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Analysis of Loss-of-Offsite-Power Events

1987 - 2017

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ABSTRACT

Loss of offsite power (LOOP) can have a major negative impact on a 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 are based on the operating experience during calendar years 1987 through 2017. LOOP events during critical operation 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 are identified. Adverse trends in LOOP durations are 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 are found to show statistically significant seasonality. The engineering analysis of LOOP data shows 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 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 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 2017 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.

As in previous studies, the LOOP data were studied for four categories: plant-centered, switchyard-centered, grid-related, and weather-related. There are four LOOP data changes in this study: (1) three new LOOP events occurred in 2017; (2) three previous LOOP events were recently reviewed and reclassified to different categories; (3) three previous LOOP events were recently reviewed and reclassified to different operational modes; and (4) a previously not identified LOOP event was added.

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 2008–2017 period.

To characterize the variation in LOOP frequencies in each category, for each plant operating mode, 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 difference 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 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 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) potential LOOP recovery times at a site level showed an extremely statistically significant increasing trend for switchyard-centered LOOPs (p-value = 2.22E-4). A statistically significant 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 total LOOP recovery time trend is the most significant (p-value = 1.82E-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 = 2.79E-3). 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 weather-related LOOPs have the longest recovery times.

Seasonal Effects. To study seasonal patterns in the LOOP occurrences, the 1997-2017 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 (i.e., seasonal effects on LOOP frequency do exist) for critical operation grid-related LOOPs (highly statistical significant, with p-value = 0.008) and for critical operations weather-related LOOPs (statistical significant, with p-value = 0.017).

Data for LOOP events that affected multiple units at a multi-unit site was reviewed. There were 7 occasions during 1987–1996 and 13 occasions during 1997–2017 when more than one unit at a site was affected by the same incident. The 13 occasions contributed 27 of the 96 unit events during 1997–2017. When multiple units at a site experience a LOOP on the same day, the LOOP events are not independent. This situation would benefit from further study. For the most part, the analyses in this report treat the events independently.

The engineering review of the LOOP data found that for period of 1997-2017 equipment failures are dominated by failures of circuits, relays, and transformers. Human errors associated with the events occurred primarily in maintenance and testing. The weather events are dominated by tornado, high winds, and hurricanes. This review shows that human errors have been much less frequent during 1997–2017 than in the 1987–1996 time period.

ACRONYMS

EDG	emergency diesel generator
EB	empirical Bayes
IE	initiating event
INL	Idaho National Laboratory
LOOP	loss of offsite power
MLE	maximum likelihood estimator
MSPI	Mitigating System Performance Indicator
NERC	North American Electric Reliability Council
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment

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 not loaded in response to a loss of offsite power to all safety buses should still be classified as a LOOP event.*

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 include 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).*

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 from 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 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 lines of demarcation between switchyard-related events and grid-related events *are the points 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

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

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 was there. 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 to restore offsite power 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 LOOPs and Initiating Events (IEs)

LOOP initiating event (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). These two subcategories are described further below:

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.

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; see below).

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

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 (i.e., 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.

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 - 2017

1. INTRODUCTION

United States commercial nuclear power plants (NPPs) rely on alternating current 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 some 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 2017 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.[1]

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 http://nrcoe.inl.gov/resultsdb/LOSP) . This study continues the work by covering data through 2017. As in the previous studies, the events are studied based on four LOOP categories: plant-centered, switchyard-centered, grid-related, and weather-related. 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.[2] 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 the states, but most states with deregulation had implemented the change 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 has accrued, the older data are no longer displayed in the graphs or used in the frequency analyses. Recent data in the graphs is easier to see with fewer years on the horizontal axis. Frequency data from 1987 to the current update year are summarized in section 2.3. Appendix A lists the licensee event reports 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 (2008-2017 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 here is the potential recovery time. Because the

[1] The LOOP frequency distribution results in this report include more recent LOOP data and could be used to update the LOOP initiating event frequency in PRA model instead of those from the NRC less-frequent data update for industry average parameter estimates (e.g., 2015 Updates in https://nrcoe.inl.gov/resultsdb/publicdocs/AvgPerf) or the baseline frequencies in the NRC initiating event update study (e.g., INL/EXT-18-45524 for 2017 IE report).
[2] 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 could be different from each other. The ranges of data are included in the associated table titles.

data are limited, the data from 1988 to 2017 are used here. In the trend analysis of the recovery times, the time span is 1997-2017.

The data cover both critical (at power) and shutdown operations. Partial LOOP events, in which some but not all offsite power is lost, and LOOP events at power that do not result in a reactor trip are not included in this study.

Since 2009, the annual LOOP updates have included a discussion of emergency diesel generator (EDG) repair times. This report does not include that analysis, because it fits well in the EDG component study report (Schroeder 2018) which can be accessed from http://nrcoe.inl.gov/resultsdb/CompPerf/.

1.1 LOOP Data Changes in this Study

The LOOP data changes in this study include:

(1) Three new LOOP events occurred in 2017;

- Arkansas 1 on April 26, 2017 (LER 3132017001) as critical operation weather-related
- Arkansas 2 on April 26, 2017 (LER 3682017002) as shutdown operation weather-related
- Waterford 3 on July 17, 2017 (LER 3822017002) as critical operation plant-centered

(2) Three previous LOOP events were reclassified to different LOOP categories;

- Milestone 2 on May 25, 2014 (LER 3362014006) from critical switchyard-centered to critical grid-related
- Milestone 3 on May 25, 2014 (LER 3362014006) from critical switchyard-centered to critical grid-related
- Pilgrim on February 8, 2013 (LER 2932013003) from critical switchyard-centered to critical weather-related

(3) Three previous LOOP events were reclassified to different operational modes;

- Byron 1 on 2/28/2012 (LER 4542012001) from Power Ops to Power Ops-No Trip
- Crystal River 3 on 6/16/1989 (LER 3021989023) from Shutdown to Critical
- Point Beach 1 on 2/6/2013 (LER 2662013001) from Power Ops to Power Ops-No Trip

(4) One previously not identified LOOP event was added.

- Arkansas 1 on March 31, 2013 (LER 3132013001) as shutdown plant-centered

2. INDUSTRY-WIDE LOOP FREQUENCIES

Industry-average LOOP frequencies were determined for calendar years 1997-2017. 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. 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*. Note that while the MLE values are provided in Table 1, the LOOP frequency mean values as well as the distributions are estimated and provided in Section 2.2 and Table 2.

Table 1. Average LOOP frequencies for 1997–2017.

Mode	LOOP Category	Events	Reactor Critical or Shutdown Years	Maximum Likelihood Estimate (MLE) (Events/Years)	Percent
Critical Operation[a]	Plant-centered	6	1935.79	3.10E-03	10.53
	Switchyard-centered	19	1935.79	9.82E-03	33.33
	Grid-related	20	1935.79	1.03E-02	35.09
	Weather-related	12	1935.79	6.20E-03	21.05
	All LOOPs	57	1935.79	2.94E-02	100
Shutdown Operation[b]	Plant-centered	8	227.25	3.52E-02	20.51
	Switchyard-centered	17	227.25	7.48E-02	43.59
	Grid-related	4	227.25	1.76E-02	10.26
	Weather-related	10	227.25	4.40E-02	25.64
	All LOOPs	39	227.25	1.72E-01	100

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. Switchyard-centered events are likewise the most common type of LOOP during shutdown operation at close to 44%.

In Section 2.1 below, annual data are shown and trends in industry average LOOP frequencies for the most recent 10 years are considered. Section 2.2 discusses variation in the frequencies between plants. It also provides uncertainty distributions for critical operation grid-related LOOPs for plants grouped in regions established by the North American Electric Reliability Council (NERC). Finally, the raw data used for the LOOP frequency analyses are summarized in Section 2.3.

2.1 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 include in the trend period requires a judgement about what constitutes current and for this update study that is considered to be the most recent 10 years. To provide more perspective, the plots include data since 1997 when implementation of deregulation of the electrical system was well underway.

Figure 1 shows the annual estimated LOOP frequencies from 1997 through 2017 and the trend for the most recent 10 years (from 2008 through 2017) during critical operation for all LOOP categories. 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. The 90% confidence intervals of the LOOP frequency (plotted vertically) are confidence intervals for the estimated rate associated with each individual year's 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.

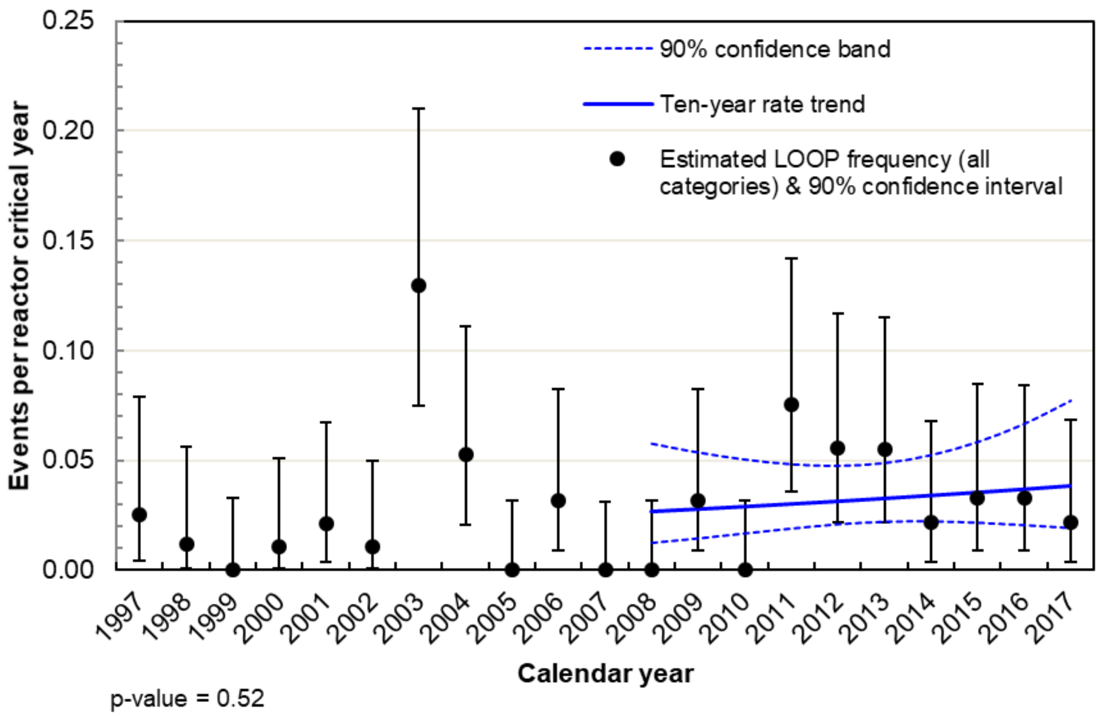

Figure 1. Estimated LOOP frequencies (all categories) and 10-year trend during critical operations.

Figures 2–5 show the annual frequencies and 10-year trends for critical operations for each of the four LOOP categories. The licensee event reports for the events supporting the plots are listed in the Appendix A tables.

There are no statistically significant[1] 10-year trends identified in critical operation LOOP frequencies for all LOOP categories as well as for each of the four LOOP categories over the 2008-2017 period.

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[1] 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 that there is a trend in the data (reject the null hypothesis of no trend.) By convention, we use the "Michelin Guide" scale: p-value < 0.05 (statistically significant), p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant).

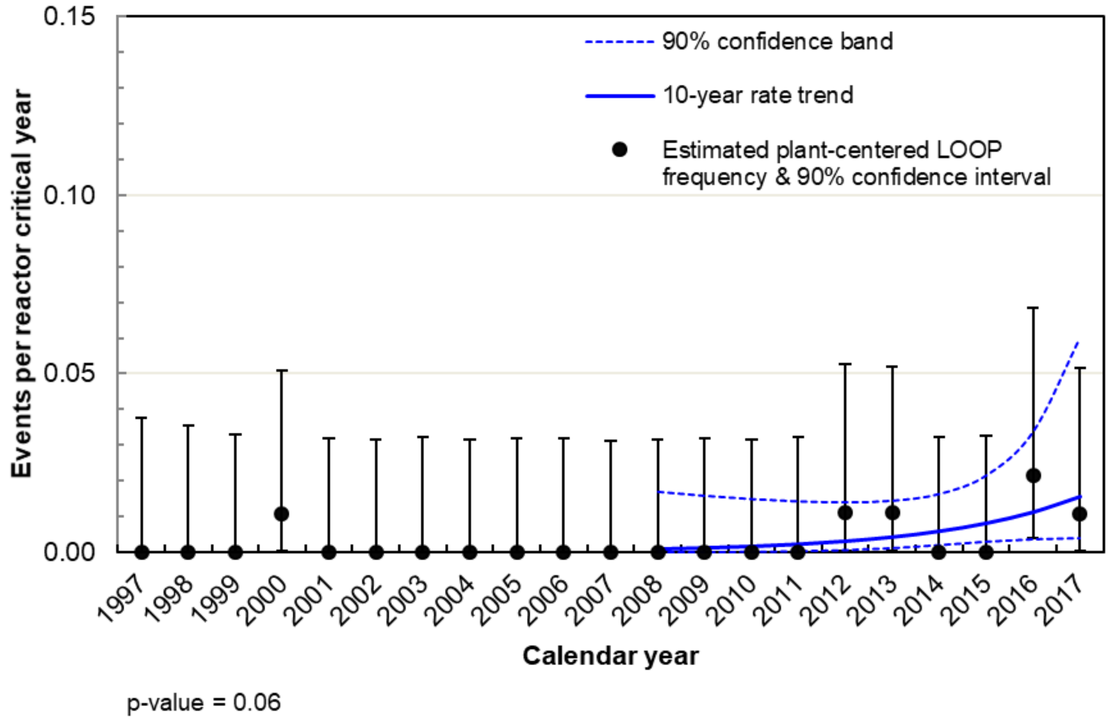

Figure 2. Estimated plant-centered LOOP frequency and 10-year trend during critical operation.

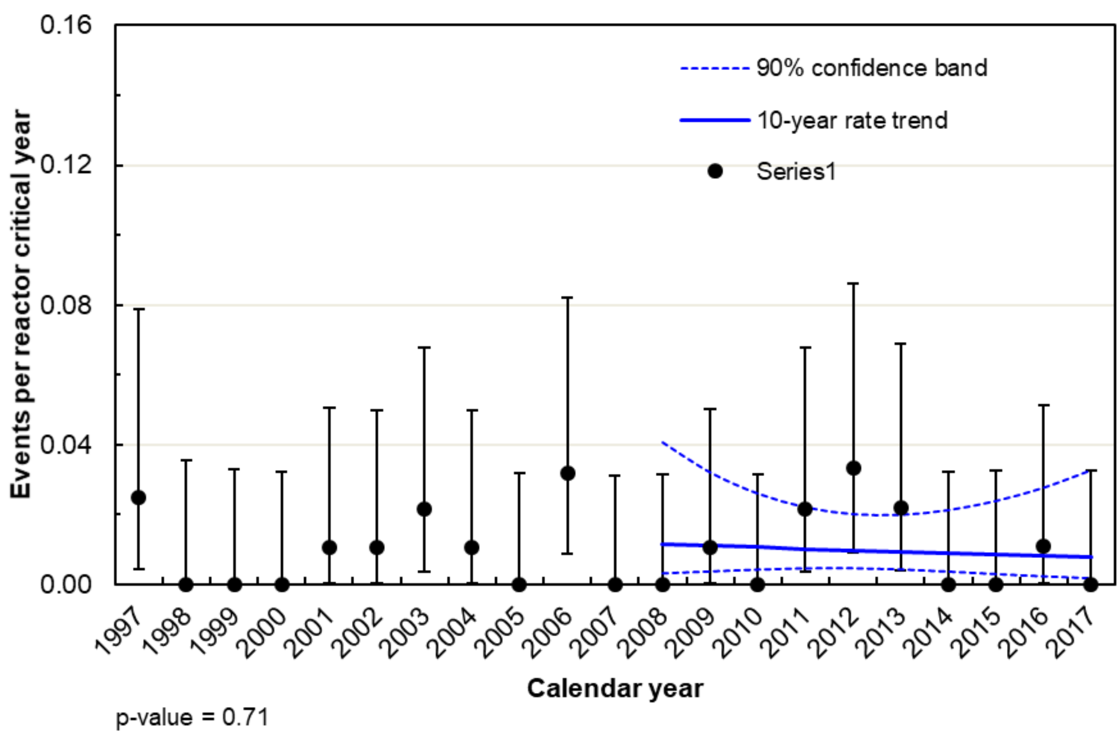

Figure 3. Estimated switchyard-centered LOOP frequency and 10-year trend during critical operation.

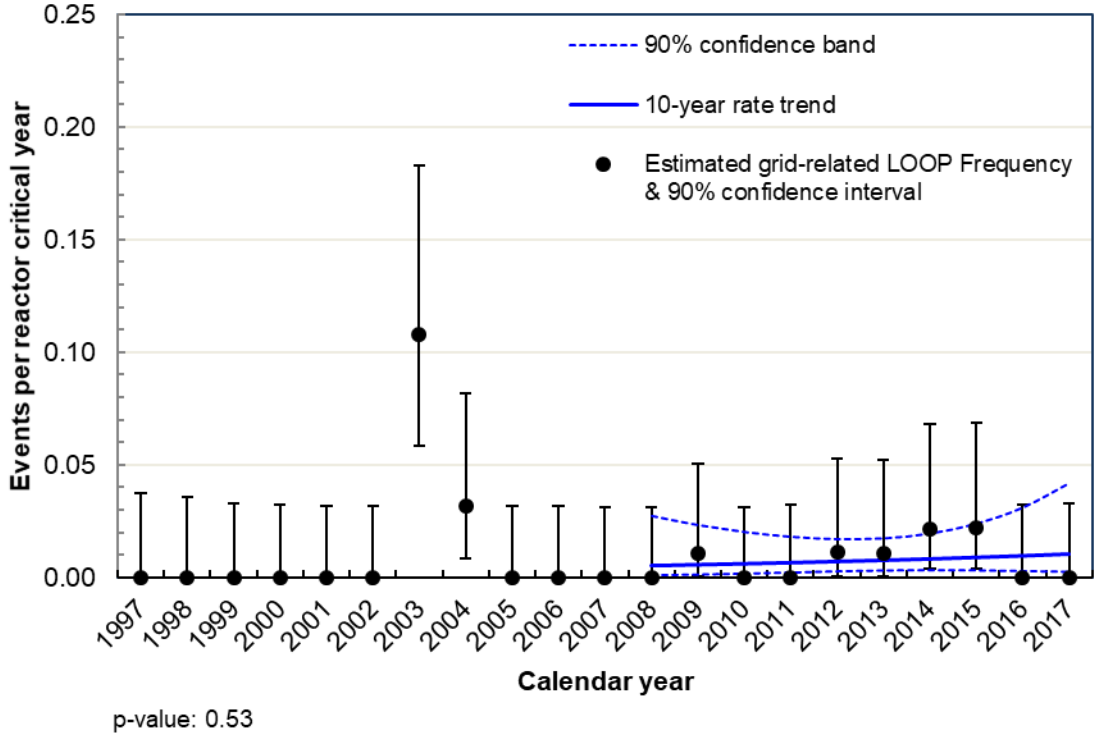

Figure 4. Estimated grid-related LOOP frequency and 10-year trend during critical operation.

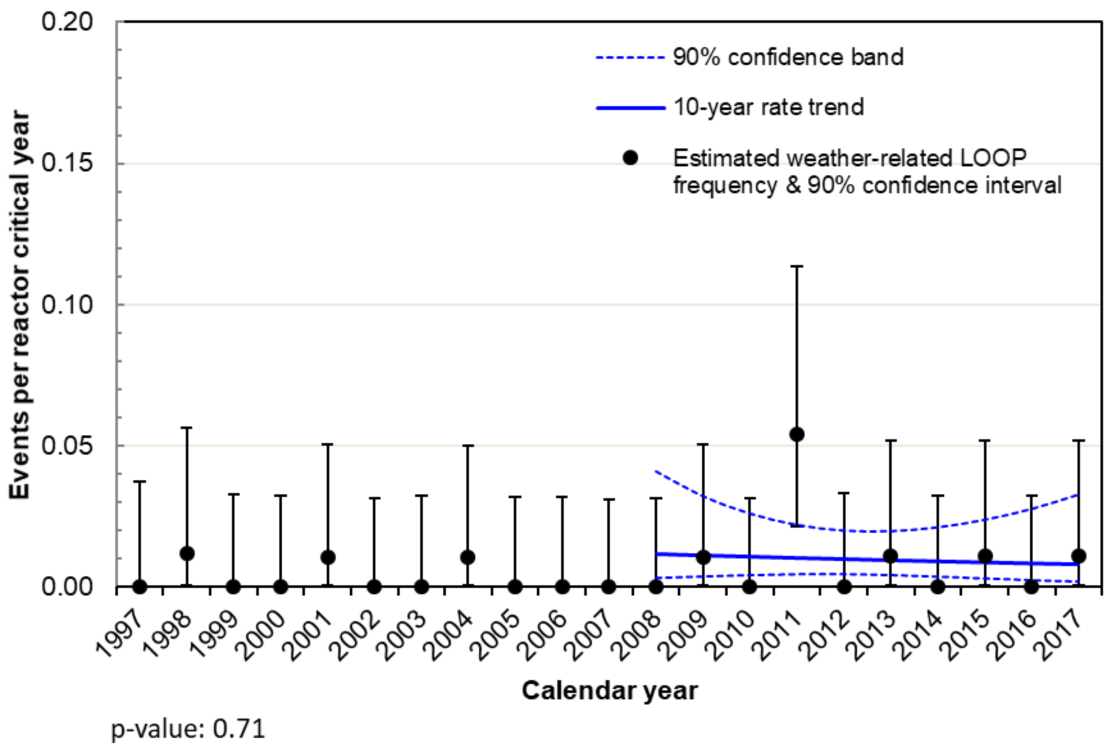

Figure 5. Estimated weather-related LOOPs frequency and 10-year trend during critical operation.

2.2 LOOP Frequency Variation: Distributions for PRA Use

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, an empirical Bayes distribution representing that variation can be obtained, then the empirical Bayes distribution result is reported in Table 2. If the tests for variation indicate the data appear homogeneous for each grouping, then a Jeffreys noninformative prior is used 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, the 5th, 50th, 95th percentiles, and mean are tabulated.

Past data support the separation of data by plant mode of operation for grid and weather-related LOOPs, but recent data has shown fewer differences. The decision was 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- 2017).

Mode	LOOP Category	Shape (α)	Scale (β)	5%	Median	95%	Gamma Mean	Simple MLE	Notes
Critical Operation	Plant-centered	6.5	1940	1.52E-03	3.18E-03	5.78E-03	3.36E-03	3.10E-03	a
	Switchyard-centered	19.50	1940	6.64E-03	9.88E-03	1.41E-02	1.01E-02	9.82E-03	a
	Grid-related	0.51	46.70	4.94E-05	5.11E-03	4.18E-02	1.10E-02	1.03E-02	b
	Weather-related	1.53	246	7.51E-04	4.93E-03	1.61E-02	6.21E-03	6.20E-03	c
	All	57.50	1940	2.36E-02	2.95E-02	3.64E-02	2.97E-02	2.94E-02	a
Shutdown Operation	Plant-centered	0.65	18.80	4.52E-04	1.92E-02	1.21E-01	3.45E-02	3.52E-02	c
	Switchyard-centered	17.50	227	4.94E-02	7.56E-02	1.09E-01	7.70E-02	7.48E-02	a
	Grid-related	1.58	88.30	2.27E-03	1.43E-02	4.58E-02	1.79E-02	1.76E-02	b
	Weather-related	2.95	63	1.26E-02	4.15E-02	9.85E-02	4.67E-02	4.40E-02	b
	All	9.75	56.70	9.23E-02	1.66E-01	2.71E-01	1.72E-01	1.72E-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. Empirical Bayes. There appears to be variability in the LOOP frequency across reliability councils.

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

The results show that the critical operation grid-related, shutdown operation switchyard-centered, shutdown operation grid-related, and shutdown operation weather-related LOOPs can be described by EB distributions reflecting variation when the data are pooled by reliability councils. 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, 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.

The grid-related LOOP frequencies above are modeled based on variation in different geographical regions as defined by the North American Electric Reliability Corporation (NERC). Figure 6 contains a map showing these regions, which are also called Power Pools or Reliability Councils.[1] Because of the significance of grid events, which may even affect more than one plant station, the critical operations grid-related LOOP data were grouped according to the NERC region containing each plant. Table 3 reports the number of LOOPs during critical operation, grouped by electric reliability council, together with the resulting posterior variability distributions.

It is, in principle, possible to group the data in any number of ways (by season, year, site, state, proximity to the coast, NERC 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.

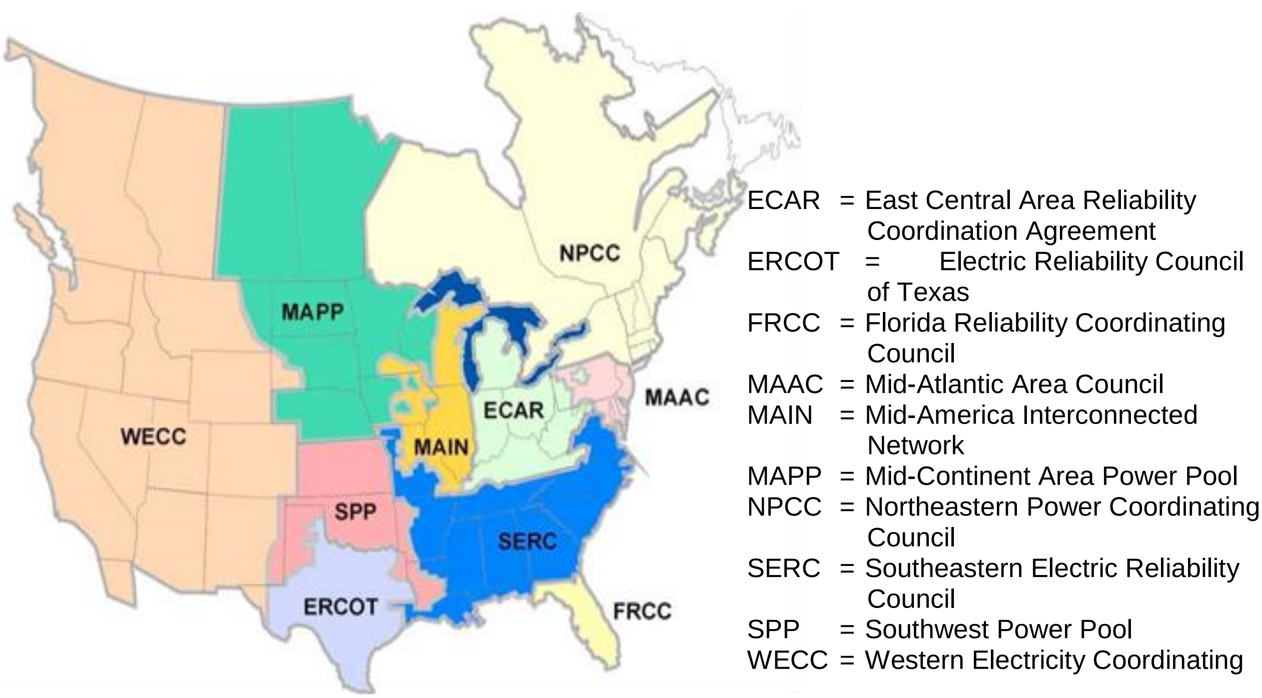

Figure 6. NERC Reliability Council regions.

[1] The study uses the same NERC reliability council regions as in NUREG/CR-6890. It is realized that the NERC reliability council names and territories have been changed since then. The new NERC reliability council regions will be used in the future study.

Table 3. Estimated grid-related LOOP frequencies by reliability council during critical operation (1997-2017).

Reliability Council	LOOP Events	Critical Years	Shape (α)	Scale (β)	5%	Median	95%	Gamma Mean	Simple MLE
East Central	2	140.9	2.46	185	3.00E-03	1.15E-02	2.96E-02	1.33E-02	1.42E-02
Florida	0	86	0.50	120	1.71E-05	1.92E-03	1.61E-02	4.19E-03	0.00E+00
Texas	0	76.9	0.51	113	1.91E-05	2.07E-03	1.71E-02	4.49E-03	0.00E+00
Mid−America	2	320.4	2.52	365	1.60E-03	6.02E-03	1.53E-02	6.92E-03	6.24E-03
Mid−Atlantic	4	213.5	4.34	252	6.20E-03	1.59E-02	3.26E-02	1.72E-02	1.87E-02
Mid−Continent	0	109.8	0.50	138	1.33E-05	1.62E-03	1.38E-02	3.58E-03	0.00E+00
Northeastern	9	205.3	7.88	212	1.83E-02	3.56E-02	6.12E-02	3.71E-02	4.38E-02
Southeastern	0	530.6	0.45	450	2.16E-06	4.10E-04	3.98E-03	9.98E-04	0.00E+00
Southwestern	0	112.9	0.49	141	1.29E-05	1.58E-03	1.35E-02	3.51E-03	0.00E+00
Western	3	139.3	3.28	176	5.48E-03	1.68E-02	3.81E-02	1.86E-02	2.15E-02

2.3 Summary of LOOP Event Count Data

Table 4 shows a summary of LOOP data for 1987–2017, including reactor years and LOOP counts by plant status and LOOP category. The Shutdown operations: Grid and Plant columns of Table 4 show the industry's improvement in avoiding shutdown operation LOOP events[1] and shortening of shutdown periods in the last 16 years. The annual shutdown exposure and the number of LOOP events have both been approximately constant (≈ 9 reactor-years and 0-3 LOOP events per calendar year) in this period. Only one plant-centered and no grid –related shutdown LOOP events has occurred since 2008 accounting for this trend.

[1] 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, 1987–2017[a]

Calendar Year	Reactor Years			Critical Operations				Shutdown Operations				Total by Status		Total by Type				
	Critical	Shut down	Total	Plant	Syard	Grid	Wx	Plant	Syard	Grid	Wx	Up	Down	Plant	Syard	Grid	Wx	Total
1987	70.56	30.23	100.80	0	5	0	0	2	5	1	2	5	10	2	10	2	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

a. Abbreviations: Plant—plant-centered, Syard—switchyard-centered, Grid, grid-related, and Wx, weather-related., SD, shut down.

3. LOOP DURATION AND RECOVERY

Sustained potential LOOP recovery times were selected for modeling the duration of recovery from LOOP. The potential 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 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. The individual duration times are not used in this study. This choice is based on the premise 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 with these times. First, the data were analyzed to see if trends in the recovery times exist. Then distributions characterizing the times were sought.

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 (1997-2017).

The recovery times for each LOOP category are trended using ordinary log linear regression. The recovery time trend data show in Figure 7. Table 5 provides the trend equations for each of the data subsets.

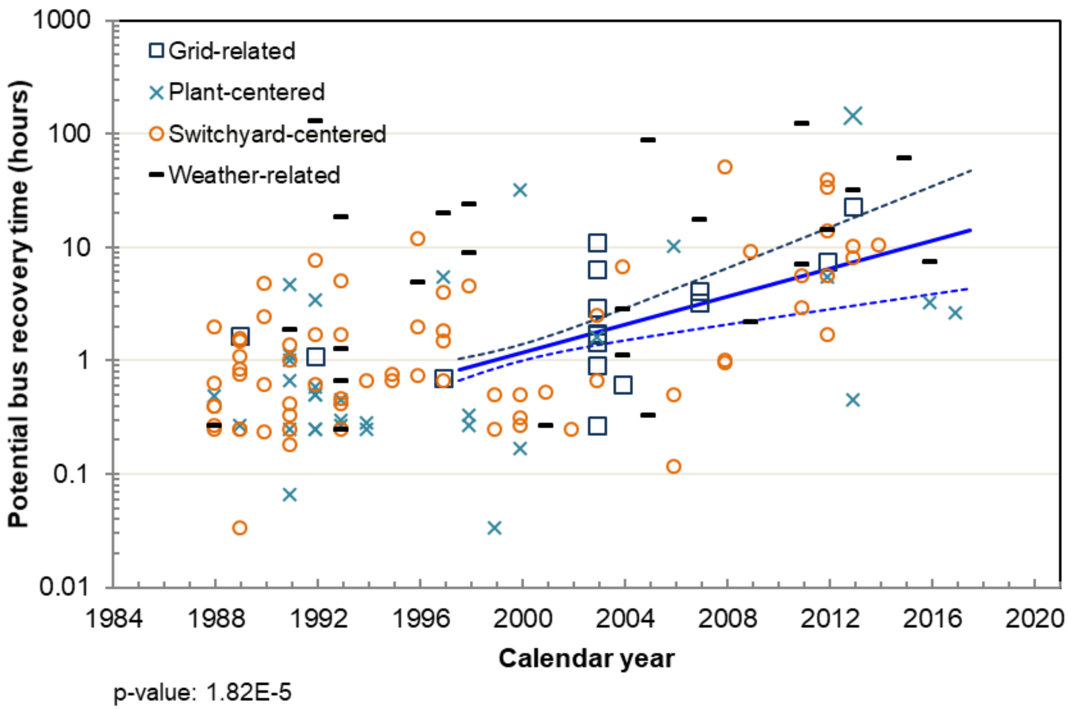

Figure 7. Extremely statistically significant trend toward increasing LOOP durations (all event types) for the post-deregulation period.

Table 5. Results of log linear regression of LOOP durations for the post-deregulation period (1997-2017)

Subset	# of LOOP Events[b]	Trend Line Equation[a]	Standard Error of Slope	p-value for significance of trend
Plant-centered	13	Exp(0.119 x (year-2017) +2.002)	0.084	1.85E-01
Switchyard-centered	32	Exp(0.161 x (year-2017) +2.563)	0.038	2.22E-04
Grid-related	14	Exp(0.196 x (year-2017) +3.312)	0.066	1.22E-02
Weather-related	16	Exp(0.081 x (year-2017) +2.985)	0.077	3.07E-01
All LOOPs	75	Exp(0.142 x (year-2017) +2.656)	0.031	1.82E-05
Critical Operations	39	Exp(0.129 x (year-2017) +2.493)	0.042	4.21E-03
Shutdown Operations	36	Exp(0.158 x (year-2017) +2.902)	0.049	2.79E-03

a. The best fitting regression line defined by exp(intercept + slope*(year difference). The (year-2017) terms goes from -19 to 0.

b. Multi-Unit LOOPs are counted as a single LOOP.

An extremely statistically significant increasing trend in recovery times is identified for switchyard-centered LOOPs (p-value = 2.22E-4). A statistically significant 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 total LOOP trend is the most significant (p-value = 1.82E-5). Highly statistically significant increasing trend are also identified for overall data during critical operations (p-value = 4.21E-3) and for overall data during shutdown operations (p-value = 2.79E-3).

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

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 2017. 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:

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

$$F(t) = \Phi\left[\frac{\ln(t)-\mu}{\sigma}\right]$$ = 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 = error function.

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

Table 6. Fitted lognormal recovery time distributions (1988-2017).

Parameter	Plant-centered	Switchyard-centered	Grid-related	Weather-related
LOOP event count	32	70	16	24
Mu (μ)	-0.19	0.15	0.80	1.73
Standard error of μ	0.31	0.18	0.29	0.41
Sigma (σ)	1.76	1.49	1.17	1.99
Standard error of σ	0.22	0.13	0.21	0.29
Fitted median	0.83	1.16	2.23	5.62
Fitted mean	3.88	3.53	4.40	40.98
Fitted 95th percentile	14.92	13.48	15.18	149.21
Error Factor	17.99	11.65	6.81	26.56

The Table 6 distributions are plotted as probability-of-exceedance versus duration curves (1-F(t)) in Figure 8. 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 8 shows visually that weather-related LOOPs have the longest recovery times.

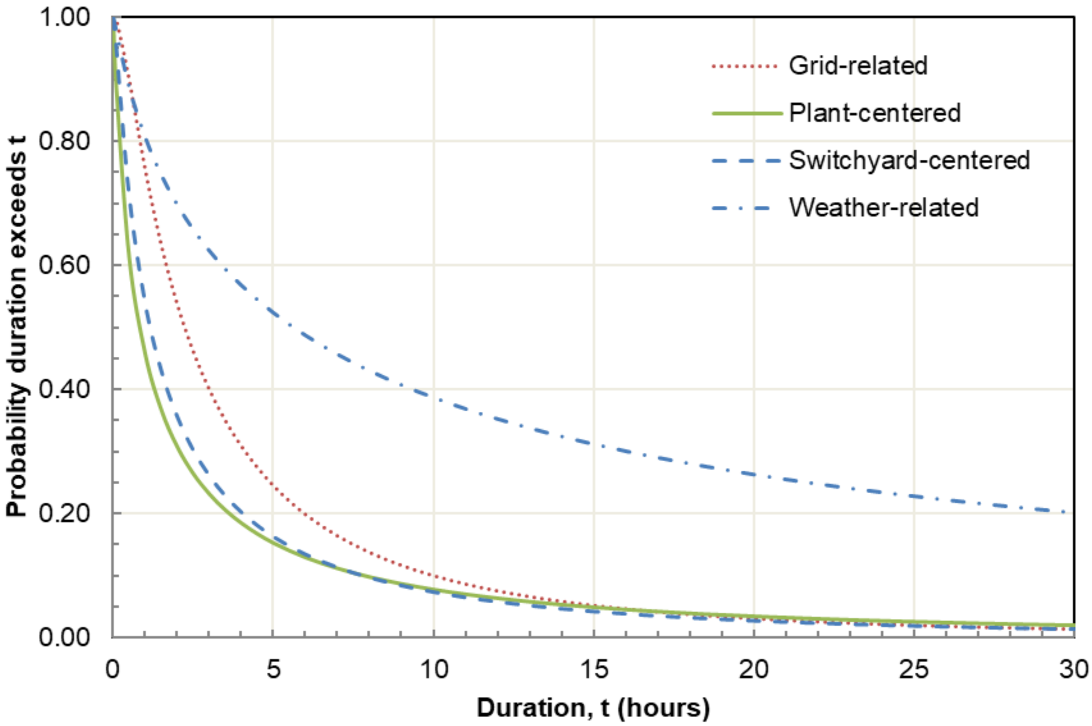

Figure 8. Probability of exceedance (non-recovery probability) vs duration curves for all event types and operating modes (1988 – 2017).

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 7 of the 8 LOOPs (87%) involving a reactor trip since 1997 occurred in the summer - May to September - in contrast to 23 to 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 can be seen from 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 (1997-2017).

	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	0
Apr	2	2	3	6	1	2	3	2
May	2	1	4	0	1	1	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 2016 report (Johnson and Schroeder 2017) due to the data changes in this study as described in 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 = 0.008).
- The counts for critical operation weather-related LOOPs are not uniformly distributed across the 12 months. The variation is statistically significant (p-value = 0.017).

4.2 Multi-Unit LOOP Events

Unit LOOP events are sometimes thought of as independent events. This is not quite true, however, as most spectacularly demonstrated on August 14, 2003, when a large power blackout affected 9 units (8 critical and 1 in shutdown) at 7 sites. There were 7 occasions during 1987–1996 and 13 occasions during 1997–2017 when more than one unit at a site was affected by the same incident. The 13 occasions contributed 27 of the 96 unit events counted in Table 1 (28%). This calls the simplifying assumption of treating each LOOP as independent into serious question.

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 less likely to affect more than one site within a few hours to a few days but more likely to affect more than one unit at the same site.
- 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.[1]

[1] 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.)

Among the 186 LOOP unit-level events (from 1987 to 2017) considered in this study, there were 20 occurrences involving more than one unit at a site for the same event and 145 single-unit LOOP occurrences. The multi-unit events are listed in chronological order in Table 8. Seventeen of these occurrences involved both units at two-unit sites, one involved all three units at a three-unit site, and two involved two units at three-unit sites. Of the single-unit LOOPs, 73 occurred at sites with more than one unit (i.e., multi-unit sites).

Table 9 lists the 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 and, as such, unit-based LOOP events are not independent.

Table 8. Multi-unit LOOP events for 1987–2017.

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	2	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]	5/25/2014	3	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			**43**	**41**		

a. In these cases, the units shut down in anticipation of bad weather. The weather events subsequently resulted in LOOPs at the site.

b. This event was 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.

c. This occurrence was reclassified this year. It went from switchyard- centered to grid-related.

Table 9. 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	5	16	1.55E-01	3.16E-01	3.24E-01	5.17E-01	5.5	11.5
Plant-centered	0	21	9.25E-05	1.06E-02	2.27E-02	8.64E-02	0.5	21.5
Switchyard-centered	7	60	6.20E-02	1.19E-01	1.23E-01	1.98E-01	7.5	53.5
Weather-related	6	19	1.67E-01	3.19E-01	3.25E-01	5.03E-01	6.5	13.5
All	18	116	1.06E-01	1.56E-01	1.58E-01	2.17E-01	18.5	98.5

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 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 beta(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).

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 9 categorizes LOOP events from equipment failure by failed component. From 1997 to 2017, the largest subcategories are failed circuits, transformers, and relays. Circuit and relay failure events have nearly tripled from the 1987-1996 period to the 1997-2017 period,[1] while the transformer failures (dominant during the 1987-1996 period) reduced by half in the 1997-2017 period.

In Figure 10 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 11 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.

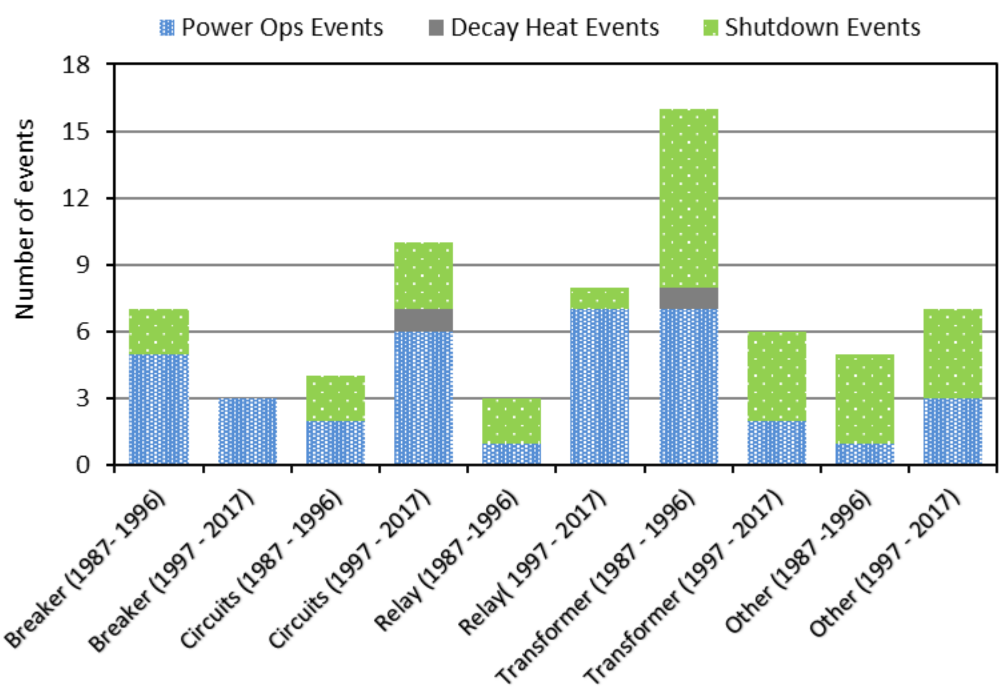

Figure 9. Failed components causing LOOP events from equipment failures (1987-1996 and 1997-2017).

[1] 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 1997-2017 period represents a duration of more than 20 years.

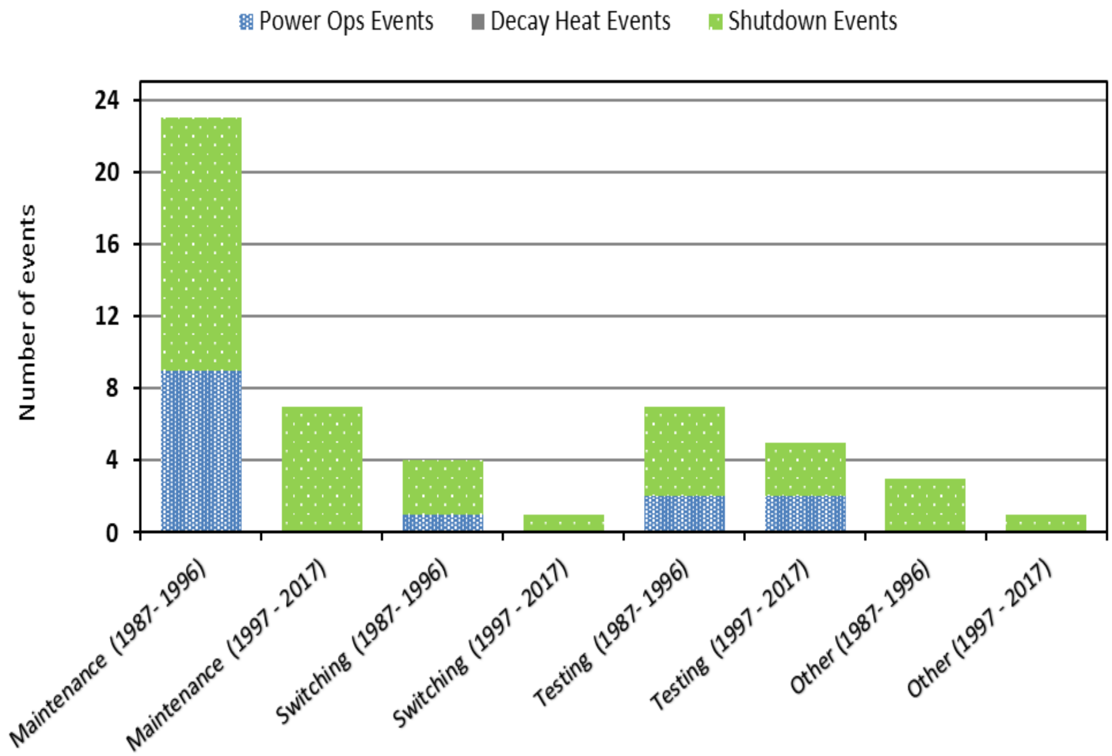

Figure 10. Activities causing LOOP events from human error (1987-1996 and 1997-2017).

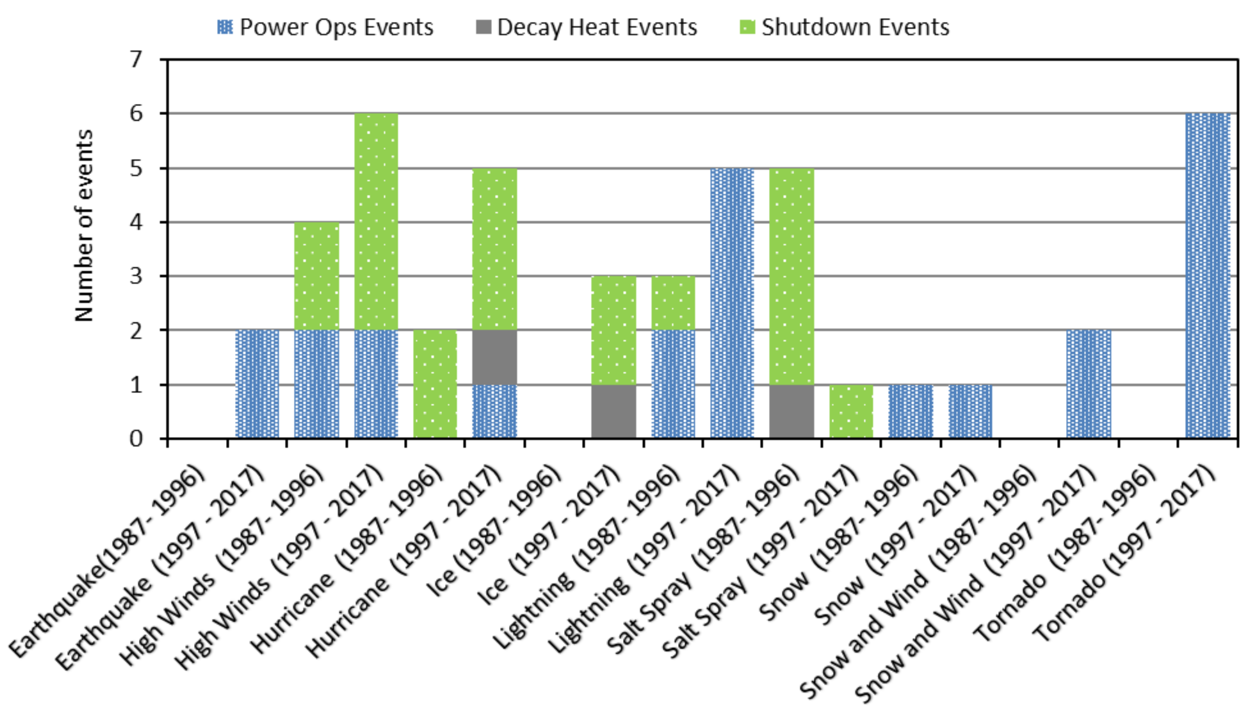

Figure 11. Natural disasters causing LOOP events from weather (1987-1996 and 1997-2017).

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Appendix A
LOOP Events Listing

Appendix A - LOOP Events Listing (1987 – 2017)

Table A-1 LOOP events for 1987-2017, sorted by plant.

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
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
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

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
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
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

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
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
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

					Restoration Time (minutes)				
LER	**Plant Name**	**Date**	**Operational Mode**	**LOOP Category**	**Switchyard Restoration Time**	**Potential Bus Recovery Time**	**Actual Bus Restoration Time**	**Cause**	**Specific Cause**
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
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

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
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
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

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
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
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
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

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		
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
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

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		
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
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
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

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
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
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

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
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
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.