
Units/Site	**Single-Unit**	**Two-Unit**	**Three-Unit**	**LOOP Events**
Single	73	N/A	N/A	73
Two	60[a]	18[a]	N/A	96
Three	13	0	2	19
Total	146	18	2	188

a. Any Millstone LOOP occurrences occurred after June 1998, when Millstone Unit 1 was decommissioned, are counted as LOOPs on a two-unit site instead of three-unit site. There were two single-unit LOOPs (4/25/2007 at Millstone Unit 3 and 5/24/2008 at Millstone Unit 2) and one multi-unit LOOP (5/23/2014 at Millstone Units 2 and 3) at the Millstone site which were categorized as being from a 2 unit site.

The total number of unit-level LOOP events can be calculated by the following equation:

$$N = \sum_{u=1}^{3}(u * \sum_{i=1}^{3} n_{u,i})$$

Where

N = total number of unit-level LOOP events

u = number of units affected in a LOOP occurrence, u = 1, 2, 3, and $u \leq i$

i = number of units in a site, i = 1, 2, 3

$n_{u,I}$ = number of LOOP occurrences at a site

The total number of unit-level LOOP events from 1987-2018 is

$$N = 1 * (72 + 60 + 14) + 2 * (18 + 0) + 3 * 2 = 188$$

Table 9 shows the multi-unit LOOP occurrences from 1987-2018 listed in chronological order.

For multi-unit LOOP events, in general, there is a three-part question to be answered: First, what is the frequency of the underlying occurrence that led to a LOOP event? Second, how many sites were affected by the occurrence? Finally, how many units at each site were affected by the occurrence? A qualitative analysis of the multi-unit LOOP event data provides the following insights:

- A weather-related event is more likely to affect more than one unit at the same site within a few hours to a few days, but less likely to affect more than one site within a few hours to a few days.
- A grid-related event could affect multiple sites, even sites hundreds of miles away (the likelihood to affect two or more sites is low, but the probability of affecting a large number of sites is much higher than a simple Poisson approximation), and usually affects all units at the same site.
- A switchyard-centered event may affect more than one unit at the same site, depending on where in the switchyard it happens, but should not affect a unit at another site.
- A plant-centered event should not affect any other unit, even at the same site.[8]

[8] The only exception to date occurred at Catawba on April 4, 2012. Unit 2 was down for refueling and cross-connected to Unit 1's offsite power in an abnormal way. Unit 1 experienced a plant-centered LOOP, which caused Unit 2 to also experience a LOOP (coded in INL's database as a switchyard-centered LOOP).

Table 9. Multi-unit LOOP events for 1987–2018.

Event	Site	Date	# of Units at Site	# of Units Affected	LOOP Category	Mode
1	Calvert Cliffs	7/23/1987	2	2	Switchyard-centered	Critical Operation
2	Peach Bottom	7/29/1988	2	2	Switchyard-centered	Shutdown Operation
3	Turkey Point	8/24/1992	2	2	Weather-related	Shutdown Operation[a]
4	Sequoyah	12/31/1992	2	2	Switchyard-centered	Critical Operation
5	Brunswick	3/17/1993	2	2	Weather-related	Shutdown Operation
6	Beaver Valley	10/12/1993	2	2	Switchyard-centered	Critical Operation/ Shutdown Operation
7	Prairie Island	6/29/1996	2	2	Weather-related	Critical Operation
8	Fitzpatrick/ Nine Mile Point 1	8/14/2003	2	2	Grid-related	Critical Operation
9	Indian Point	8/14/2003	2	2	Grid-related	Critical Operation
10	Peach Bottom	9/15/2003	2	2	Grid-related	Critical Operation
11	Palo Verde	6/14/2004	3	3	Grid-related	Critical Operation
12	St. Lucie	9/25/2004	2	2	Weather-related	Shutdown Operation
13	Catawba	5/20/2006	2	2	Switchyard-centered	Critical Operation
14	Surry	4/16/2011	2	2	Weather-related	Critical Operation
15	Browns Ferry	4/27/2011	3	3	Weather-related	Critical Operation[b]
16	North Anna	8/23/2011	2	2	Switchyard-centered	Critical Operation
17	LaSalle	4/17/2013	2	2	Switchyard-centered	Critical Operation
18	Millstone[c,d]	5/25/2014	2	2	Grid-related	Critical Operation
19	Calvert Cliffs	4/7/2015	2	2	Grid-related	Critical Operation
20	Arkansas	4/26/2017	2	2	Weather related	Critical Operation/ Shutdown Operation
Totals			**42**	**42**		

[a] The units shut down in anticipation of bad weather. The weather events subsequently resulted in LOOPs at the site.

[b] Treated as though all three units experienced a LOOP, although a 161-kV offsite power line remained available for Browns Ferry 3. The unit responded as though it, too, had experience a LOOP. The # of units affected is changed from two to three in this study.

[c] Reclassified in the 1987–2017 LOOP analysis from switchyard-centered to grid-related.

[d] The number of units at the Millstone site is changed from three to two in this study. Millstone Unit 1 was decommissioned in June 1998. Any Millstone LOOP events that occurred after June 1998 should be treated as a dual-unit site instead of three-unit site.

4.2.2 Conditional Probability of Multi-Unit LOOPs

Table 10 estimates the conditional probability of all units at a multi-unit site experiencing a LOOP if a LOOP occurs at one of the units. As shown in this table, a large portion of the LOOP events affect multiple units, which further reveals that unit-level LOOP events are not independent.

Table 10. Conditional probability of all units at a site experiencing a LOOP given a LOOP at one of the units.

Loop Category	LOOP Events at Multi-Unit Sites Affecting all Units at the Site	Total LOOP Events at Multi-Unit Sites	Conditional Probability of All Units at a Multi-Unit Site Experiencing a LOOP Given a LOOP at One Unit at the Site[a]				Beta Distribution Parameters	
			5%	Median	Mean	95%	α	β
Grid-centered	6	16	2.02E-01	3.78E-01	3.82E-01	5.79E-01	6.5	10.5
Plant-centered	0	22	8.84E-05	1.02E-02	2.17E-02	8.27E-02	0.5	22.5
Switchyard-centered	7	58	6.42E-02	1.23E-01	1.27E-01	2.04E-01	7.5	51.5
Weather-related	7	19	2.08E-01	3.71E-01	3.75E-01	5.56E-01	7.5	12.5
All	20	115	1.22E-01	1.75E-01	1.77E-01	2.38E-01	20.5	95.5

[a] The difference between total LOOPs and LOOPs affecting all units at a multi-unit site is the number of those LOOPs that affected only one unit. The beta distributions reflect the proportion of the events that affected the other units. The distributions are obtained by updating the Jeffreys non-informative beta distribution prior, beta (α, β) = beta (0.5, 0.5), with the row-specific data. Since the beta distribution is a conjugate distribution for binomial data, the updated distribution in each row is also a beta distribution (0.5 + number of events affecting all units, 0.5 + number of events affecting just one unit). The mean is α / (α + β) = (0.5 + all-unit event count) / (1 + total events).

4.2.3 Approaches to Treat Multi-Unit LOOP

The discussions in previous subsections show the need to improve the current method for estimating LOOP frequency, which is based on unit-level LOOP events with the assumption that these unit-level LOOP events are independent from each other. This subsection investigates other approaches that could address the dependency as shown in multi-unit LOOP events.

Approach I

The first approach treats the single-unit site LOOP frequency ($\lambda_{1,1}$) and the multi-unit site LOOP frequency (λ_M) separately, and splits multi-unit site LOOP frequency (λ_M) into unit-level single-unit LOOP frequency (λ_u) and site-level multi-unit LOOP frequency (λ_s):

$$\lambda_M = \lambda_u + \lambda_s$$

The single-unit site LOOP frequency ($\lambda_{1,1}$) can be estimated with the number of single-unit LOOP occurrences ($n_{1,1}$) and the associated unit reactor years (t_1):

$$\hat{\lambda}_{1,1} = n_{1,1}/t_1$$

For multi-unit site LOOP frequency, the unit-level single-unit LOOP frequency (λ_u) can be estimated with the number of single-unit LOOP occurrences ($n_{1,i}$ with *i* = 2, 3) and the associated unit-level reactor years (t_u). The site-level multi-unit LOOP frequency (λ_s) can be estimated with the number of multi-unit LOOP occurrences ($n_{2,i}$ with *i* = 2, 3, $n_{3,3}$) and the associated site-level reactor years (t_s). The MLEs of λ_u and λ_s are:

$$\hat{\lambda}_u = \frac{\sum_{i=2}^{3} n_{1,i}}{t_u} = \frac{n_{1,2} + n_{1,3}}{t_u}$$

$$\hat{\lambda}_s = \frac{\sum_{i=2}^{3} n_{2,i} + n_{3,3}}{t_s} = \frac{(n_{2,2} + n_{2,3}) + n_{3,3}}{t_s}$$

Approach II

The second approach is similar to the first one, but assumes that single-unit LOOPs at single-unit sites and multi-unit sites can be pooled together. So the single-unit LOOP frequency (λ_u) is now estimated with the number of single-unit LOOP occurrences ($n_{1,i}$ with i = 1, 2, 3) and the associated unit-level reactor years (t_u). The site-level multi-unit LOOP frequency (λ_s) is estimated with the same equation as in the first approach. The MLEs of λ_u and λ_s are presented below:

$$\hat{\lambda}_u = \frac{\sum_{i=1}^{3} n_{1,i}}{t_u} = \frac{n_{1,1} + n_{1,2} + n_{1,3}}{t_u}$$

$$\hat{\lambda}_s = \frac{\sum_{i=2}^{3} n_{2,i} + n_{3,3}}{t_s} = \frac{(n_{2,2} + n_{2,3}) + n_{3,3}}{t_s}$$

Both the first and second approaches can be applied toward the four LOOP categories: LOOP-PC, LOOP-SC, LOOP-GR, and LOOP-WR.

It should be noted that these approaches do not consider regional LOOPs, which are actually part of multi-unit LOOPs. Other approaches will also be investigated before a determination is made on which approach is best to address the multi-unit LOOP dependence issue.

4.3 Consequential LOOPs

4.3.1 Consequential LOOP Given a Reactor Trip

NUREG/CR-6890 provides an estimate of conditional probabilities of a consequential LOOP (CLOOP) given a reactor trip, 5.3E-3 for the period 1997–2004 and 3.0E-3 for the period 1986–1996. The estimated conditional probability of 5.3E-3 has been used in the SPAR models to date. This study presents an update of the conditional probability using data from 1997–2018.

The estimation uses the same method as in NUREG/CR-6890 with the number of CLOOP events (LOOP-IE-C), the number of reactor trip, and the number of LOOP events that cause the reactor trip (LOOP-IE-I). The conditional probability of CLOOP, $p(CLOOP|RT)$ given a reactor trip is calculated as (Bayesian update with Jeffreys noninformative prior):

$$p(CLOOP|RT) = (n_{CLOOP} + 0.5)/[(\, n_{RT} - n_{LOOP-IE-I}) + 1]$$

Where,

n_{CLOOP} = number of CLOOP events

n_{RT} = number of reactor trips (RTs)

$n_{LOOP-IE-I}$ = number of LOOP events that cause the reactor trip

There are currently seven events classified as CLOOP events during the period 1987–2018: four CLOOPs from 1987–1996, and three CLOOPs from 1997-2018 (see Table 11)[9]. For 1987–1996 period, there were 2,096 reactor trips, 23 of them caused by LOOP (i.e., 23 LOOP-IE-I events). For 1997–2018 period, there were 1,560 reactor trips, 44 of them caused by LOOP.

[9] NUREG/CR-6890 lists nine CLOOP events, in which two CLOOPs occurred in 1986 are outside of the period in this study, two CLOOPs (8/31/1999 at Indian Point 2 and 4/24/2003 at Grand Gulf) have been recoded and are no longer classified as CLOOP. Two new CLOOPs occurred after 2004 which is the last year of the study in NUREG/CR-6890.

Table 11. Consequential LOOP events from 1987 to 2018.

Event	LER	Plant Name	Date	LOOP Category
1	4551987019	Byron 2	10/2/1987	Switchyard centered
2	3011989002	Point Beach 2	3/29/1989	Switchyard centered
3	3951989012	Summer	7/11/1989	Grid related
4	2371990002	Dresden 2	1/16/1990	Switchyard centered
5	2191997010	Oyster Creek	8/1/1997	Switchyard centered
6	4132012001	Catawba 1	4/4/2012	Plant centered
7	3352016003	St. Lucie 1	8/21/2016	Plant centered

Table 12 shows the updated conditional probabilities of CLOOP given a reactor trip: 2.3E-3 for the period of 1997–2018 and 2.2 E-3 for the period of 1987–1996. The results of those from NUREG/CR-6890 and NUREG-1784 are also provided in the table for comparison. The value of 2.3E-3 (based on data from 1997–2018) could be used to replace the value of 5.3E-3 (based on data from 1997–2004), which represents a reduction of about 56% with more operational data after deregulation, in the PRA model.

Table 12. Conditional probability of consequential LOOP given reactor trip.

LOOP Classifications	This Study		NUERG/CR-6890		NURE-1784[10]	
	1987-1996	1997-2018	1986-1996	1997-2004	1985-1996	1997-2001
CLOOPs	4	3	6	3	7	2
Total Rx Trips (RTs)	2,096	1,560	2,168	680	3,161	441
LOOP-Caused Rx Trips	23	44	32	19	Not Applied	
P(CLOOP|RT)	2.2E-03	2.3E-03	3.0E-03	5.3E-03	2.2E-03	4.5E-03

It should be noted that the estimations of LOOP frequency in Section 2 include the number of consequential LOOP events in the calculation. This presents a potential double-counting issue if a PRA model contains the top event of consequential loss of offsite power in the transient event trees. While CLOOP events (three from 1997–2018) contribute less than 5% of the total critical operation LOOP events (57 from 1997–2018), the contributions may be more significant for some LOOP categories. For example, two out of six plant-centered LOOP events from 1997–2018 are CLOOPs.

Table 13 presents adjusted industry average critical operation LOOP frequencies, both the gamma distribution and MLE values, after consequential LOOP events are excluded from the estimations. The adjusted mean value of plant-centered LOOP (LOOP-PC) frequency is 1.73E-3/rcry, nearly 50% reduction from 3.21E-3/rcry before the adjusting. The adjusted switchyard-centered LOOP (LOOP-SC) frequency is 9.12E-3/rcry, a 5% reduction from 9.62E-3/rcry. There is no change on grid-related or weather-related LOOP frequency. The overall critical operation LOOP frequency is 2.64E-2/rcry after the adjusting, a 7% reduction from 2.84E-2/rcry.

[10] NUREG-1784 does not exclude the LOOP-caused reactor trips from the CLOOP conditional probability estimations. Also, the estimation uses n(CLOOPs)/n(RTs) instead of Bayesian update.

Table 13. Adjusted industry average critical operation LOOP frequencies after excluding consequential LOOP events (1997–2018).

LOOP Category	Events	rcry	Shape (α)	Scale (β)	Gamma Mean	Simple MLE	Notes
LOOP-PC	*4*	2027.68	4.5	2027.7	*2.22E-03*	*1.97E-03*	a
LOOP-SC	*18*	2027.68	18.5	2027.7	*9.12E-03*	*8.88E-03*	a
LOOP-GR	20	2027.68	20.5	2027.7	*1.01E-02*	*9.86E-03*	a
LOOP-WR	12	2027.68	1.54	259	*5.95E-03*	*5.92E-03*	c
All	*54*	2027.68	53.5	2027.7	*2.64E-02*	*2.66E-02*	a

[a] Homogeneous. The data rule out the possibility of wide variations among plants or within the other data groupings that were considered. The Jeffreys prior is used.
[b] Empirical Bayes. There appears to be variability in the LOOP frequency across NERC reliability council regions.
[c] Empirical Bayes. There appears to be variability between plants.

4.3.2 Consequential LOOP Given a LOCA

Conditional probability of a consequential LOOP given a loss of coolant accident (LOCA) event was not estimated in NUREG/CR-6890 or previous annual LOOP analyses, but rather in other technical reports. This section does not provide an updated analysis on conditional probability of a consequential LOOP given a LOCA, but rather presents the results from previous analyses. NUREG/CR-6538 (Martinez-Guridi, et al., 1997) uses data from 1984–1993 to estimate the probability of a LOOP given a LOCA as 2.1E-2. A more recent Brookhaven National Laboratory report (Martinez-Guridi and Lehner, 2006) uses data from Jan. 1, 1986, to July 31, 2006, and estimates the generic probability of LOOP given a large break LOCA to be 2.0E-2.

5. ENGINEERING ANALYSIS OF LOOP DATA

To provide additional qualitative insights, LOOP events can be classified by cause. (For example, what type of weather event caused a weather-related LOOP or what kind of human activity caused a plant-centered LOOP?)

Figure 11 categorizes LOOP events from equipment failure by failed component. From 1997 to 2018, the largest subcategories are failed circuits, transformers, and relays. Circuit and relay failure events have nearly tripled from the 1987–1996 period to the 1997–2018 period,[11] while the transformer failures (dominant during the 1987–1996 period) reduced by half in the 1997–2018 period.

In Figure 12 LOOP events from human error are tallied according to the type of activity in progress at the time. There have been very few LOOPs from human error since 1997, a 62% reduction compared to 1996 and before.

Figure 13 categorizes weather-related LOOP events by the type of natural disaster. Since 1997, the most common causes of weather-related LOOPs have been tornadoes and high winds. From 1987 to 1996, the most common causes were salt spray and high winds. The breakdown between critical and shutdown operations reflects the fact that tornadoes and lightning occur with little warning while hurricane paths are forecast days in advance, enabling plants to preemptively shut down before the storm arrives.

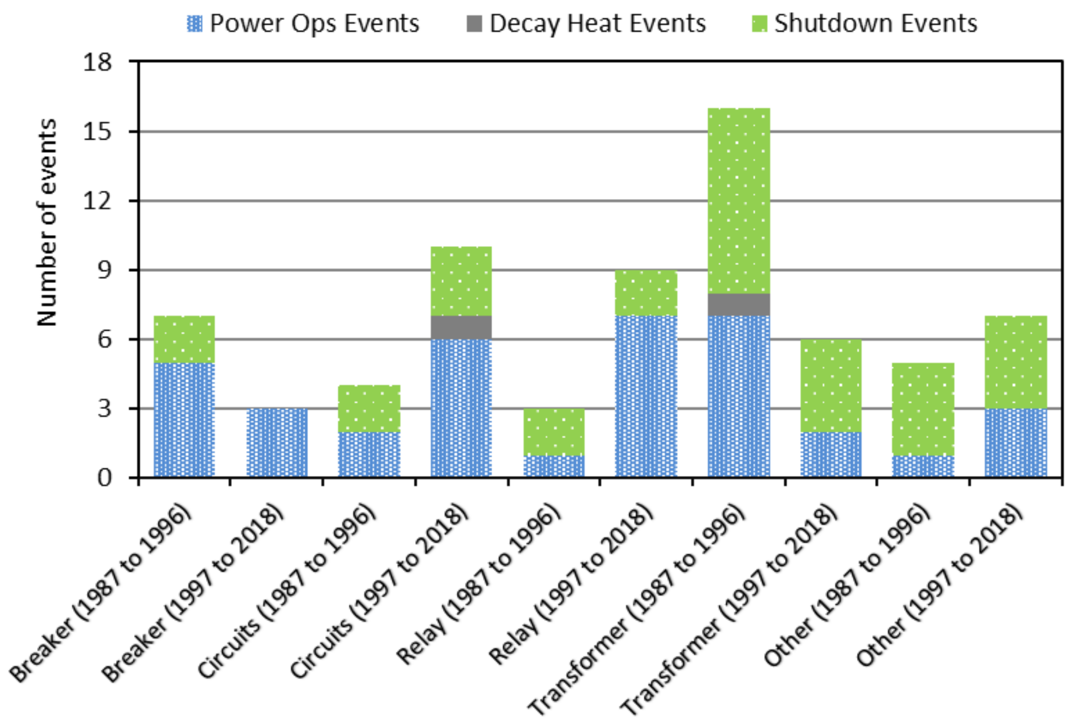


Figure 11. Failed components causing LOOP events from equipment failures (1987–1996 and 1997–2018).

[11] When comparing the data between the two periods, one should be aware that the 1987–1996 period represents a duration of 10 years, while the 1997–2018 period represents a duration of more than 20 years.

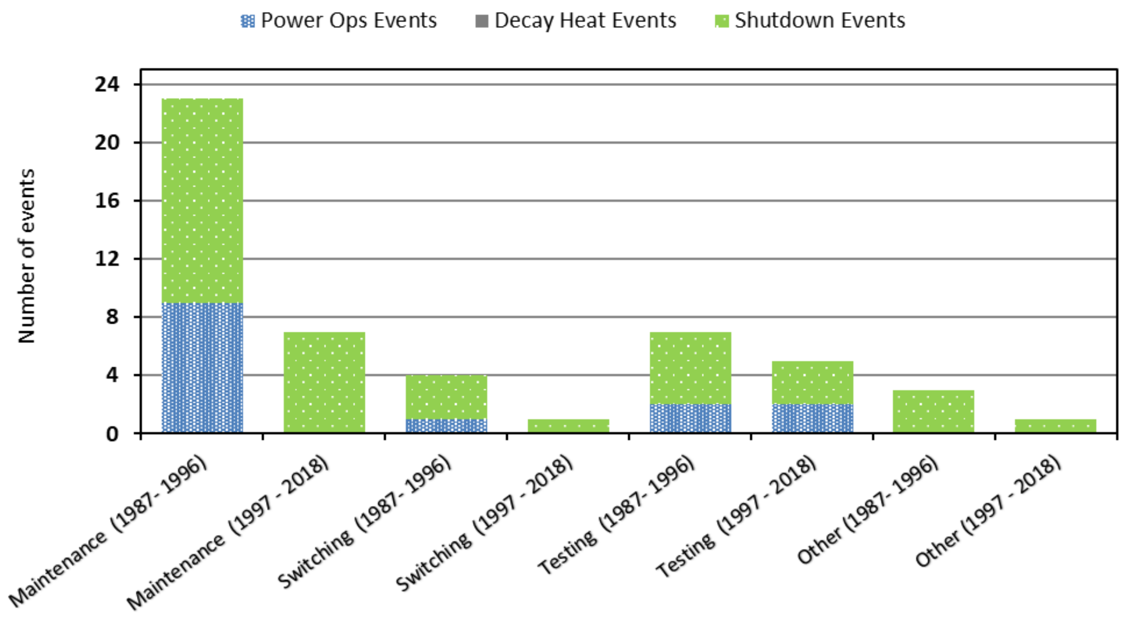


Figure 12. Activities causing LOOP events from human error (1987–1996 and 1997–2018).

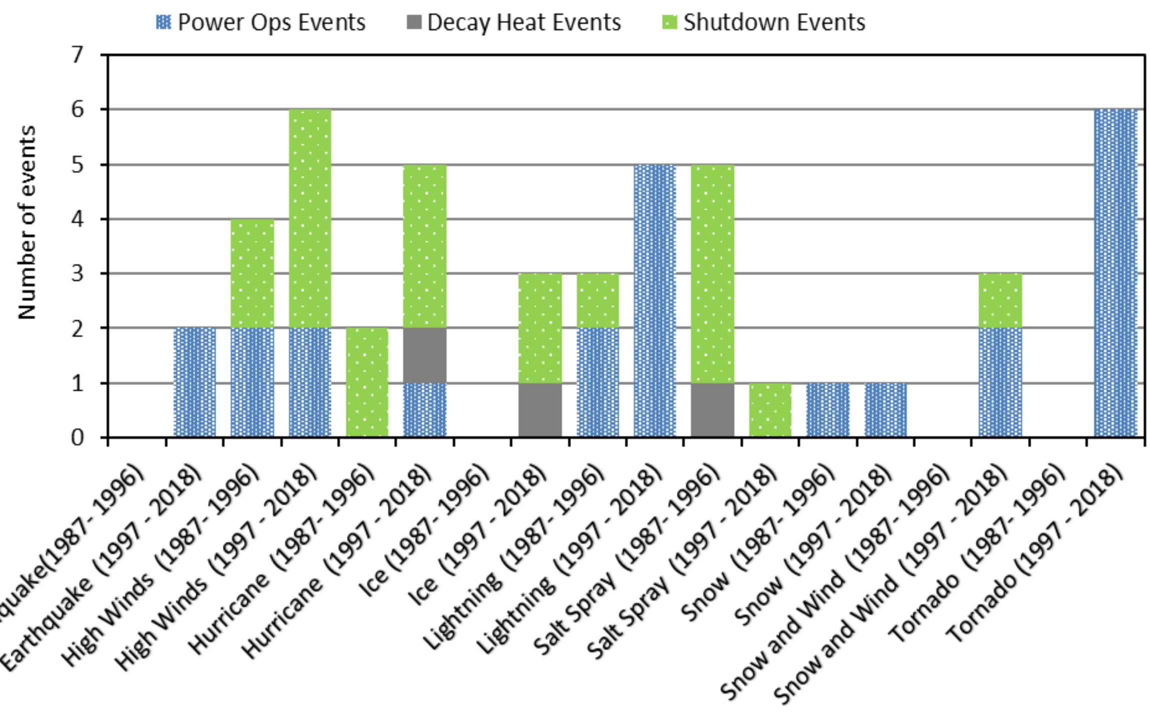


Figure 13. Natural disasters causing LOOP events from weather (1987–1996 and 1997–2018).

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Appendix A
LOOP Events Listing

Appendix A - LOOP Events Listing (1987–2018)

Table A-1 LOOP events for 1987–2018, sorted by plant.

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes)			Cause	Specific Cause
					Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time		
3132013001	Arkansas 1	3/31/2013	Shutdown	Plant centered	0	8640	8640	HES	Other
3132017001	Arkansas 1	4/26/2017	Critical	Weather related	0	0	0	SEE	High Winds
3682017002	Arkansas 2	4/26/2017	Shutdown	Weather related	0	0	0	SEE	High Winds
3341993013	Beaver Valley 1	10/12/1993	Critical	Switchyard centered	15	28	28	HES	Maintenance
4121987036	Beaver Valley 2	11/17/1987	Critical	Switchyard centered	0	4	4	Equip	Breaker
3341993013	Beaver Valley 2	10/12/1993	Shutdown	Switchyard centered	15	28	28	HES	Maintenance
1551992000	Big Rock Point	1/29/1992	Shutdown	Switchyard centered	77	82	82	Equip	Other
4561987048	Braidwood 1	9/11/1987	Shutdown	Switchyard centered	62	63	63	Equip	Transformer
4561988022	Braidwood 1	10/16/1988	Critical	Switchyard centered	95	118	213	Equip	Breaker
4561998003	Braidwood 1	9/6/1998	Shutdown	Weather related	528	533	533	SEE	High Winds
4572009002	Braidwood 2	7/30/2009	Critical	Switchyard centered	3097	3098	3099	Equip	Relay
2592011001	Browns Ferry 1	4/27/2011	Critical	Weather related	3324	7414	7414	EEE	Tornado
2592011001	Browns Ferry 2	4/27/2011	Critical	Weather related	4764	7414	7414	EEE	Tornado
2961997001	Browns Ferry 3	3/5/1997	Shutdown	Switchyard centered	39	44	44	Equip	Transformer

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes) Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time	Cause	Specific Cause
2592011001	Browns Ferry 3	4/27/2011	Critical	Weather related	4764	7414	7414	EEE	Tornado
2962012003	Browns Ferry 3	5/22/2012	Critical	Switchyard centered	0	101	101	Equip	Relay
3251993008	Brunswick 1	3/17/1993	Shutdown	Weather related	1120	1125	1508	SEE	Salt Spray
3252000001	Brunswick 1	3/3/2000	Shutdown	Switchyard centered	15	30	136	HES	Testing
3252004002	Brunswick 1	8/14/2004	Critical	Weather related	167	172	183	EEE	Hurricane
3252016001	Brunswick 1	2/7/2016	Critical	Plant centered	0	195	196	Equip	Breaker
3241989009	Brunswick 2	6/17/1989	Critical	Switchyard centered	85	90	403	HE	Maintenance
3251993008	Brunswick 2	3/16/1993	Shutdown	Weather related	813	818	1018	SEE	Salt Spray
3241994008	Brunswick 2	5/21/1994	Shutdown	Plant centered	2	17	42	HES	Testing
3242006001	Brunswick 2	11/1/2006	Critical	Switchyard centered	0	30	1402	Equip	Transformer
4541996007	Byron 1	5/23/1996	Shutdown	Switchyard centered	715	720	1763	Equip	Transformer
4542014003	Byron 1	3/15/2014	Shutdown	Switchyard centered	613	613	613	Equip	Transformer
4551987019	Byron 2	10/2/1987	Critical	Switchyard centered	1	16	507	HES	Switching
4542012001	Byron 2	1/30/2012	Critical	Switchyard centered	2035	2035	2172	Equip	Transformer
3171987012	Calvert Cliffs 1	7/23/1987	Critical	Switchyard centered	113	118	118	Equip	Circuits
3172015002	Calvert Cliffs 1	4/7/2015	Critical	Grid related	0	0	0	G	Equip - other
3171987012	Calvert Cliffs 2	7/23/1987	Critical	Switchyard centered	113	118	118	Equip	Circuits
3172015002	Calvert Cliffs 2	4/7/2015	Critical	Grid related	0	0	0	G	Equip - other

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes) Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time	Cause	Specific Cause
4132006001	Catawba 1	5/20/2006	Critical	Switchyard centered	0	400	542	Equip	Circuits
4132012001	Catawba 1	4/4/2012	Critical	Plant centered	0	326	393	Equip	Circuits
4141996001	Catawba 2	2/6/1996	Critical	Switchyard centered	115	120	330	Equip	Transformer
4132006001	Catawba 2	5/20/2006	Critical	Switchyard centered	0	387	570	Equip	Circuits
4132012001	Catawba 2	4/4/2012	Shutdown	Switchyard centered	0	334	574	Equip	Circuits
4611999002	Clinton 1	1/6/1999	Shutdown	Switchyard centered	270	275	492	Equip	Other
3971989016	Columbia	5/14/1989	Shutdown	Switchyard centered	0	15	29	HES	Maintenance
3151991004	Cook 1	5/12/1991	Critical	Plant centered	0	15	81	Equip	Other
3021987025	Crystal River 3	10/16/1987	Shutdown	Switchyard centered	18	28	59	HES	Maintenance
3021989023	Crystal River 3	6/16/1989	Critical	Switchyard centered	60	65	65	HE	Testing
3021989025	Crystal River 3	6/29/1989	Shutdown	Switchyard centered	0	2	2	SEE	Lightning
3021991010	Crystal River 3	10/20/1991	Shutdown	Plant centered	0	4	4	HES	Other
3021992001	Crystal River 3	3/27/1992	Critical	Plant centered	20	30	150	HE	Maintenance
3021993000	Crystal River 3	3/17/1993	Shutdown	Weather related	72	77	102	SEE	Salt Spray
3021993002	Crystal River 3	3/29/1993	Shutdown	Weather related	0	15	37	SEE	Flooding
3021993004	Crystal River 3	4/8/1993	Shutdown	Plant centered	1	16	136	HES	Maintenance
3461998006	Davis-Besse	6/24/1998	Critical	Weather related	1364	1428	1495	EEE	Tornado

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes) Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time	Cause	Specific Cause
3462000004	Davis-Besse	4/22/2000	Shutdown	Plant centered	0	10	10	HES	Testing
3462003009	Davis-Besse	8/14/2003	Shutdown	Grid related	652	657	849	G	Other - load
2751991004	Diablo Canyon 1	3/7/1991	Shutdown	Switchyard centered	261	285	285	HES	Maintenance
2751995014	Diablo Canyon 1	10/21/1995	Shutdown	Switchyard centered	40	45	951	HES	Maintenance
2752000004	Diablo Canyon 1	5/15/2000	Critical	Plant centered	1901	1906	2014	Equip	Other
2752007001	Diablo Canyon 1	5/12/2007	Shutdown	Grid related	209	245	279	Equip	Other
3231988008	Diablo Canyon 2	7/17/1988	Critical	Switchyard centered	33	38	38	Equip	Transformer
2371990002	Dresden 2	1/16/1990	Shutdown	Switchyard centered	0	45	759	Equip	Transformer
2491989001	Dresden 3	3/25/1989	Critical	Switchyard centered	45	50	50	Equip	Breaker
2492004003	Dresden 3	5/5/2004	Critical	Switchyard centered	146	151	151	Equip	Breaker
3311990007	Duane Arnold	7/9/1990	Shutdown	Switchyard centered	0	37	37	HES	Testing
3312007004	Duane Arnold	2/24/2007	Shutdown	Weather related	5	1048	1829	SEE	Ice
3482000005	Farley 1	4/9/2000	Shutdown	Switchyard centered	0	19	19	Equip	Relay
3412003002	Fermi 2	8/14/2003	Critical	Grid related	379	384	582	G	Other - load
3331988011	FitzPatrick	10/31/1988	Shutdown	Weather related	1	16	70	SEE	High Winds
3332003001	FitzPatrick	8/14/2003	Critical	Grid related	169	174	414	G	Other - load
3332012005	FitzPatrick	10/5/2012	Shutdown	Switchyard centered	847	847	847	HE	Maintenance
2851987008	Fort Calhoun	3/21/1987	Shutdown	Switchyard centered	37	38	38	HES	Maintenance
2851987009	Fort Calhoun	4/4/1987	Shutdown	Switchyard centered	0	4	4	HES	Maintenance

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes) Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time	Cause	Specific Cause
2851990006	Fort Calhoun	2/26/1990	Shutdown	Switchyard centered	0	14	14	HES	Maintenance
2851998005	Fort Calhoun	5/20/1998	Shutdown	Switchyard centered	104	109	109	Equip	Transformer
2851999004	Fort Calhoun	10/26/1999	Shutdown	Plant centered	2	2	2	Equip	Other
2442003002	Ginna	8/14/2003	Critical	Grid related	49	54	297	G	Other - load
4162003002	Grand Gulf	4/24/2003	Critical	Switchyard centered	0	15	75	SEE	High Winds
2131993009	Haddam Neck	6/22/1993	Shutdown	Plant centered	12	27	35	Equip	Circuits
2131993010	Haddam Neck	6/26/1993	Shutdown	Plant centered	3	18	40	Equip	Circuits
4002016005	Harris	10/8/2016	Shutdown	Weather related	0	443	524	EEE	Hurricane
2471991006	Indian Point 2	3/20/1991	Shutdown	Switchyard centered	0	15	29	Equip	Other
2471991010	Indian Point 2	6/22/1991	Shutdown	Plant centered	0	60	60	Equip	Breaker
2471998013	Indian Point 2	9/1/1998	Shutdown	Plant centered	1	16	67	HES	Testing
2471999015	Indian Point 2	8/31/1999	Shutdown	Switchyard centered	0	15	779	Equip	Circuits
2472003005	Indian Point 2	8/14/2003	Critical	Grid related	97	102	214	G	Other - load
2861995004	Indian Point 3	2/27/1995	Shutdown	Switchyard centered	30	40	132	HES	Maintenance
2861996002	Indian Point 3	1/20/1996	Shutdown	Switchyard centered	30	40	145	Equip	Transformer
2861997008	Indian Point 3	6/16/1997	Shutdown	Grid related	37	42	42	HE	Maintenance
2862003005	Indian Point 3	8/14/2003	Critical	Grid related	97	102	241	G	Other - load
3731993015	La Salle 1	9/14/1993	Critical	Switchyard centered	0	15	70	Equip	Transformer
3732013002	La Salle 1	4/17/2013	Critical	Switchyard centered	481	481	482	SEE	Lightning

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes) Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time	Cause	Specific Cause
3732013002	La Salle 2	4/17/2013	Critical	Switchyard centered	481	481	482	SEE	Lightning
3091988006	Maine Yankee	8/13/1988	Critical	Switchyard centered	14	15	15	Equip	Transformer
3691987021	McGuire 1	9/16/1987	Shutdown	Plant centered	0	6	6	HES	Testing
3691991001	McGuire 1	2/11/1991	Critical	Plant centered	0	40	60	HE	Testing
3691988014	McGuire 2	6/24/1988	Shutdown	Switchyard centered	8	8	8	HES	Switching
3701993008	McGuire 2	12/27/1993	Critical	Switchyard centered	96	101	131	Equip	Transformer
2451989012	Millstone 1	4/29/1989	Shutdown	Switchyard centered	0	15	75	HES	Other
3361988011	Millstone 2	10/25/1988	Critical	Plant centered	19	29	29	HE	Maintenance
3362008004	Millstone 2	5/24/2008	Shutdown	Switchyard centered	57	57	1612	G	Equip - other
3362014006	Millstone 2	5/25/2014	Critical	Grid related	0	0	433	Equip	Other
4232007002	Millstone 3	4/25/2007	Shutdown	Grid related	133	193	220	HES	Switching
3362014006	Millstone 3	5/25/2014	Critical	Grid related	0	0	433	Equip	Other
2632008006	Monticello	9/17/2008	Shutdown	Switchyard centered	0	0	0	HES	Maintenance
2202003002	Nine Mile Pt. 1	8/14/2003	Critical	Grid related	105	110	448	G	Other - load
4101988062	Nine Mile Pt. 2	12/26/1988	Shutdown	Switchyard centered	9	24	54	Equip	Transformer
4101992006	Nine Mile Pt. 2	3/23/1992	Shutdown	Plant centered	20	30	50	HES	Maintenance
4102003002	Nine Mile Pt. 2	8/14/2003	Critical	Grid related	100	105	551	G	Other - load
3382011003	North Anna 1	8/23/2011	Critical	Switchyard centered	467	547	547	SEE	Earthquake
3382011003	North Anna 2	8/23/2011	Critical	Switchyard centered	467	547	547	SEE	Earthquake

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes) Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time	Cause	Specific Cause
2701992004	Oconee 2	10/19/1992	Critical	Plant centered	207	207	207	HE	Maintenance
2871987002	Oconee 3	3/5/1987	Shutdown	Switchyard centered	150	155	155	HES	Maintenance
2872006001	Oconee 3	5/15/2006	Shutdown	Plant centered	606	606	1730	HES	Maintenance
2872018002	Oconee 3	5/10/2018	Shutdown	Plant centered	807	807	807	Equip	Relay
2191989015	Oyster Creek	5/18/1989	Critical	Plant centered	1	16	54	HE	Maintenance
2191992005	Oyster Creek	5/3/1992	Critical	Grid related	5	65	1029	SEE	Fire
2191997010	Oyster Creek	8/1/1997	Critical	Switchyard centered	30	40	40	Equip	Relay
2192009005	Oyster Creek	7/12/2009	Critical	Grid related	0	0	150	SEE	Lightning
2192012001	Oyster Creek	7/23/2012	Critical	Grid related	271	451	511	Equip	Relay
2192012002	Oyster Creek	10/29/2012	Shutdown	Weather related	861	861	4394	SEE	High Winds
2551987024	Palisades	7/14/1987	Critical	Switchyard centered	388	388	446	HE	Maintenance
2551992032	Palisades	4/6/1992	Shutdown	Plant centered	0	15	30	HES	Testing
2551998013	Palisades	12/22/1998	Shutdown	Plant centered	0	20	20	Equip	Transformer
2552003003	Palisades	3/25/2003	Shutdown	Plant centered	91	96	3261	HES	Maintenance
5282004006	Palo Verde 1	6/14/2004	Critical	Grid related	32	37	57	G	Equip - other
5282004006	Palo Verde 2	6/14/2004	Critical	Grid related	32	37	106	G	Equip - other
5282004006	Palo Verde 3	6/14/2004	Critical	Grid related	32	37	59	G	Equip - other
2771988020	Peach Bottom 2	7/29/1988	Shutdown	Switchyard centered	9	24	125	Equip	Transformer
2772003004	Peach Bottom 2	9/15/2003	Critical	Grid related	1	16	41	Equip	Relay

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes) Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time	Cause	Specific Cause
2771988020	Peach Bottom 3	7/29/1988	Shutdown	Switchyard centered	9	24	125	Equip	Transformer
2772003004	Peach Bottom 3	9/15/2003	Critical	Grid related	1	16	103	Equip	Relay
4402003002	Perry	8/14/2003	Critical	Grid related	82	87	123	G	Other - load
2931987005	Pilgrim	3/31/1987	Shutdown	Weather related	1	16	45	SEE	High Winds
2931987014	Pilgrim	11/12/1987	Shutdown	Weather related	1258	1263	1263	SEE	Salt Spray
2931989010	Pilgrim	2/21/1989	Shutdown	Switchyard centered	1	16	920	Equip	Other
2931991024	Pilgrim	10/30/1991	Shutdown	Weather related	109	114	152	SEE	Salt Spray
2931993004	Pilgrim	3/13/1993	Critical	Weather related	30	40	298	SEE	Snow
2931993010	Pilgrim	5/19/1993	Shutdown	Switchyard centered	36	37	37	HES	Testing
2931993022	Pilgrim	9/10/1993	Critical	Switchyard centered	10	25	200	SEE	Lightning
2931997007	Pilgrim	4/1/1997	Shutdown	Weather related	347	1200	1208	SEE	High Winds
2932008007	Pilgrim	12/20/2008	Shutdown	Switchyard centered	2	60	120	SEE	Ice
2932013003	Pilgrim	2/8/2013	Critical	Weather related	720	1907	2177	SEE	Snow and Wind
2932013003	Pilgrim	2/10/2013	Shutdown	Switchyard centered	2271	2387	3333	SEE	Ice
2932013009	Pilgrim	10/14/2013	Critical	Grid related	1334	1382	1382	G	Equip - other
2932015001	Pilgrim	1/27/2015	Critical	Weather related	3641	3641	3641	SEE	Snow and Wind
2932018004	Pilgrim	3/13/2018	Shutdown	Weather related	0	0	0	SEE	Snow and Wind
2661992003	Point Beach 1	4/28/1992	Shutdown	Plant centered	0	15	30	HES	Maintenance
2662011001	Point Beach 1	11/27/2011	Shutdown	Switchyard centered	0	334	334	Equip	Other

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes)			Cause	Specific Cause
					Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time		
3011989002	Point Beach 2	3/29/1989	Critical	Switchyard centered	90	95	202	HE	Maintenance
2661994010	Point Beach 2	9/27/1994	Shutdown	Plant centered	0	15	15	HES	Switching
2821996012	Prairie Island 1	6/29/1996	Critical	Weather related	292	297	297	SEE	High Winds
2821996012	Prairie Island 2	6/29/1996	Critical	Weather related	292	297	297	SEE	High Winds
2651991005	Quad Cities 1	4/2/1991	Shutdown	Plant centered	0	0	0	Equip	Transformer
2651992011	Quad Cities 2	4/2/1992	Shutdown	Plant centered	35	35	35	Equip	Transformer
2652001001	Quad Cities 2	8/2/2001	Critical	Switchyard centered	15	30	154	SEE	Lightning
2611992017	Robinson 2	8/22/1992	Critical	Switchyard centered	454	459	914	Equip	Transformer
2612016005	Robinson 2	10/8/2016	Critical	Switchyard centered	1	621	621	G	Equip - other
2722003002	Salem 1	7/29/2003	Critical	Switchyard centered	30	40	480	Equip	Circuits
3111994014	Salem 2	11/18/1994	Shutdown	Switchyard centered	295	300	1675	Equip	Relay
3622002001	San Onofre 3	2/27/2002	Critical	Switchyard centered	32	32	32	HE	Testing
4431988004	Seabrook	8/10/1988	Shutdown	Plant centered	0	0	0	HES	Switching
4431991008	Seabrook	6/27/1991	Critical	Switchyard centered	0	20	20	Equip	Relay
4432001002	Seabrook	3/5/2001	Critical	Weather related	1	16	2122	SEE	Snow
3271992027	Sequoyah 1	12/31/1992	Critical	Switchyard centered	96	101	116	Equip	Breaker
3271997007	Sequoyah 1	4/4/1997	Shutdown	Plant centered	325	330	345	HE	Maintenance
3271992027	Sequoyah 2	12/31/1992	Critical	Switchyard centered	96	101	116	Equip	Breaker

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes)			Cause	Specific Cause
					Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time		
3352004004	St. Lucie 1	9/25/2004	Shutdown	Weather related	8	68	667	EEE	Hurricane
3352016003	St. Lucie 1	8/21/2016	Critical	Plant centered	0	0	70	Equip	Circuits
3352004004	St. Lucie 2	9/25/2004	Shutdown	Weather related	8	68	613	EEE	Hurricane
3951989012	Summer	7/11/1989	Shutdown	Grid related	95	100	120	G	Equip - other
2802011001	Surry 1	4/16/2011	Critical	Weather related	303	346	1394	EEE	Tornado
2802011001	Surry 2	4/16/2011	Critical	Weather related	303	424	1580	EEE	Tornado
2891997007	Three Mile Isl 1	6/21/1997	Critical	Switchyard centered	85	90	90	Equip	Circuits
2501991003	Turkey Point 3	7/24/1991	Shutdown	Switchyard centered	0	11	11	Equip	Breaker
2501992000	Turkey Point 3	8/24/1992	Shutdown	Weather related	7916	7921	7921	EEE	Hurricane
2511991001	Turkey Point 4	3/13/1991	Shutdown	Plant centered	62	67	67	Equip	Relay
2501992000	Turkey Point 4	8/24/1992	Shutdown	Weather related	7916	7921	7921	EEE	Hurricane
2512000004	Turkey Point 4	10/21/2000	Shutdown	Switchyard centered	1	16	111	Equip	Circuits
2512005005	Turkey Point 4	10/31/2005	Shutdown	Weather related	0	20	1615	SEE	Salt Spray
2512013002	Turkey Point 4	4/19/2013	Critical	Plant centered	24	27	30	HE	Testing
2711987008	Vermont Yankee	8/17/1987	Shutdown	Grid related	2	17	77	Equip	Other
2711991009	Vermont Yankee	4/23/1991	Critical	Plant centered	277	282	822	HE	Maintenance
4241990006	Vogtle 1	3/20/1990	Shutdown	Switchyard centered	140	145	217	HES	Other
3822005004	Waterford 3	8/29/2005	Shutdown	Weather related	4981	5242	5242	EEE	Hurricane

LER	Plant Name	Date	Operational Mode	LOOP Category	Restoration Time (minutes)			Cause	Specific Cause
					Switchyard Restoration Time	Potential Bus Recovery Time	Actual Bus Restoration Time		
3822017002	Waterford 3	7/17/2017	Critical	Plant centered	145	158	158	Equip	Relay
4821987048	Wolf Creek	10/14/1987	Shutdown	Plant centered	0	17	17	HES	Maintenance
4822008004	Wolf Creek	4/7/2008	Shutdown	Switchyard centered	7	7	153	HES	Maintenance
4822009002	Wolf Creek	8/19/2009	Critical	Weather related	1	133	133	SEE	Lightning
4822012001	Wolf Creek	1/13/2012	Critical	Switchyard centered	177	177	198	Equip	Breaker
291991002	Yankee-Rowe	6/15/1991	Critical	Switchyard centered	24	25	25	SEE	Lightning
2951997007	Zion 1	3/11/1997	Shutdown	Switchyard centered	235	240	240	Equip	Circuits
3041991002	Zion 2	3/21/1991	Critical	Switchyard centered	0	60	60	Equip	Transformer

Note:

1. Refer to Glossary section for the definitions of the switchyard restoration time, potential bus recovery time, and actual bus restoration time in the table. Refer to Section 6.7 and Appendix A-1.7 of NUREG/CR-6890 for more detailed discussions.
2. The acronyms used in the Cause column are described below:
    a. EEE - Extreme external events: hurricane, winds > 125 mph, tornado, earthquake > R7, flooding > 500-year flood for the site, sabotage
    b. EQUIP - Hardware related failures
    c. G - Interconnected grid transmission line events, outside direct plant control
    d. HE - Human error during any operating mode
    e. HES - Human error during any shutdown mode
    f. SEE - Severe external events: lightening, high winds, snow and ice, salt spray, dust contamination, fires and smoke contamination, earthquake < R7, flooding < 500-year flood for the site.