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Revision 1

Analysis of Loss-of-Offsite-Power Events

1987 - 2016

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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 1986 through 2016. 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. Adverse trends in overall LOOP frequency and in plant-centered LOOP frequency are identified for the most recent 10-year period. An adverse trend in LOOP durations is identified. Grid-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.

Revision History

Revision Number	Reason for Revision	Date
Rev. 0	Initial issuance	August 2017
Rev. 1	Table 3 was inadvertently copied and pasted incorrectly in Rev. 0	June 2018

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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 overall 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 2016 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. For critical operation, switchyard-centered LOOPs contribute 42% to the total critical operation LOOP frequency, while grid-related LOOPs contribute 32% of the total. Switchyard-centered events are likewise the most common type of LOOP during shutdown operation at 46%. Switchyard centered LOOPs are the most frequent type during both critical and shutdown operations.

An investigation of possible trends in the LOOP occurrence rates for the most recent 10 years shows a barely statistically significant increasing trend in critical LOOP frequencies the plant-centered LOOP category (p-value = 0.04) and for all LOOP categories combined (p-value=0.045).

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). Empirical Bayes (EB) gamma distributions were sought to describe any identified variation. The results show that both critical operation and shutdown operation grid-related LOOPs can be described by EB distributions reflecting variation when the data are pooled by reliability councils. Also, the shut-down plant-centered data and the combined shutdown data can be modeled using EB distributions showing variation between plants. For the remaining data groupings, the hypothesis of homogeneity could not be rejected, indicating that only sampling variation could be modeled. 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.

A trend analysis of the sustained (greater than 2 minute) potential LOOP recovery times at a site level showed a very highly significant increasing trend for switchyard-centered LOOPs (p-value 1.2E-4). A significant trend is present for grid-related LOOPs. 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=3.8E-5). The increasing trend is present both for overall data during critical operations and for overall data during shutdown operations. The hypothesis of no trend in the recovery times is not rejected 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 fitted to lognormal distributions by matching moments for the underlying normal distributions. The results show that weather-related LOOPs have the longest recovery times.

To study seasonal patterns in the LOOP occurrences, the 1997-2016 data were grouped by months and evaluated to see if the counts could be uniformly distributed. This hypothesis was rejected for critical operation grid-related LOOPs (p-value = 0.019) and for critical operations weather data (p-value=0.046).

Data for LOOP events that affected multiple units at a site was reviewed. There were 7 occasions during 1987–1996 and 12 occasions during 1997–2016 when more than one plant (unit) at a station was affected by the same incident. The 12 occasions contributed 23 of the 94 plant (unit) events counted in Table 1 (25%). 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 equipment failures are dominated by failures of circuits and transformers, human errors associated with the events occurred primarily in maintenance and testing, and the weather events are dominated by tornado, hurricanes, and high winds. This review shows that human errors have been much less frequent during 1997–2016 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

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.

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.

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 LOOP Glossary 3 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 output bus bar in 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 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.

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-5496 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 LOOP Glossary 2 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 - 2016

1. INTRODUCTION

United States commercial nuclear power plants (NPP) 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 overall 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 years 2016 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.

NUREG/CR-6890, *Reevaluation of Station Blackout Risk at Nuclear Power Plants: Analysis of Loss of Offsite Power Events* (Eide, Gentillon, and Wierman) 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 2016. 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. 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 a table.

This report contains trending information as well as distributions that describe variation in the data. Since the 2014 update, the frequency trends have been for the most recent 10 years (2007-2016).

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 data are limited, the data from 1988 to 2016 are used here. In the trend analysis of the recovery times, the time span is 1997-2016.

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 which can be accessed from http://nrcoe.inl.gov/resultsdb/CompPerf/.

2. INDUSTRY-WIDE LOOP FREQUENCIES

Industry-average LOOP frequencies were determined for calendar years 1997-2016. 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 operation in four event categories: plant-centered, switchyard-centered, grid-related, and weather-related. Table 1 reports the observed event counts and reactor years. 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 1997–2016.

Mode	LOOP Category	Events	Reactor Critical or Shutdown Years	Maximum Likelihood Estimate (MLE) (Events/Years)[a]	Percent
Critical Operation[a]	Plant-centered	5	1843.9	2.71E-03	8.8
	Switchyard-centered	24	1843.9	1.30E-02	42.1
	Grid-related	18	1843.9	9.76E-03	31.6
	Weather-related	10	1843.9	5.42E-03	17.5
	All LOOPs	57	1843.9	3.09E-02	100
Shutdown Operation[b]	Plant-centered	7	220.12	3.18E-02	18.9
	Switchyard-centered	17	220.12	7.72E-02	46
	Grid-related	4	220.12	1.82E-02	10.8
	Weather-related	9	220.12	4.09E-02	24.3
	All LOOPs	37	220.12	1.68E-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 42% to the total critical operation LOOP frequency, while grid-related LOOPs contribute 32% of the total. Switchyard-centered events are likewise the most common type of LOOP during shutdown operation at 46%.

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 estimated LOOP frequencies during critical operation since 1997 and the recent 10-year trend in LOOP frequencies. The confidence interval is a simultaneous band, intended to cover 90% of the possible trend lines that might underlie the data. The 90% intervals (plotted vertically) are frequentist 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.

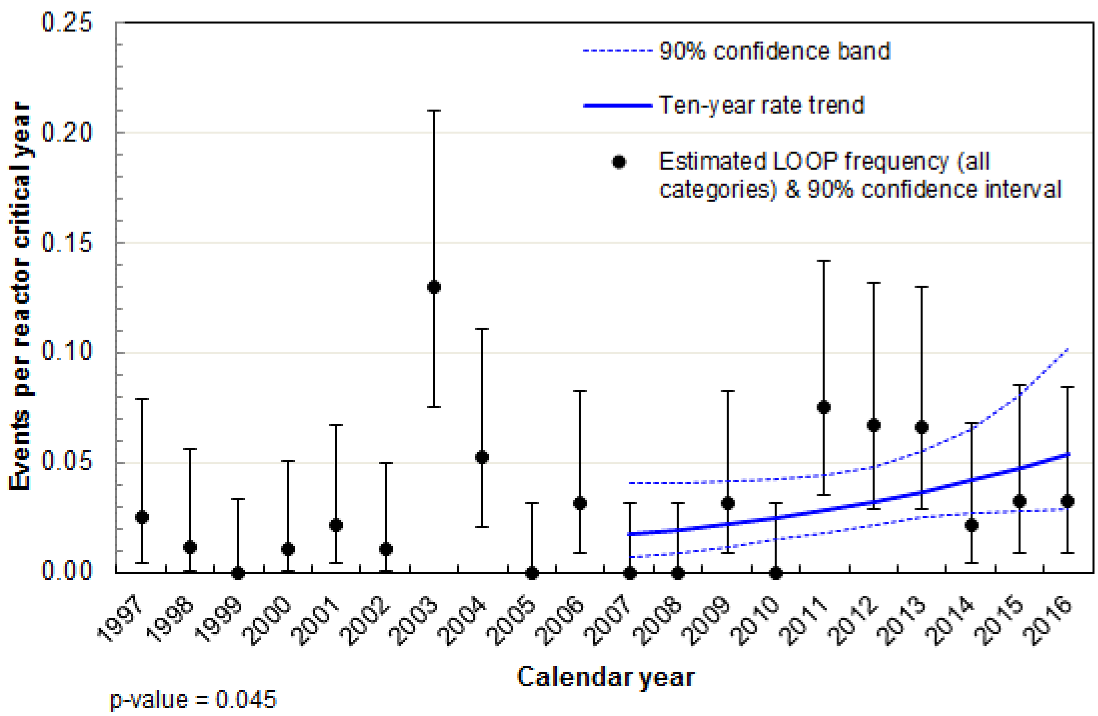

Figure 1. Estimated LOOP frequencies (all categories) and 10-year statistically significant increasing trend during critical operations.

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.

Statistically significant[a] increasing 10-year trends were found in critical LOOP frequencies for all LOOP events and for the plant-centered LOOP category. Plant-centered LOOP events have been rare in the post-deregulation period, with only one event prior to 2012. Events in 2012, 2013 and 2016 are causing the 10-year trend result. The combined LOOP result also shows a pattern of increased counts in recent years. No causal pattern was discerned in the 10-year trend data.

[a] 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).

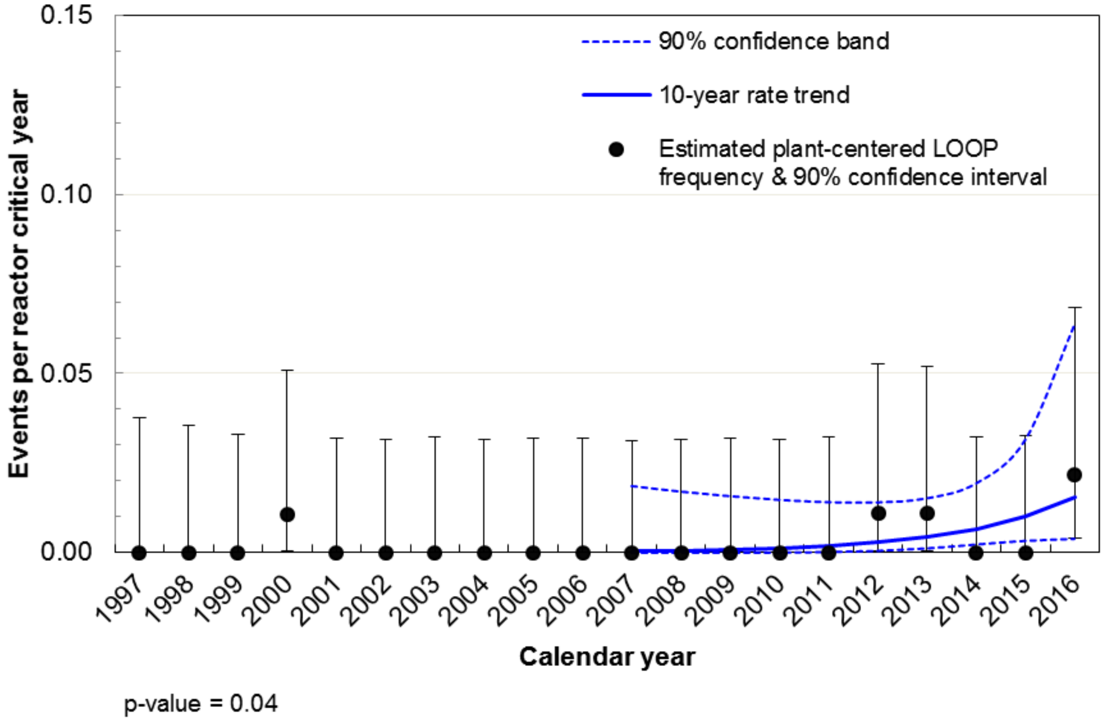

Figure 2. Ten-year statistically significant increasing trend in estimated plant-centered LOOP frequency during critical operation.

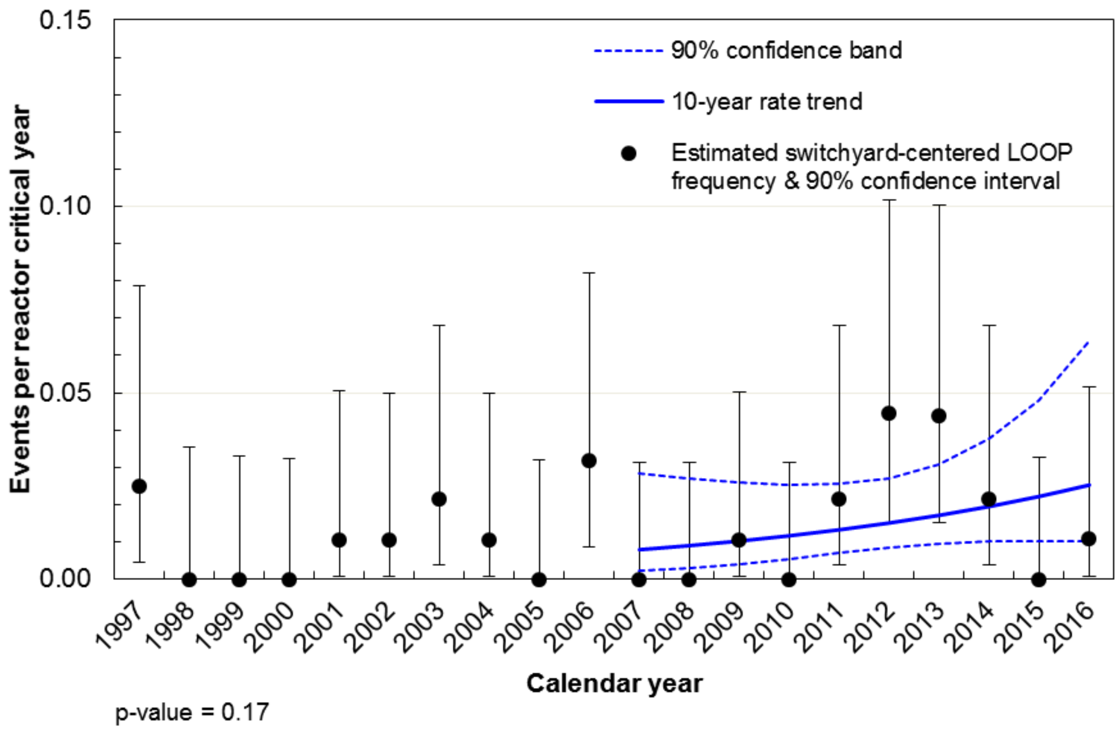

Figure 3. Ten-year trend in estimated switchyard-centered LOOP frequency during critical operation.

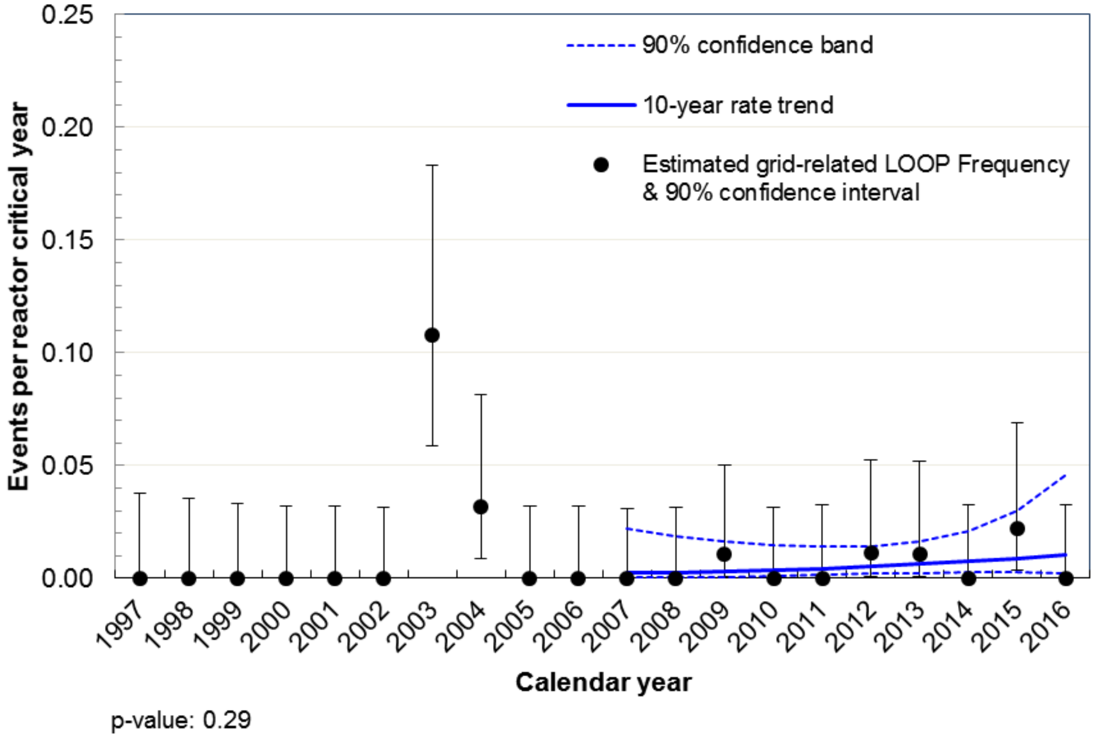

Figure 4. Ten-year trend in estimated grid-related LOOP frequency during critical operation.

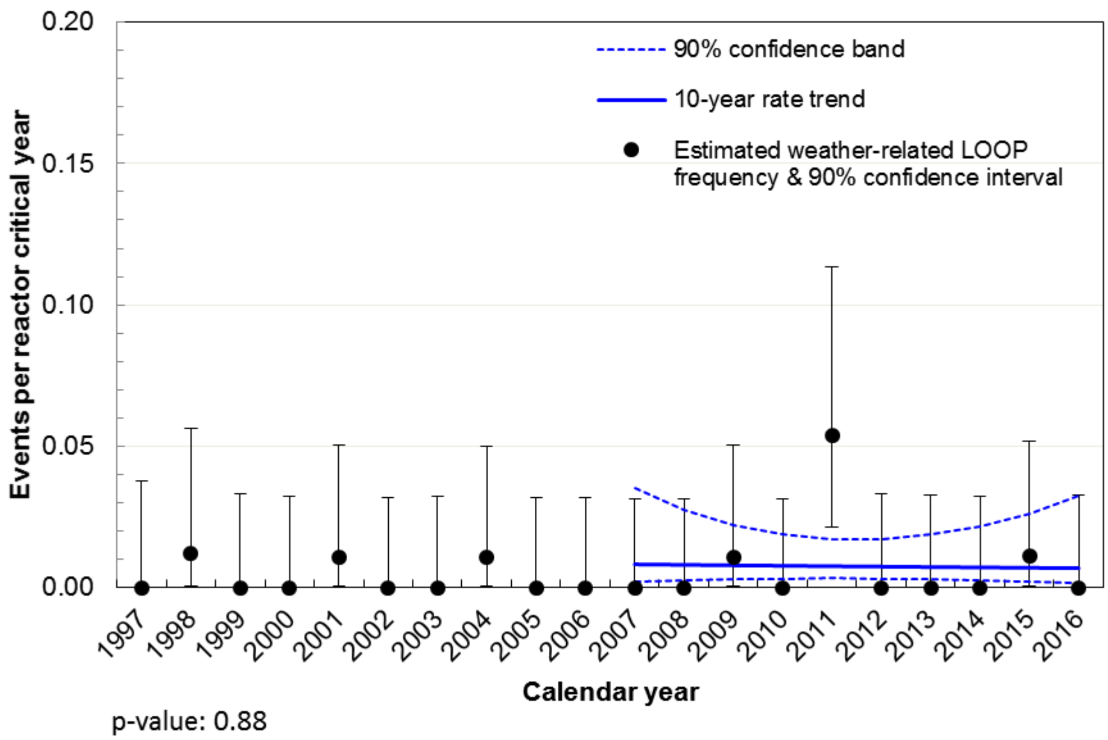

Figure 5. Ten-year trend in estimated weather-related LOOPs frequency during critical operation.

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.

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 current data show 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- 2016).

Mode	LOOP Category	Shape (α)	Scale (β)	5%	Median	95%	Gamma Mean	Simple MLE	Notes
Critical Operation	Plant-centered	5.5	1840	1.24E-03	2.81E-03	5.34E-03	2.98E-03	2.71E-03	a
	Switchyard-centered	24.5	1840	9.20E-03	1.31E-02	1.80E-02	1.33E-02	1.30E-02	a
	Grid-related	0.608	58	1.04E-04	5.57E-03	3.76E-02	1.05E-02	9.76E-03	b
	Weather-related	10.5	1840	3.14E-03	5.53E-03	8.86E-03	5.70E-03	5.42E-03	a
	All	57.5	1840	2.47E-02	3.11E-02	3.82E-02	3.12E-02	3.09E-02	a
Shutdown Operation	Plant-centered	0.47	15.20	8.38E-05	1.31E-02	1.21E-01	3.08E-02	3.18E-02	c
	Switchyard-centered	17.50	220	5.10E-02	7.80E-02	1.13E-01	7.95E-02	7.72E-02	a
	Grid-related	1.61	87.5	2.43E-03	1.48E-02	4.69E-02	1.84E-02	1.82E-02	b
	Weather-related	9.50	220	2.30E-02	4.17E-02	6.84E-02	4.31E-02	4.09E-02	a
	All	4.62	27.4	6.33E-02	1.57E-01	3.15E-01	1.69E-01	1.68E-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 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. 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. For each region or reliability council, the industry-wide critical operation grid distribution in Table 2 (with α=0.608 and β=58.0) was used as a prior distribution for a Bayesian update. To obtain a variability distribution for each reliability council, the industry prior was updated with the specific data for that council. Table 3 reports the number of LOOPs during critical operation, grouped by electric reliability council, together with the resulting posterior variability distributions. Since gamma distributions are conjugate distributions for Poisson-distributed data, the posterior distributions have the prior alpha plus the reliability-council-specific number of events as the alpha parameter and the prior beta plus the reliability-council-specific critical years as the beta parameter.

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.

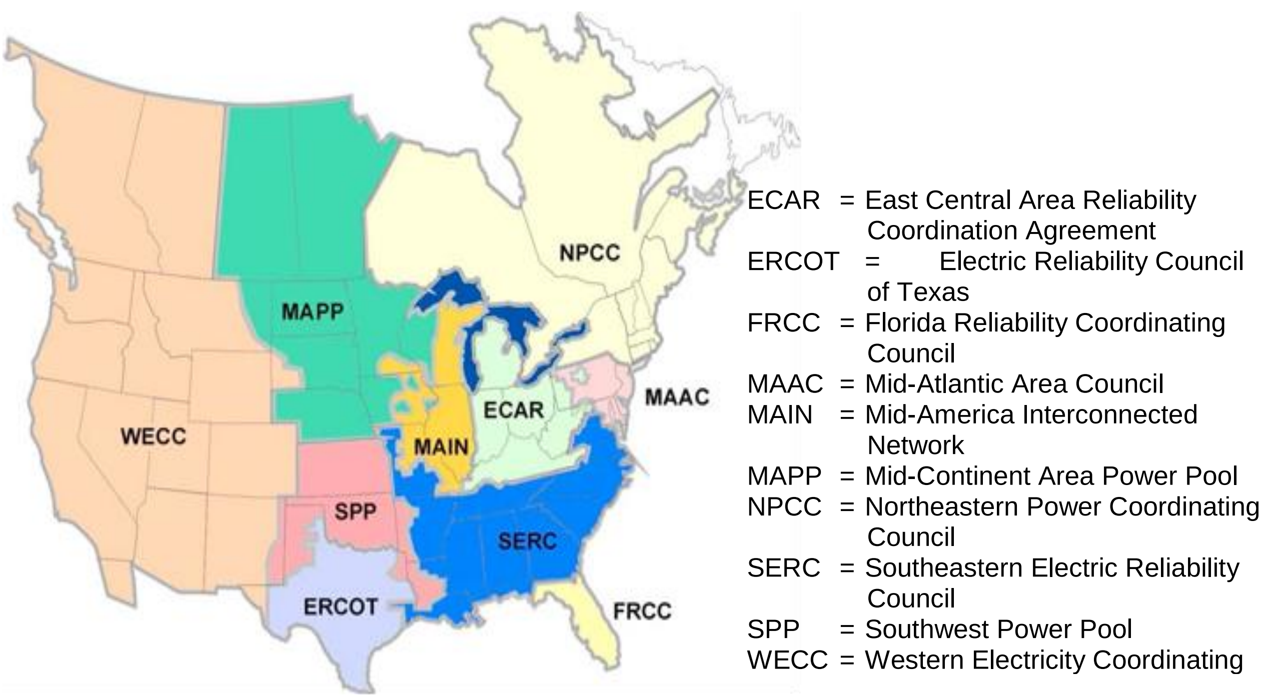

Figure 6. NERC Reliability Council regions.

Table 3. Estimated grid-related LOOP frequencies by reliability council during critical operation (1997-2016).

Reliability Council	LOOP Events	Critical Years	Shape (α)	Scale (β)	5%	Median	95%	Gamma Mean	Simple MLE
East Central	2	133.5	2.608	191.5	3.26E-03	1.19E-02	2.98E-02	1.36E-02	1.50E-02
Florida	0	82.4	0.608	140.4	4.31E-05	2.30E-03	1.55E-02	4.33E-03	0.00E+00
Texas	0	73.3	0.608	131.3	4.61E-05	2.46E-03	1.66E-02	4.63E-03	0.00E+00
Mid-America	2	305.3	2.608	363.3	1.72E-03	6.28E-03	1.57E-02	7.18E-03	6.55E-03
Mid-Atlantic	4	203.1	4.608	261.1	6.62E-03	1.64E-02	3.30E-02	1.76E-02	1.97E-02
Mid-Continent	0	105	0.608	163	3.71E-05	1.98E-03	1.34E-02	3.73E-03	0.00E+00
North East	7	196.2	7.608	254.2	1.46E-02	2.86E-02	4.97E-02	2.99E-02	3.57E-02
South East	0	503.4	0.608	561.4	1.08E-05	5.75E-04	3.88E-03	1.08E-03	0.00E+00
South West	0	107.8	0.608	165.8	3.65E-05	1.95E-03	1.31E-02	3.67E-03	0.00E+00
Western	3	133.8	3.608	191.8	5.96E-03	1.71E-02	3.75E-02	1.88E-02	2.24E-02

2.3 Summary of LOOP Event Count Data

Table 4 shows a summary of LOOP data for 1987–2016, 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[b] and shortening of shutdown periods in the last 15 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. Grid and plant-centered shutdown LOOP events have not occurred since 2008 accounting for this trend.

[b] 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, 1987–2016[a]

Calendar	Reactor Years			Critical Operations				Shutdown Operations				Total by Status		Total by Type				
Year	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	3	0	0	0	5	1	0	4	6	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	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	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	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	1	0	0	0	1	3	0	0	1	4	2	3	0	0	5
2001	93.96	9.04	103	0	1	0	1	0	0	0	0	2	0	0	1	0	1	2
2002	94.88	8.12	103	0	1	0	0	0	0	0	0	1	0	0	1	0	0	1
2003	92.61	10.39	103	0	2	10	0	1	0	1	0	12	2	1	2	11	0	14
2004	94.94	8.06	103	0	1	3	1	0	0	0	2	5	2	0	1	3	3	7
2005	93.92	9.08	103	0	0	0	0	0	0	0	2	0	2	0	0	0	2	2
2006	94.34	8.66	103	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	0	0	0	0	0	4	0	0	0	4	0	4	0	0	4
2009	94.34	9.66	104	0	1	1	1	0	0	0	0	3	0	0	1	1	1	3
2010	95.44	8.56	104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2011	92.61	11.39	104	0	2	0	5	0	1	0	0	7	1	0	3	0	5	8
2012	90.02	13.98	104	1	4	1	0	0	2	0	1	6	3	1	6	1	1	9
2013	91.23	10.34	101.57	1	4	1	0	0	1	0	0	6	1	1	5	1	0	7
2014	92.44	7.56	100	0	2	0	0	0	1	0	0	2	1	0	3	0	0	3
2015	91.44	7.56	99	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

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. Sustained recovery times are times that are at least 2 minutes long.

When a LOOP event affects more than one unit at a plant 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 idea 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 (1997-2016).

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.

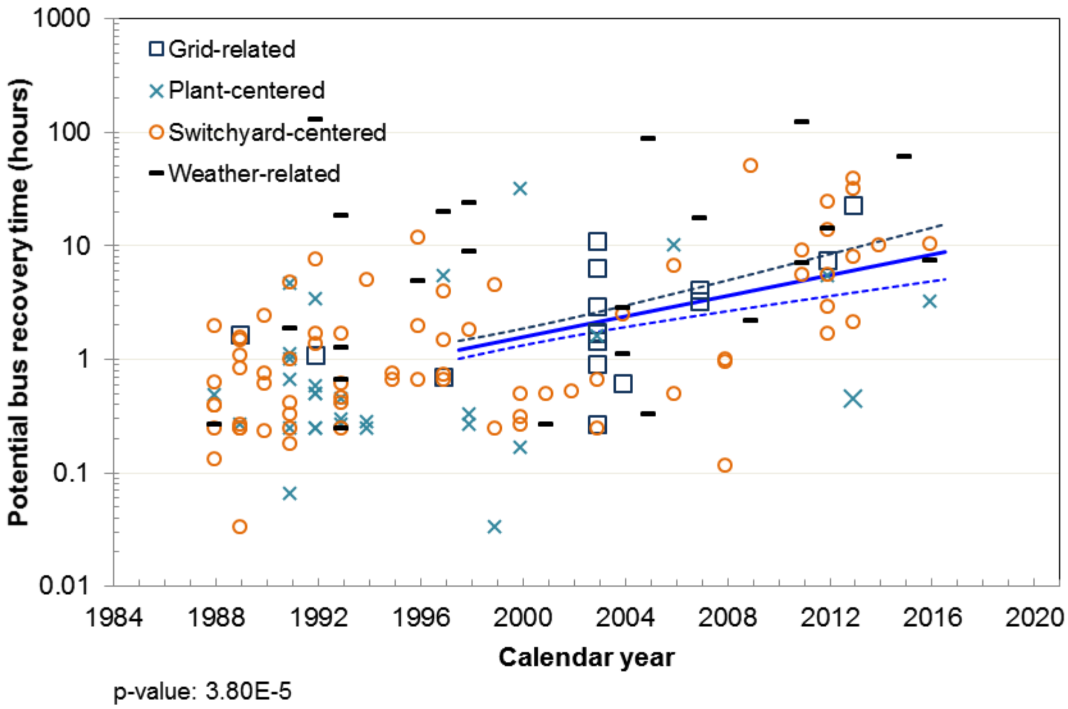

Figure 7. Extremely statistically significant trend toward increasing LOOP durations (all event types) for the post-deregulation period.

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

Subset	# of LOOP Events	Trend Line Equation[a]	Standard Error of Slope	p-value for significance of trend
Plant-centered	11	Exp(0.081 x (year-2016) +1.201)	0.096	4.248E-01
Switchyard-centered	34	Exp(0.162 x (year-2016) +2.409)	0.037	1.050E-04
Grid-related	14	Exp(0.196 x(year-2016) +3.116)	0.066	1.215E-02
Weather-related	15	Exp(0.071 x (year-2016)) +2.748)	0.082	4.040E-01
All LOOPs	74	Exp(0.136 x (year-2016) +2.416)	0.031	3.795E-05
Critical Operations	39	Exp(0.135 x (year-2016)+2.413)	0.043	3.412E-03
Shutdown Operations	35	Exp(0.137 x (year-2016) +2.412)	0.049	9.049E-03

a. The best fitting regression line defined by exp(intercept + slope*(year difference) . The (year-2016) terms goes from -19 to 0.

A very highly significant increasing trend is noted in the data for switchyard-centered LOOPs. A significant trend is present for grid-related LOOPs. 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. The increasing trend is present both for overall data during critical operations and for overall data during shutdown operations.

The hypothesis of no trend is not rejected for plant-centered or weather-related events.

3.2 Variation in Recovery Times

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 2016. Also, in accordance with NUREG-6890, the data for shutdown and critical operations were combined.

As is 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 + σ2/2), and exp(μ + 1.645σ), respectively.

Table 6. Fitted lognormal recovery time distributions (1988-2016).

Parameter	Plant-centered	Switchyard-centered	Grid-related	Weather-related
LOOP event count	30	72	16	23
Mu (μ)	-0.40	0.20	0.80	1.65
Standard error of μ	0.28	0.18	0.29	0.42
Sigma (σ)	1.51	1.51	1.17	2.00
Standard error of σ	0.20	0.13	0.21	0.30
Fitted median	0.67	1.22	2.23	5.21
Fitted mean	2.11	3.83	4.40	38.74
Fitted 95th percentile	8.10	14.70	15.18	140.58
Error Factor	12.05	12.08	6.81	26.98

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

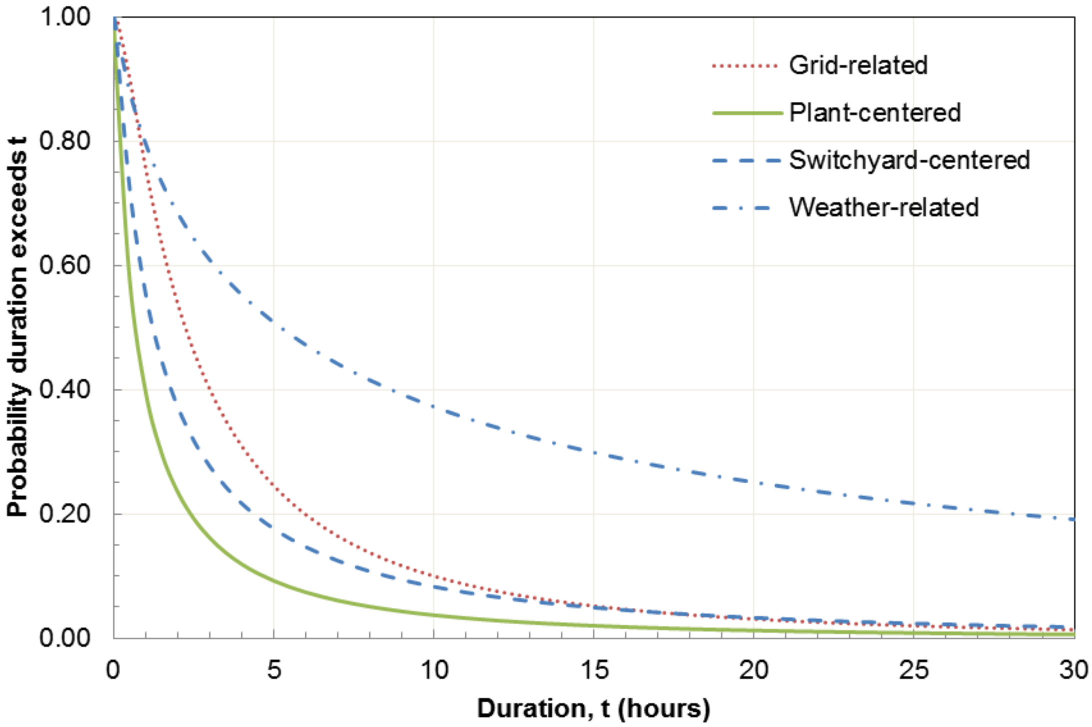

Figure 8. Probability of exceedance (non-recovery probability) vs duration curves for all event types and operating modes (1988 – 2016).

4. SPECIAL TOPICS IN IN LOOP FREQUENCY

Two issues are considered in this section: seasonal variation in LOOP frequency, and the effect of multi-plant 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 (1997-2016).

	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	4	0	0	0	1	1
Mar	0	0	0	1	0	1	4	0
Apr	2	2	3	5	1	2	3	1
May	0	1	6	0	1	1	2	0
Jun	3	0	1	1	1	0	0	0
Jul	2	0	2	0	0	0	0	0
Aug	8[a]	1	4[b]	2	1	0	1	1
Sep	2	0	0	0	0	1	1	3
Oct	1	0	1	0	0	1	2	2
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.

b. The North Anna event on August 23, 2011, was recently reviewed and re-coded in the INL database from critical grid-related to critical switchyard-related. The counts reflect this change.

Prior to evaluating the statistical test, two adjustments were made in the data. First, the North Anna event on August 23, 2011, was recently reviewed and re-coded in the INL database from critical grid-related to critical switchyard-related, thus changing the counts in Table 7 for these categories compared to the 2015 report (Bower and Schroeder 2016). Also, 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 hypothesis that the counts could be uniformly distributed across the 12 months is rejected for critical operation grid-related LOOPs (p-value = 0.019).
- The hypothesis of uniform counts is also rejected for critical operations for weather-related LOOPs. The evidence is not as strong since the p-values is 0.046.
- The hypothesis of uniform counts is not rejected for critical operations plant-centered or switchyard-centered LOOPs nor for any of the shutdown operations LOOP categories.

4.2 Multi-Plant LOOP Events

Plant LOOPs 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 plants (8 critical and 1 in shutdown) at 7 sites. There were 7 occasions during 1987–1996 and 12 occasions during 1997–2016 when more than one plant (unit) at a station was affected by the same incident. The 12 occasions contributed 23 of the 94 plant (unit) events counted in Table 1 (25%). 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 plants at each site were affected by the occurrence? The details are different for each type of LOOP:

- A weather-related event has a moderately low probability of affecting more than one site within a few hours to a few days and a considerably higher probability of affecting more than one plant unit at the same site.
- A grid-related event has some probability of affecting multiple sites, even sites hundreds of miles away (the probability of affecting 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 plant units at the same site.
- A switchyard-centered event may affect more than one plant at the same site, depending on where in the switchyard it happens, but should not affect a plant at another site.
- A plant-centered event should not affect any other plant unit, even at the same site.[c]

c. 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 184 LOOP plant-level events considered in this study, there were 19 occurrences involving more than one plant at a site for the same event (39 events) and 141 single-plant LOOP occurrences. The multi-plant events are listed in chronological order in Table 8. Eighteen of these events involved two plants, one event (Palo Verde on June 14, 2004) involved all three plants at the site, and two events (Browns Ferry on April 27, 2011, and Millstone on May 25, 2014) caused the trip of two of the three plants. Of the single-plant LOOPs, 76 occurred at sites with more than one plant unit.

Table 9 lists the probability of all plants at a site experiencing a LOOP if a LOOP occurs at one of the plants. As shown in this table, a large portion of the LOOP events affect multiple plant units and, as such, plant-based LOOP events are not independent. More research is needed to devise estimates that account for this dependency.

Table 8. Multi-plant LOOP events for 1987–2016.

Event	Site	Date	# of Plant Units at Site	# of Plants 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	5/25/2014	3	2	Switchyard-centered	Critical Operation
19	Calvert Cliffs	4/7/2015	2	2	Grid-related	Critical Operation
Totals			**41**	**39**		

a. In these cases, the plants 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 plants experienced a LOOP, although a 161-kV offsite power line remained available for Browns Ferry 3. The plant responded as though it, too, had experience a LOOP.

Table 9. Conditional probability of all plants at a site experiencing a LOOP given a LOOP at one of the plants.

Loop Category	LOOP Events at Multi-Plant Sites Affecting all Plants at the Site	Total LOOP Events at Multi-Plant Sites	Conditional Probability of All Plants at a Multi-Plant Site Experiencing a LOOP Given a LOOP at One Plant at the Site[a]				Beta Distribution Parameters	
			5%	Median	Mean	95%	α	β
Grid-centered	5	12	2.12E−01	4.19E−01	4.23E−01	6.48E−01	5.5	7.5
Plant-centered	0	19	1.02E−04	1.17E−02	2.50E−02	9.49E−02	0.5	19.5
Switchyard-centered	8	52	8.61E−02	1.56E−01	1.60E−01	2.49E−01	8.5	44.5
Weather-related	6	17	1.89E−01	3.56E−01	3.61E−01	5.51E−01	6.5	11.5
All	19	100	1.32E−01	1.91E−01	1.93E−01	2.61E−01	19.5	81.5

a. The difference between total LOOPs and LOOPs affecting all plants at a site with multiple plant units is the number of those LOOPs that affected only one plant 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 plant units, 0.5 + number of events affecting just one unit). The mean is α / (α + β) = (0.5 + all-plant-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 2016, the two largest subcategories were failed circuits and transformers. A large number of transformer failures occurred from 1986 to 1996; previous LOOP annual updates (e.g., the LOOP 2010 Summary Update provided on the Operating Experience web site, http://nrcoe.inel.gov/resultsdb/publicdocs/LOSP/loop-summary-update-2010.pdf), which aggregated from 1986 to the present for the engineering analysis, reported transformers as dominating equipment failures, but this has not been the case in more recent years.

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 50% 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 hurricanes. From 1987 to 1996, the most common causes were lightning 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.

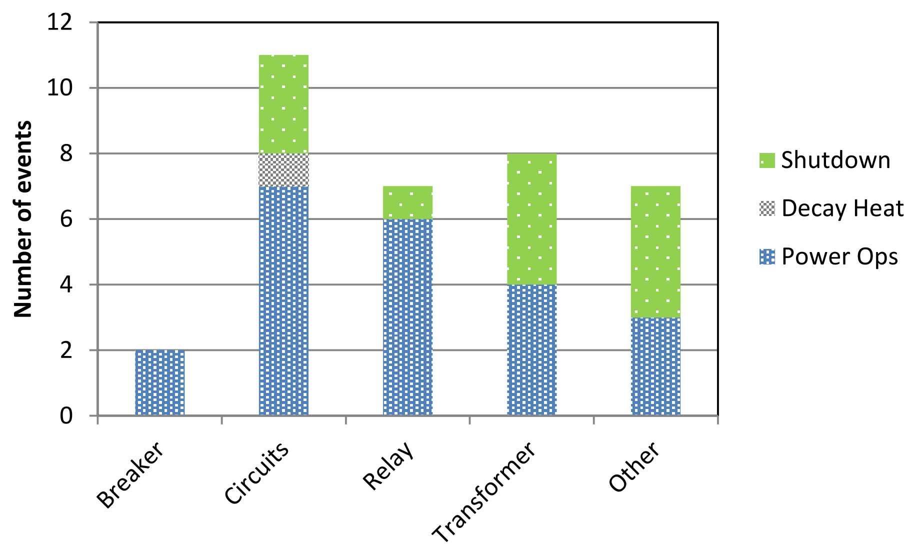

Figure 9. Failed components causing LOOP events from equipment failures (1997-2016).

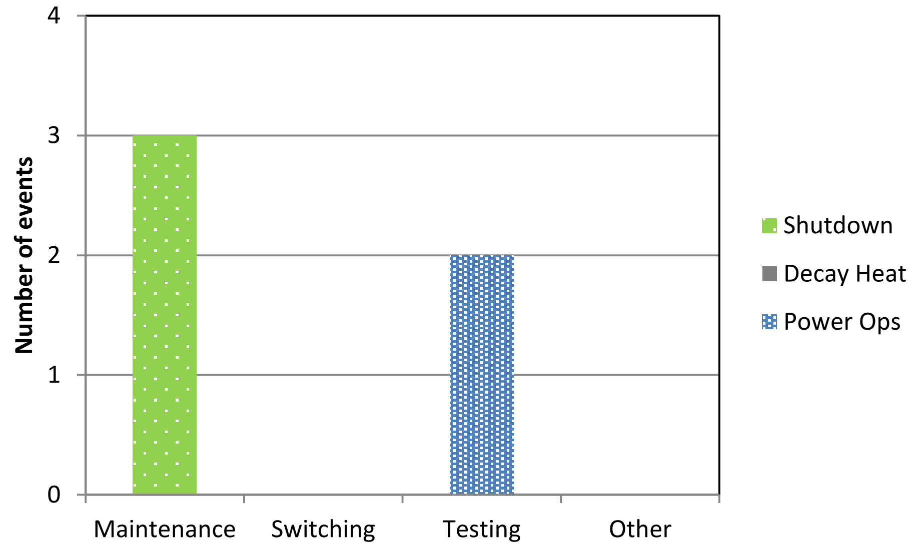

Figure 10. Activities causing LOOP events from human error (1997-2016).

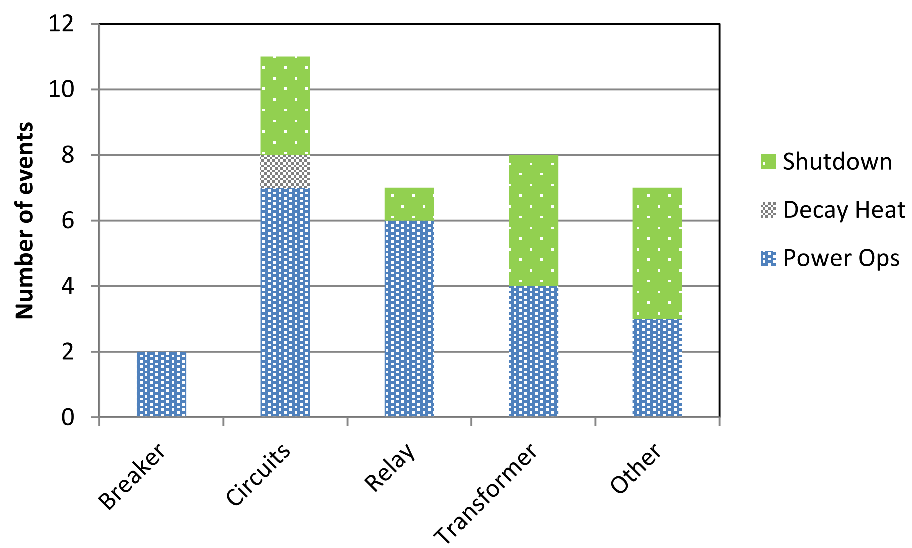

Figure 11. Natural disasters causing LOOP events from weather (1997-2016).

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Appendix A
LOOP LER Listing

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LOOP LER Listing

Table A-1. Critical Plant-Centered LERs.

Plant Name	LER	CY	Event Date
Millstone 2	3361988011	1988	10/25/1988
Oyster Creek	2191989015	1989	5/18/1989
McGuire 1	3691991001	1991	2/11/1991
Vermont Yankee	2711991009	1991	4/23/1991
Cook 1	3151991004	1991	5/12/1991
Crystal River 3	3021992001	1992	3/27/1992
Oconee 2	2701992004	1992	10/19/1992
Diablo Canyon 1	2752000004	2000	5/15/2000
Catawba 1	47805	2012	4/4/2012
Turkey Point 4	2512013002	2013	4/19/2013
Brunswick 1	3252016001	2016	2/7/2016
St. Lucie 1	3352016003	2016	8/21/2016

Table A-2. Shutdown Plant-Centered LERs.

Plant Name	LER	CY	Event Date
McGuire 1	3691987021	1987	9/16/1987
Wolf Creek	4821987048	1987	10/14/1987
Seabrook	4431988004	1988	8/10/1988
Turkey Point 4	2511991001	1991	3/13/1991
Quad Cities 1	2651991005	1991	4/2/1991
Indian Point 2	2471991010	1991	6/22/1991
Crystal River 3	3021991010	1991	10/20/1991
Nine Mile Pt. 2	4101992006	1992	3/23/1992
Quad Cities 2	2651992011	1992	4/2/1992
Palisades	2551992032	1992	4/6/1992
Point Beach 1	2661992003	1992	4/28/1992
Crystal River 3	3021993004	1993	4/8/1993
Haddam Neck	2131993009	1993	6/22/1993
Haddam Neck	2131993010	1993	6/26/1993
Brunswick 2	3241994008	1994	5/21/1994
Point Beach 2	2661994010	1994	9/27/1994
Sequoyah 1	3271997007	1997	4/4/1997
Indian Point 2	2471998013	1998	9/1/1998
Palisades	2551998013	1998	12/22/1998
Fort Calhoun	2851999004	1999	10/26/1999
Davis-Besse	3462000004	2000	4/22/2000
Palisades	2552003003	2003	3/25/2003
Oconee 3	2872006001	2006	5/15/2006

Table A-3. Critical Switchyard-Centered LERs.

Plant Name	LER	CY	Event Date
Palisades	2551987024	1987	7/14/1987
Calvert Cliffs 1	3171987012	1987	7/23/1987
Calvert Cliffs 2	3171987012	1987	7/23/1987
Byron 2	4551987019	1987	10/2/1987
Beaver Valley 2	4121987036	1987	11/17/1987
Diablo Canyon 2	3231988008	1988	7/17/1988
Maine Yankee	3091988006	1988	8/13/1988
Braidwood 1	4561988022	1988	10/16/1988
Dresden 3	2491989001	1989	3/25/1989
Point Beach 2	3011989002	1989	3/29/1989
Brunswick 2	3241989009	1989	6/17/1989
Zion 2	3041991002	1991	3/21/1991
Yankee-Rowe	291991002	1991	6/15/1991
Robinson 2	2612016005	2016	10/8/2016
Seabrook	4431991008	1991	6/27/1991
Robinson 2	2611992017	1992	8/22/1992
Sequoyah 1	3271992027	1992	12/31/1992
Sequoyah 2	3271992027	1992	12/31/1992
Pilgrim	2931993022	1993	9/10/1993
La Salle 1	3731993015	1993	9/14/1993
Beaver Valley 1	3341993013	1993	10/12/1993
McGuire 2	3701993008	1993	12/27/1993
Catawba 2	4141996001	1996	2/6/1996
Three Mile Isl 1	2891997007	1997	6/21/1997
Oyster Creek	2191997010	1997	8/1/1997
Quad Cities 2	2652001001	2001	8/2/2001
San Onofre 3	3622002001	2002	2/27/2002
Grand Gulf	4162003002	2003	4/24/2003
Salem 1	2722003002	2003	7/29/2003
Dresden 3	2492004003	2004	5/5/2004
Catawba 1	4132006001	2006	5/20/2006
Catawba 2	4132006001	2006	5/20/2006
Brunswick 2	3242006001	2006	11/1/2006
Braidwood 2	4572009002	2009	7/30/2009
North Anna 1	3382011003	2011	8/23/2011
North Anna 2	3382011003	2011	8/23/2011
Wolf Creek	4822012001	2012	1/13/2012
Byron 2	4542012001	2012	1/30/2012
Byron 1	4542012001	2012	2/28/2012
Browns Ferry 3	2962012003	2012	5/22/2012
Point Beach 1	2662013001	2013	2/6/2013
Pilgrim	2932013003	2013	2/8/2013

Plant Name	LER	CY	Event Date
La Salle 1	3732013002	2013	4/17/2013
La Salle 2	3732013002	2013	4/17/2013
Millstone 2	3362014006	2014	5/25/2014
Millstone 3	3362014006	2014	5/25/2014
Robinson 2	2612016005	2016	10/8/2016

Table A-4. Shutdown Switchyard-Centered LERs.

Plant Name	LER	CY	Event Date
Oconee 3	2871987002	1987	3/5/1987
Fort Calhoun	2851987008	1987	3/21/1987
Fort Calhoun	2851987009	1987	4/4/1987
Braidwood 1	4561987048	1987	9/11/1987
Crystal River 3	3021987025	1987	10/16/1987
McGuire 2	3691988014	1988	6/24/1988
Peach Bottom 2	2771988020	1988	7/29/1988
Peach Bottom 3	2771988020	1988	7/29/1988
Nine Mile Pt. 2	4101988062	1988	12/26/1988
Pilgrim	2931989010	1989	2/21/1989
Millstone 1	2451989012	1989	4/29/1989
Columbia 2	3971989016	1989	5/14/1989
Crystal River 3	3021989023	1989	6/16/1989
Crystal River 3	3021989025	1989	6/29/1989
Dresden 2	2371990002	1990	1/16/1990
Fort Calhoun	2851990006	1990	2/26/1990
Vogtle 1	4241990006	1990	3/20/1990
Duane Arnold	3311990007	1990	7/9/1990
Diablo Canyon 1	2751991004	1991	3/7/1991
Indian Point 2	2471991006	1991	3/20/1991
Turkey Point 3	2501991003	1991	7/24/1991
Big Rock Point	1551992000	1992	1/29/1992
Pilgrim	2931993010	1993	5/19/1993
Beaver Valley 2	3341993013	1993	10/12/1993
Salem 2	3111994014	1994	11/18/1994
Indian Point 3	2861995004	1995	2/27/1995
Diablo Canyon 1	2751995014	1995	10/21/1995
Indian Point 3	2861996002	1996	1/20/1996
Byron 1	4541996007	1996	5/23/1996
Browns Ferry 3	2961997001	1997	3/5/1997
Zion 1	2951997007	1997	3/11/1997
Fort Calhoun	2851998005	1998	5/20/1998
Clinton 1	4611999002	1999	1/6/1999
Indian Point 2	2471999015	1999	8/31/1999

Plant Name	LER	CY	Event Date
Brunswick 1	3252000001	2000	3/3/2000
Farley 1	3482000005	2000	4/9/2000
Turkey Point 4	2512000004	2000	10/21/2000
Wolf Creek	4822008004	2008	4/7/2008
Millstone 2	3362008004	2008	5/24/2008
Monticello	2632008006	2008	9/17/2008
Pilgrim	2932008007	2008	12/20/2008
Point Beach 1	2662011001	2011	11/27/2011
Catawba 2	4132012001	2012	4/4/2012
Fitz Patrick	3332012005	2012	10/5/2012
Pilgrim	2932013003	2013	2/8/2013
Byron 1	4542014003	2014	3/15/2014

Table A-5. Critical Grid-Related LERs.

Plant Name	LER	CY	Event Date
Oyster Creek	2191992005	1992	5/3/1992
Nine Mile Pt. 1	2202003002	2003	8/14/2003
Ginna	2442003002	2003	8/14/2003
Indian Point 2	2472003005	2003	8/14/2003
Indian Point 3	2862003005	2003	8/14/2003
Fitz Patrick	3332003001	2003	8/14/2003
Fermi 2	3412003002	2003	8/14/2003
Nine Mile Pt. 2	4102003002	2003	8/14/2003
Perry	4402003002	2003	8/14/2003
Peach Bottom 2	2772003004	2003	9/15/2003
Peach Bottom 3	2772003004	2003	9/15/2003
Palo Verde 1	5282004006	2004	6/14/2004
Palo Verde 2	5282004006	2004	6/14/2004
Palo Verde 3	5282004006	2004	6/14/2004
Oyster Creek	2192009005	2009	7/12/2009
Oyster Creek	2192012001	2012	7/23/2012
Pilgrim	2932013009	2013	10/14/2013
Calvert Cliffs 1	3172015002	2015	4/7/2015
Calvert Cliffs 2	3172015002	2015	4/7/2015

Table A-6. Shutdown Grid-Related LERs.

Plant Name	LER	CY	Event Date
Vermont Yankee	2711987008	1987	8/17/1987
Summer	3951989012	1989	7/11/1989
Indian Point 3	2861997008	1997	6/16/1997
Davis-Besse	3462003009	2003	8/14/2003
Millstone 3	4232007002	2007	4/25/2007
Diablo Canyon 1	2752007001	2007	5/12/2007

Table A-7. Critical Weather-Related LERs.

Plant Name	LER	CY	Event Date
Pilgrim	2931993004	1993	3/13/1993
Prairie Island 1	2821996012	1996	6/29/1996
Prairie Island 2	2821996012	1996	6/29/1996
Davis-Besse	3461998006	1998	6/24/1998
Seabrook	4432001002	2001	3/5/2001
Brunswick 1	3252004002	2004	8/14/2004
Wolf Creek	4822009002	2009	8/19/2009
Surry 1	2802011001	2011	4/16/2011
Surry 2	2802011001	2011	4/16/2011
Browns Ferry 1	2592011001	2011	4/27/2011
Browns Ferry 2	2592011001	2011	4/27/2011
Browns Ferry 3	2592011001	2011	4/27/2011
Pilgrim	2932015001	2015	1/27/2015

Table A-8. Shutdown Weather-Related LERs.

Plant Name	LER	CY	Event Date
Pilgrim	2931987005	1987	3/31/1987
Pilgrim	2931987014	1987	11/12/1987
Fitz Patrick	3331988011	1988	10/31/1988
Pilgrim	2931991024	1991	10/30/1991
Turkey Point 3	2501992000	1992	8/24/1992
Turkey Point 4	2501992000	1992	8/24/1992
Brunswick 2	3251993008	1993	3/16/1993
Crystal River 3	3021993000	1993	3/17/1993
Brunswick 1	3251993008	1993	3/17/1993
Crystal River 3	3021993002	1993	3/29/1993
Pilgrim	2931997007	1997	4/1/1997
Braidwood 1	4561998003	1998	9/6/1998
St. Lucie 1	3352004004	2004	9/25/2004
St. Lucie 2	3352004004	2004	9/25/2004
Waterford 3	3822005004	2005	8/29/2005
Turkey Point 4	2512005005	2005	10/31/2005
Duane Arnold	3312007004	2007	2/24/2007
Oyster Creek	2192012002	2012	10/29/2012
Harris	4002016005	2016	10/8/2016