INL/EXT-16-39575

# Analysis of Loss-of-Offsite-Power Events

# 1987–2015

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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 2015. 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. Emergency diesel generator reliability is also considered (failure to start, failure to load and run, and failure to run more than 1 hour). An adverse trend in overall LOOP frequency is identified. An adverse trend in LOOP durations is identified. Plant-centered and weather-related LOOP events do not show statistically significant seasonality. The engineering analysis of LOOP data shows that human errors have been much less frequent since 1997 than in the 1986–1996 time period.

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# ACRONYMS

| | |
|---|---|
| EDG | emergency diesel generator |
| INL | Idaho National Laboratory |
| LOOP | loss of offsite power |
| MLE | maximum likelihood estimator |
| MSPI | Mitigating System Performance Indicator |
| NERC | North American Electric Reliability Council |
| NRC | Nuclear Regulatory Commission |
| PRA | probabilistic risk assessment |

# Analysis of Loss-of-Offsite-Power Events 1987–2015

## 1. INTRODUCTION

Commercial nuclear power plants 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.

This study summarizes the frequency, duration, and seasonal timing of LOOP events at commercial nuclear plants in the U.S. for calendar years 1988–2015. 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.

Five years after deregulation of the electrical industry, Raughley and Lanik assessed grid performance to identify changes that could impact nuclear plant safety. They stated:

> *The assessment found that major changes related to LOOPs after deregulation compared to before include the following: (1) the frequency of LOOP events at NPPs [nuclear power plants] has decreased; (2) the average duration of LOOP events has increased; (3) where before LOOPs occurred more or less randomly throughout the year, for 1997-2001 most LOOP events occurred during the summer; and (4) the probability of a LOOP as a consequence of a reactor trip has increased* (Raughley and Lanik 2003).

NUREG/CR-6890, *Reevaluation of Station Blackout Risk at Nuclear Power Plants: Analysis of Loss of Offsite Power Events* (Eide, Gentillon, and Wierman 2005), and update studies similar to the present document (Schroeder 2016a) have been performed annually since then. The most recent such study, covering the period 1997–2014, was published by the Idaho National Laboratory (INL) in February (Bower and Schroeder 2016).

The key findings in this year's annual update, with 19 years of experience since deregulation, echo Raughley and Lanik's findings:

- There is an adverse trend toward longer LOOP durations.
- Grid-related LOOPs happen predominantly in the summer. Switchyard-centered LOOPs happen predominantly in winter and spring. Plant-centered and weather-related LOOPs do not show statistically significant seasonality.
- Traditionally, LOOP annual updates treat each plant losing offsite power as an independent event. In fact, it is possible for a single grid, switchyard, or weather event to impact more than one power plant. The best way to account for this non-independence in future analyses remains under investigation by INL staff; the results will appear in future LOOP updates.
- The engineering analysis of LOOP data shows that human errors have been much less frequent during 1997–2015 than in the 1986–1996 time period.

## 1.1 Changes from Previous Years

A major rewrite of legacy software code that was started at INL in FY-16 is continuing. Highlights of the changes this year include the following:

- The LOOP frequency histogram bars have been replaced with LOOP frequencies and 90% intervals.
- The analysis of LOOP frequencies is based on a simple count of events and exposure times. That is, the analysis assumes independence of each of the events. This is not a safe assumption for grid- and weather-related events. Work is in progress on a full solution to this non-independence issue.
- The multi-plant site event counts have been added. Statistical analysis will return once the "non-independence" issue has been resolved (planned for the 2017 annual update).
- The North Anna events of August 23, 2011, have been recorded in INL's database as switchyard-centered instead of grid-related; therefore, per-category counts in this year's data tables will not match last year's.

# 2. LOOP FREQUENCY

Industry-average LOOP frequencies were determined for calendar years 1997-2015 which includes 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 estimated rates are simply *event count/exposure time*.

*Table 1. Average LOOP frequencies for 1997–2015.*

| Mode | LOOP Category | Events | Reactor Critical or Shutdown Years | Maximum Likelihood Estimator |
|---|---|---|---|---|
| **Critical Operation**[a] | Plant-centered | 3 | 1751.74 | 1.71E−03 |
| | Switchyard-centered | 23 | 1751.74 | 1.31E−02 |
| | Grid-related | 18 | 1751.74 | 1.03E−02 |
| | Weather-related | 10 | 1751.74 | 5.71E−03 |
| | All LOOPs[b] | 54 | 1751.74 | 3.08E−02 |
| **Shutdown Operation**[b] | Plant-centered | 7 | 213.35 | 3.28E−02 |
| | Switchyard-centered | 17 | 213.35 | 7.97E−02 |
| | Grid-related | 4 | 213.35 | 1.87E−02 |
| | Weather-related | 8 | 213.35 | 3.75E−02 |
| | All LOOPs[b] | 36 | 213.35 | 1.69E−01 |

a. The frequency units for critical operation are per reactor critical year (/rcry).
b. The frequency units for shutdown operation are per reactor shutdown year (/rsy).
c. In the "All LOOPs" rows, the events and rate estimators are summed across LOOP categories. The years are calculated so that the counts divided by the years equal the rates.

For critical operation, switchyard-centered LOOPs contribute 43% to the total critical operation LOOP frequency, while grid-related LOOPs contribute 33% of the total. Switchyard-centered events are likewise the most common type of LOOP during shutdown operation at 47%. Plant- and switchyard-centered events are much more likely to occur during shutdowns because plant managers choose to perform maintenance and testing activities likely to cause power interruptions at times when they will be least disruptive to plant operations. Grid- and weather-related events occur approximately uniformly in time; however, plants may choose to shut down in advance of a forecast severe weather event rather than risk a trip during a storm. Therefore, the frequency of weather-related events during shutdown (events per unit time) is much higher; the amount of time spent shut down is much lower.

In Section 2.1 below, annual data are shown and trends in industry average LOOP frequencies 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

Figure 1 shows estimated LOOP frequencies during critical operation since 1997 and the 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 are confidence intervals for the estimated rate associated with each individual year's data.

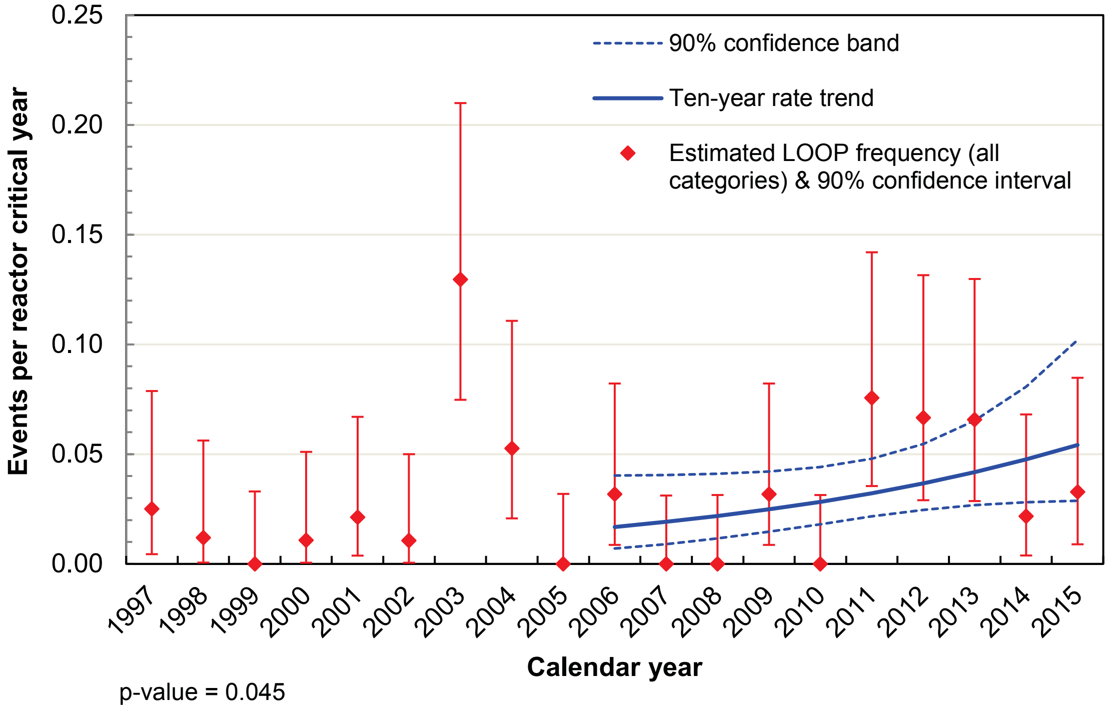


*Figure 1. Estimated LOOP frequencies and 10-year trend during critical operations.*

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. A statistically significant[a] 10-year trend was found in the overall frequency for critical operation estimate.

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

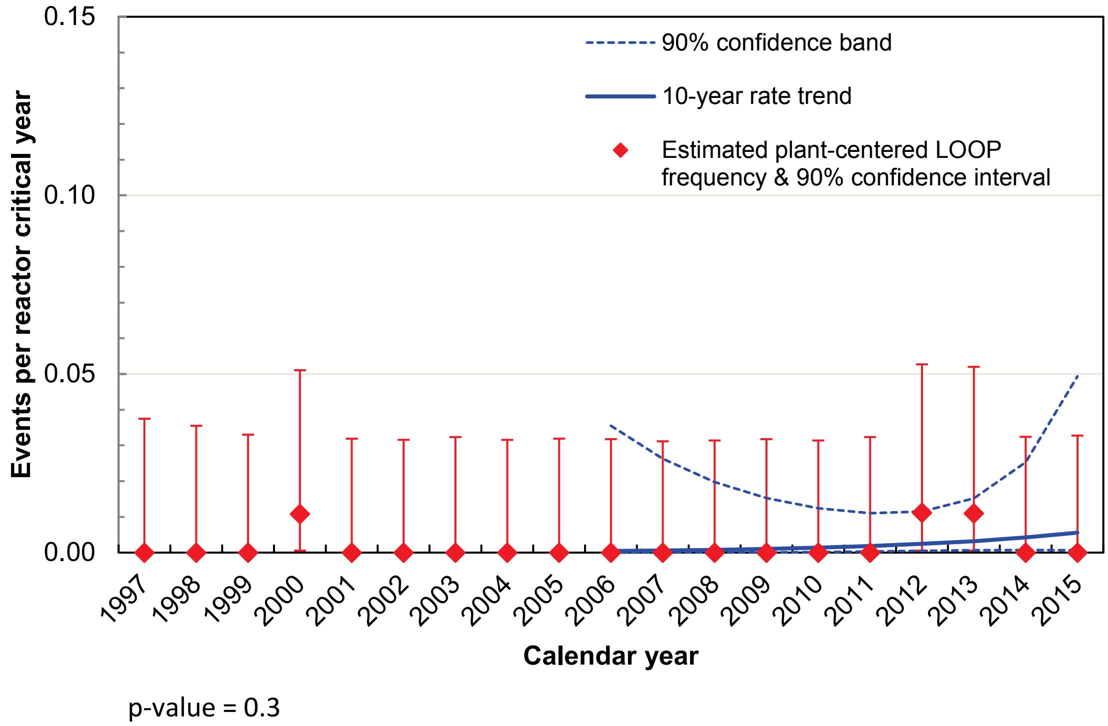


*Figure 2. Ten-year trend in estimated plant-centered LOOP frequency during critical operation.*

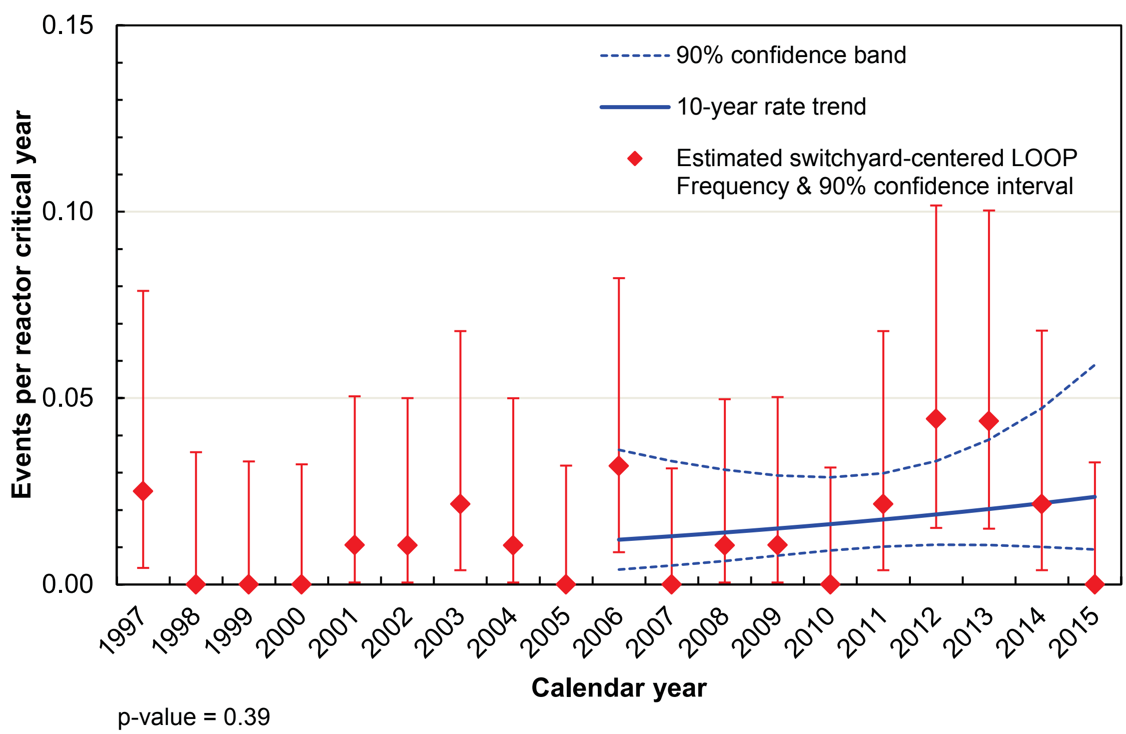


*Figure 3. Ten-year trend in estimated switchyard-centered LOOP frequency during critical operation.*

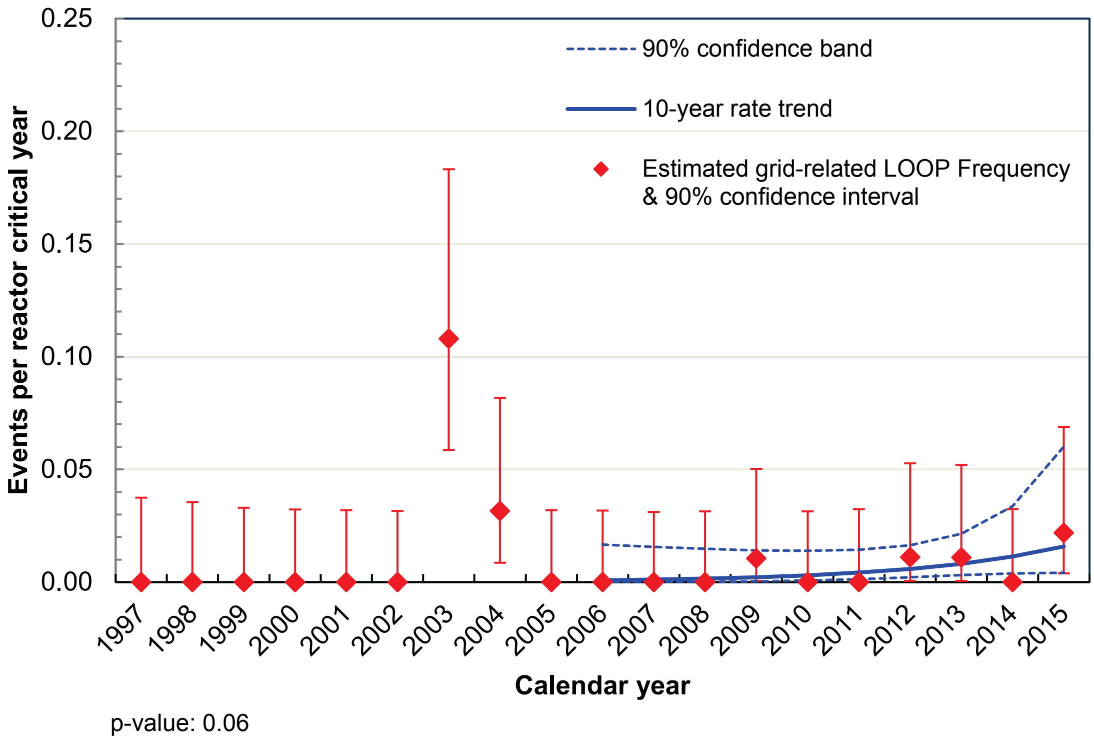


*Figure 4. Ten-year trend in estimated grid-related LOOP frequency during critical operation.*

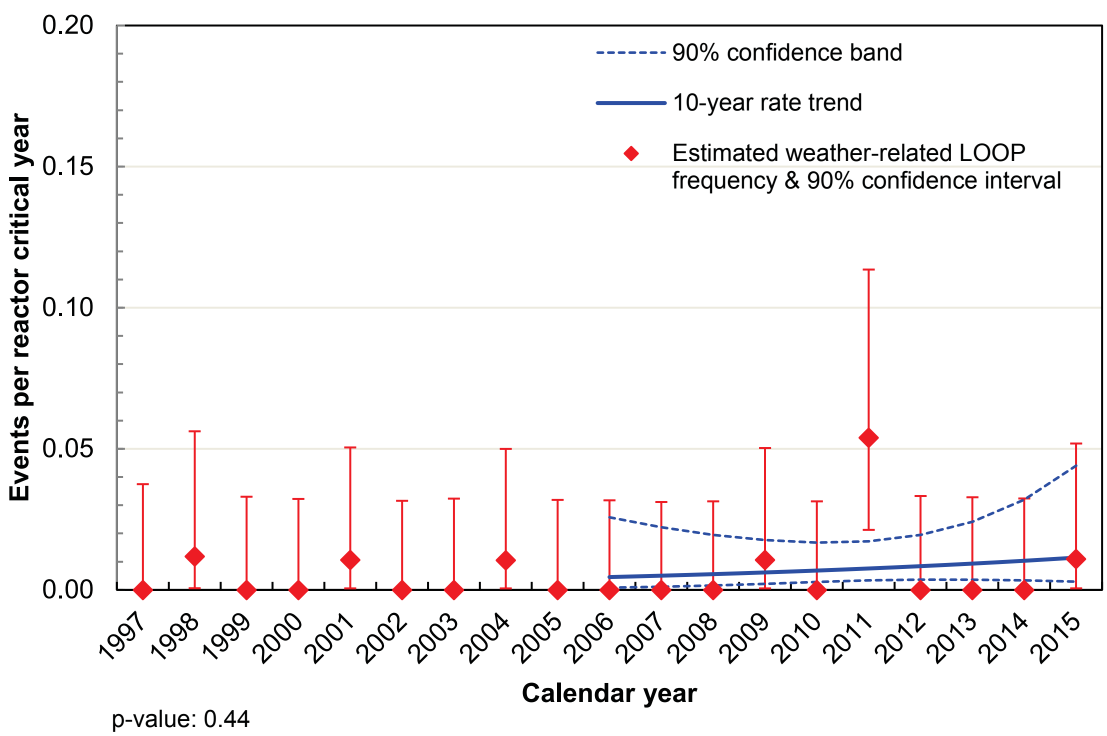


*Figure 5. Ten-year trend in estimated weather-related LOOPs frequency during critical operation.*

## 2.2 Variation Among Plants

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 plant performance. In this update 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 using several grouping schemes: plant, electrical grid area, operating mode, and others. The variability is sought for each LOOP frequency estimate using chi-squared tests and empirical Bayes analyses.

When the statistical tests detect variation, and an empirical Bayes distribution representing that variation can be obtained, then the empirical Bayes distribution result is reported in Table 2 for calendar years 1997-2015. If the tests for variation indicate the data appear homogeneous, then a Jeffreys prior is used to construct the industry estimate. Table 2 presents gamma distributions describing plant-to-plant variation in LOOP frequencies. For each distribution, the 5th, 50th, 95th percentiles, and mean are tabulated.

Past data support the separation of data by 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 modes 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 plant-to-plant variation (1997- 2015).*

| Mode | LOOP Type | Shape (α) | Scale (β) | 5% | Median | 95% | Gamma Mean | Simple MLE | Notes |
|---|---|---|---|---|---|---|---|---|---|
| Critical Operation | Plant-centered | 3.5 | 1750 | 6.19E-04 | 1.81E-03 | 4.02E-03 | 2.00E-03 | 1.71E-03 | a |
| | Switchyard-centered | 23.5 | 1750 | 9.22E-03 | 1.32E-02 | 1.83E-02 | 1.34E-02 | 1.31E-02 | a |
| | Grid-related | 0.609 | 55.3 | 1.10E-04 | 5.86E-03 | 3.94E-02 | 1.10E-02 | 1.03E-02 | b |
| | Weather-related | 10.5 | 1750 | 3.31E-03 | 5.81E-03 | 9.33E-03 | 5.99E-03 | 5.71E-03 | a |
| | All | 54.5 | 1750 | 2.45E-02 | 3.10E-02 | 3.84E-02 | 3.11E-02 | 3.08E-02 | a |
| Shutdown Operation | Plant-centered | 4.5 | 213 | 7.81E-03 | 1.96E-02 | 3.97E-02 | 2.11E-02 | 1.87E-02 | c |
| | Switchyard-centered | 17.5 | 213 | 5.27E-02 | 8.06E-02 | 1.17E-01 | 8.20E-02 | 7.96E-02 | a |
| | Grid-related | 1.67 | 87.6 | 2.65E-03 | 1.54E-02 | 4.79E-02 | 1.90E-02 | 1.87E-02 | b |
| | Weather-related | 8.5 | 213 | 2.04E-02 | 3.84E-02 | 6.48E-02 | 3.98E-02 | 3.75E-02 | a |
| | All | 3.4 | 20.1 | 5.12E-02 | 1.53E-01 | 3.43E-01 | 1.69E-01 | 1.69E-01 | c |

a. Homogeneous. The data rule out the possibility of wide variations among plants. Jeffreys prior is used.
b. Empirical Bayes. There appears to be variability by power pool.
c. Empirical Bayes. There appears to be variability by plant.

In the same manner as described above, the variation in LOOP frequencies among plants in the NERC regions can also be modeled. Figure 6 contains a map showing the NERC regions. Table 3 reports the number of LOOPs during critical operation, grouped by electric reliability council, together with the variability distributions. In this update an empirical Bayes solution could not be obtained to represent the variability in the region data when all LOOP category data is combined.

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.

There is no doubt such variations exist—rolling blackouts in California, hurricanes along the Gulf Coast, and ice storms in the Northeast have occurred in recent years. Attempting to model all such variations is beyond the scope of this LOOP report.

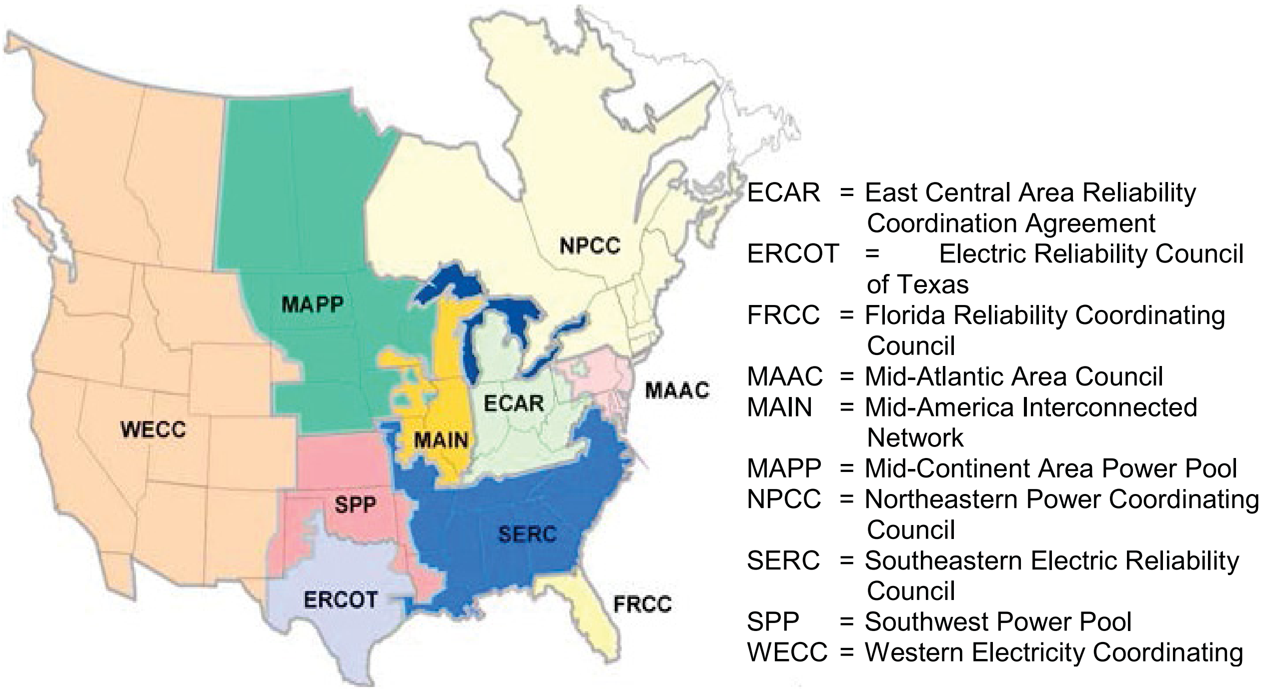


*Figure 6. NERC Reliability Council regions.*

*Table 3. Estimated grid-related LOOP frequencies by reliability council during critical operation (1997-2015).*

| Reliability Council | LOOP Events | Critical Years | Shape (α) | Scale (β) | 5% | Median | 95% | Gamma Mean | Simple MLE |
|---|---|---|---|---|---|---|---|---|---|
| East Central | 2 | 126.20 | 2.51 | 176.0 | 3.28E-03 | 1.24E-02 | 3.015E-02 | 1.42E-02 | 1.58E-02 |
| Florida | 0 | 78.7 | 0.59 | 120.0 | 4.03E-05 | 2.56E-03 | 1.78E-02 | 4.92E-03 | 2.56E-03 |
| Texas | 0 | 69.5 | 0.60 | 113.00 | 4.81E-05 | 2.76E-03 | 1.90E-02 | 5.26E-03 | 0.00E+00 |
| Mid−America | 2 | 289.9 | 2.62 | 343.0 | 1.83E-03 | 6.69E-03 | 1.67E-02 | 7.64E-03 | 6.90E-03 |
| Mid−Atlantic | 4 | 193.0 | 4.30 | 234.0 | 6.58E-03 | 1.70E-02 | 3.49E-02 | 1.83E-02 | 2.07E-02 |
| Mid−Continent | 0 | 99.6 | 0.58 | 135.00 | 3.99E-05 | 2.19E-03 | 1.56E-02 | 4.28E-03 | 0.00E+00 |
| Northeastern | 7 | 18680 | 6.16 | 200.0 | 1.36E-02 | 2.92E-02 | 5.36E-02 | 3.08E-02 | 3.75E-02 |
| Southeastern | 0 | 477.0 | 0.50 | 387.0 | 5.12E-06 | 5.90E-04 | 4.96E-03 | 1.29E-03 | 0.00E+00 |
| Southwestern | 0 | 102.9 | 0.58 | 137.0 | 3.27E-05 | 2.14E-03 | 1.53E-02 | 4.20E-03 | 0.00E+00 |
| Western | 3 | 123.10 | 3.25 | 168.0 | 5.63E-03 | 1.74E-02 | 3.96E-02 | 1.93E-02 | 2.34E-02 |

## 2.3 Summary of LOOP Frequencies

Table 4 shows a summary of LOOP data for 1987–2015, 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 rapid improvement in avoiding shutdown operation LOOPs[b] and the shortening of shutdown periods in the last 10 years—the annual shutdown exposure and the number of LOOPs have both been approximately constant (≈ 9 reactor years and 0–3 LOOPs per calendar year). Plant-centered and grid-related shutdown LOOPs show no events since 2008, which accounts for this trend.

b. Assuming each LOOP is an independent event—an assumption that is not quite true (see Section 6).

*Table 4. Summary of all LOOP data, 1987–2015.*

| 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 | Grid | Plant | Syard | Wx | Total |
| 1987 | 70.56 | 30.23 | 100.80 | 0 | 5 | 0 | 0 | 2 | 5 | 1 | 2 | 5 | 10 | 1 | 2 | 10 | 2 | 15 |
| 1988 | 76.19 | 30.77 | 106.96 | 1 | 3 | 0 | 0 | 1 | 4 | 0 | 1 | 4 | 6 | 0 | 2 | 7 | 1 | 10 |
| 1989 | 76.42 | 33.08 | 109.50 | 1 | 3 | 0 | 0 | 0 | 5 | 1 | 0 | 4 | 6 | 1 | 1 | 8 | 0 | 10 |
| 1990 | 80.66 | 29.23 | 109.88 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 | 0 | 0 | 4 | 0 | 4 |
| 1991 | 83.94 | 25.67 | 109.61 | 3 | 3 | 0 | 0 | 4 | 3 | 0 | 1 | 6 | 8 | 0 | 7 | 6 | 1 | 14 |
| 1992 | 83.61 | 24.64 | 108.25 | 2 | 3 | 1 | 0 | 4 | 1 | 0 | 2 | 6 | 7 | 1 | 6 | 4 | 2 | 13 |
| 1993 | 82.90 | 24.26 | 107.16 | 0 | 4 | 0 | 1 | 3 | 2 | 0 | 4 | 5 | 9 | 0 | 3 | 6 | 5 | 14 |
| 1994 | 85.80 | 21.20 | 107.00 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 3 | 0 | 2 | 1 | 0 | 3 |
| 1995 | 88.84 | 18.42 | 107.26 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 2 |
| 1996 | 87.09 | 21.91 | 109.00 | 0 | 1 | 0 | 2 | 0 | 2 | 0 | 0 | 3 | 2 | 0 | 0 | 3 | 2 | 5 |
| 1997 | 79.93 | 28.15 | 108.08 | 0 | 2 | 0 | 0 | 1 | 2 | 1 | 1 | 2 | 5 | 1 | 1 | 4 | 1 | 7 |
| 1998 | 84.39 | 21.61 | 106.00 | 0 | 0 | 0 | 1 | 2 | 1 | 0 | 1 | 1 | 4 | 0 | 2 | 1 | 2 | 5 |
| 1999 | 90.73 | 15.10 | 105.83 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 3 | 0 | 1 | 2 | 0 | 3 |
| 2000 | 92.92 | 10.08 | 103.00 | 1 | 0 | 0 | 0 | 1 | 3 | 0 | 0 | 1 | 4 | 0 | 2 | 3 | 0 | 5 |
| 2001 | 93.96 | 9.04 | 103.00 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 1 | 2 |
| 2002 | 94.88 | 8.12 | 103.00 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |
| 2003 | 92.61 | 10.39 | 103.00 | 0 | 2 | 10 | 0 | 1 | 0 | 1 | 0 | 12 | 2 | 11 | 1 | 2 | 0 | 14 |
| 2004 | 94.94 | 8.06 | 103.00 | 0 | 1 | 3 | 1 | 0 | 0 | 0 | 2 | 5 | 2 | 3 | 0 | 1 | 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 | 0 | 1 | 3 | 0 | 4 |
| 2007 | 96.16 | 7.45 | 103.61 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 3 | 2 | 0 | 0 | 1 | 3 |
| 2008 | 95.43 | 8.57 | 104.00 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 | 0 | 0 | 4 | 0 | 4 |
| 2009 | 94.34 | 9.66 | 104.00 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 3 | 0 | 1 | 0 | 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 | 0 | 3 | 5 | 8 |
| 2012 | 90.02 | 13.98 | 104.00 | 1 | 4 | 1 | 0 | 0 | 2 | 0 | 1 | 6 | 3 | 1 | 1 | 6 | 1 | 9 |
| 2013 | 91.23 | 10.34 | 101.57 | 1 | 4 | 1 | 0 | 0 | 1 | 0 | 0 | 6 | 1 | 1 | 1 | 5 | 0 | 7 |
| 2014 | 92.44 | 7.56 | 100.00 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 1 | 0 | 0 | 3 | 0 | 3 |
| 2015 | 91.44 | 7.56 | 99.00 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 3 | 0 | 2 | 0 | 0 | 1 | 3 |

# 3. LOOP DURATION AND RECOVERY

Probability of exceedance versus duration curves were generated by fitting lognormal distributions to the LOOP durations for each LOOP category: plant-centered, switchyard-centered, grid-related, and weather-related. Note that there is a very clear trend toward longer LOOP duration in the post-regulation years when all the category data are combined. This is illustrated in Figure 8. This trend is not as clear when the data are considered by category as shown in Table 5. The trend toward longer recovery times is most significant in the groups with the largest sample sizes (switchyard-centered and grid-related LOOPs), but appears to be fairly consistent across all groups.

Exceedance probabilities read from the fitted lognormal distributions are very sensitive to the data period on which the curves are based, and given the weak evidence of a trend in some of the categories, homogeneity tests were applied to each category to help determine the most suitable period to use. Homogeneity was confirmed for both shutdown and operating data in each category for the years 1988 through 2015. Including both the 1987 data in the same group as the 2015 data did not result in a homogeneous data set so the start date for the data period was moved from 1986 (as in previous updates) to 1988.

The parameters of the lognormal distributions for the exceedance curves are provided in Table 6. Note that the values for μ and σ completely define the distribution; the 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. These distributions are plotted as probability-of-exceedance curves $(1-F(t))$ in Figure 8.

The parameterization of the fitted lognormal density and cumulative distribution functions used in this report follows:

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

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

where

$t$ = offsite power potential bus recovery time

$\mu$ = mean of natural logarithms of data

$\sigma$ = standard deviation of natural logarithms of data

$\Phi$ = error function.

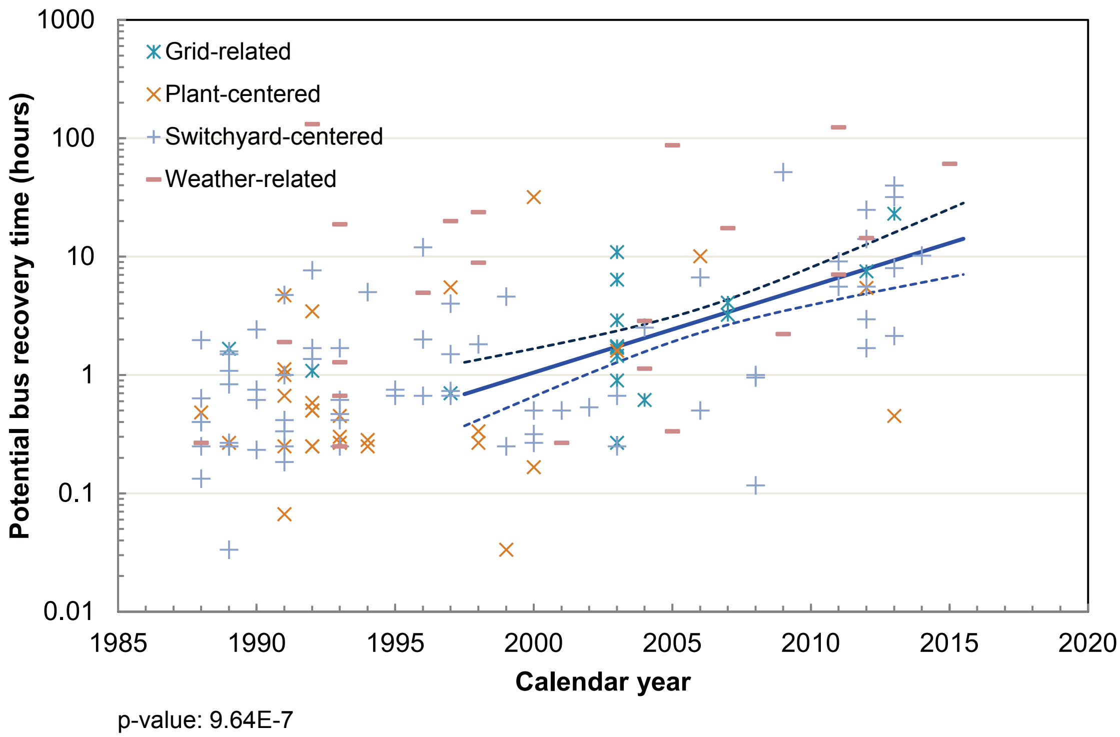


*Figure 7. Trend toward increasing LOOP durations (all event types) for the post-deregulation period.*

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

| Subset | # of LOOP Events | Equation | Standard Error of Slope | p-value |
|---|---|---|---|---|
| Plant-centered | 10 | *Exp(0.082 × (year 2015) + 1.134)* | 0.126 | 5.37E−01 |
| Switchyard-centered | 37 | *Exp(0.173 × (year 2015) + 2.446)* | 0.036 | 3.05E−05 |
| Grid-related | 19 | *Exp(0.21 × (year 2015) + 2.836)* | 0.067 | 6.24E−03 |
| Weather-related | 18 | *Exp(0.133 × (year 2015) + 3.393)* | 0.085 | 1.38E−01 |
| All LOOPs | 84 | *Exp(0.168 × (year 2015) + 2.65)* | 0.032 | 9.64E−07 |
| Critical Operations | 50 | *Exp(0.186 × (year 2015) + 2.787)* | 0.043 | 7.76E−05 |
| Shutdown Operations | 34 | *Exp(0.148 × (year 2015) + 2.437)* | 0.054 | 9.63E−03 |

Table 6. *Fitted lognormal recovery time distributions (1988-2015).*

| Parameter | Plant-centered | Switchyard-centered | Grid-related | Weather-related |
|---|---|---|---|---|
| LOOP event count | 29 | 71 | 16 | 22 |
| Mu (μ) | -0.45 | 0.17 | 0.80 | 1.63 |
| Standard error of μ | 0.28 | 0.18 | 0.29 | 0.44 |
| Sigma (σ) | 1.51 | 1.50 | 1.17 | 2.05 |
| Standard error of σ | 0.20 | 0.13 | 0.21 | 0.31 |
| Fitted median | 0.64 | 1.18 | 2.23 | 5.13 |
| Fitted mean | 1.99 | 3.66 | 4.40 | 41.83 |
| Fitted 95th percentile | 7.63 | 14.00 | 15.18 | 149.16 |
| Error Factor | 11.99 | 11.86 | 6.81 | 29.08 |

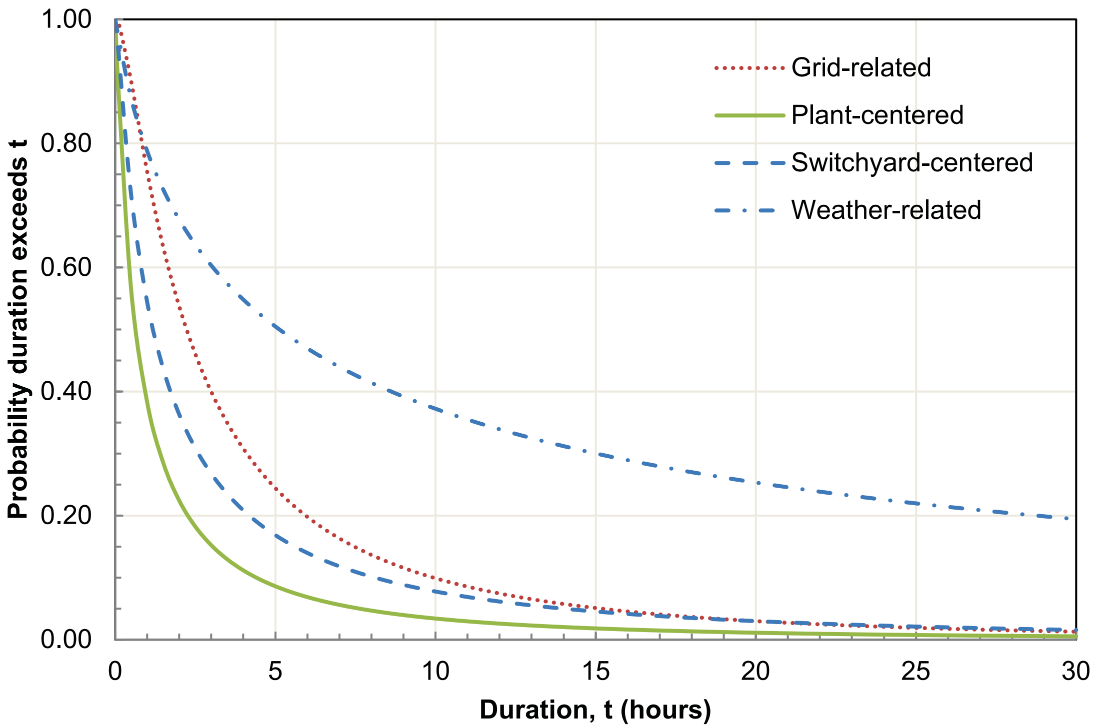


*Figure 8. Probability of exceedance vs duration (non-recovery probability) curves (1988 – 2015).*

# 4. EMERGENCY DIESEL GENERATOR REPAIR TIMES

In the event of a loss of offsite power, it is relevant to consider whether the plant's onsite emergency diesel generators (EDGs) will successfully start and continue to run for the duration of the outage. If an EDG should fail, it is relevant to consider how long it will take to restore the EDG to service.

Both of these topics were considered in the original evaluation of LOOP events (Atwood et al. 1996). The topic of unreliability of EDGs is broken down into four components:

- Probability that the EDG is unavailable due to the component being offline at the time of a demand (e.g., for routine maintenance)
- Probability of failing to start on demand
- Probability of failing to load and run for the first hour after starting
- A per-hour failure rate after the first hour.

The detailed analysis of EDG unreliability trends was discontinued with the 2013 LOOP report and is instead discussed in a standalone report, *Enhanced Component Performance Study*, which is periodically updated (Schroeder 2016b).

As of 2016, the topic of EDG repair times is not covered in the component performance study. Therefore, it remains part of the LOOP annual update. The data for repair times performed under actual emergency conditions are not available so this question was approached by examining how many hours of unplanned unavailability have been reported for each EDG from 2006 to 2015. The hourly unplanned unavailability is reported to the U.S. Nuclear Regulatory Commission (NRC) in the Mitigating Systems Performance Index (MSPI) data (NRC 2016). The MSPI data were not reported prior to 2006.

In 1996, Atwood et al. fitted a Weibull distribution to the repair time data (Atwood et al. 1996); the Weibull distribution continues to be the best fitting common distribution for the data set as a whole. The Weibull fit parameters are provided in Table 7 for the 2006–2015 data. The probability an EDG outage duration exceeds any given time (*t*) is listed in Table 8. Also reported in Table 8 are the actual fractions of the raw observations in the MSPI database that exceed the specified time. The trend toward fewer unplanned outages but longer repair times continues. Note that the correspondence between fitted and observed distributions is very good at short to moderate times but not as good at very long repair times, such as where the outage spans months. Indeed, the long right tail of the repair time distribution is fit better by a lognormal distribution than a Weibull. The reader is cautioned against using the fitted Weibull to estimate the 95th or 99th percentile of the recovery time distribution. Also note that outages spanning more than 1 month are recorded as two short outages rather than one long one in the MSPI database.

*Table 7. Weibull curve fit parameters.*

| Parameter | Value |
|---|---|
| Mean | 26.29 |
| Median | 12.32 |
| Weibull(α) | 0.7006 |
| Weibull(β) | 20.79 |

*Table 8. Probability of exceeding selected EDG repair times (2006 – 2015).*

| Recovery Time (hr) | Weibull Model Probability | Observed Data |
|---|---|---|
| 0.5 | 0.929 | 0.943 |
| 1 | 0.888 | 0.915 |
| 1.5 | 0.853 | 0.882 |
| 2 | 0.824 | 0.853 |
| 3 | 0.773 | 0.810 |
| 4 | 0.730 | 0.757 |
| 5 | 0.692 | 0.708 |
| 6 | 0.658 | 0.671 |
| 7 | 0.627 | 0.628 |
| 8 | 0.599 | 0.598 |
| 9 | 0.573 | 0.573 |
| 10 | 0.549 | 0.550 |
| 11 | 0.527 | 0.518 |
| 12 | 0.506 | 0.482 |
| 13 | 0.487 | 0.465 |
| 14 | 0.469 | 0.438 |
| 15 | 0.451 | 0.421 |
| 16 | 0.435 | 0.398 |
| 17 | 0.420 | 0.384 |
| 18 | 0.405 | 0.362 |
| 19 | 0.391 | 0.350 |
| 20 | 0.378 | 0.328 |
| 21 | 0.365 | 0.320 |
| 22 | 0.353 | 0.312 |
| 23 | 0.342 | 0.290 |
| 24 | 0.331 | 0.284 |

# 5. SEASONAL VARIATION IN 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[a] but readers of their report found this early evidence compelling. Additional summer grid-related LOOPs have continued to occur, and recent LOOP annual updates have tabulated events in two groups (May–Sept and Oct–Apr) without any formal testing of the hypothesis and without addressing the basis for choosing May to September as "the five summer months." The May–September grouping highlights the increased stress on the grid during summer air-conditioning season and may not be appropriate for all purposes. For instance, the hurricane season runs through late summer into early winter so any hurricane effect on the weather-related LOOPs will not be discovered by this grouping.

Table 9 lists the number of LOOP events in each category by month for calendar years 1997 - 2015. These data show that in actuality, no simple pattern emerges in the weather-related LOOPs (different types of adverse weather happen at different times of the year). A significant clustering of switchyard-based events in the January–May time period does exist, however, and was being hidden by the previous summer/non-summer grouping.

*Table 9. LOOP event counts by month and LOOP category (1997-2015).*

| | Critical Operations | | | | Shutdown Operations | | | |
|---|---|---|---|---|---|---|---|---|
| Month | Grid | Plant | Switchyard | Weather | Grid | Plant | Switchyard | Weather |
| Jan | 0 | 0 | 2 | 1 | 0 | 0 | 1 | 0 |
| Feb | 0 | 0 | 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] | 0 | 4[b] | 2 | 1 | 0 | 1 | 1 |
| Sep | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 3 |
| Oct | 1 | 0 | 0 | 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.

Instead of arbitrarily dividing the year into two or more "bins" (or worse, choosing bins after observing a putative pattern in the data) and applying a multinomial test, it is possible to directly test the hypothesis that a set of events are scattered uniformly through the year. The Rayleigh Test is a standard test for

a. A simple two-sample Z-test on the proportions gives p-value < 0.03 but this p-value is only valid if we decide a priori that May–September is the period of interest, not if we wait until we observe a clumping in the data and then identify that set of months as the period of interest.

whether points are distributed uniformly around a circle (wind directions, fracture orientations) and adapts readily to testing whether seasonal trends exist (Mardia and Jupp 2000).

Applying the Rayleigh Test to the counts in Table 9 shows a statistically significant seasonality is present for grid-related LOOPs during critical operations ($p = 0.019$) and for switchyard-centered LOOPs during critical operations ($p = 0.041$). Driven by those two subgroups, the distribution of LOOPs as a whole shows a significant seasonality. Please note that 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 9 for these categories compared to last year's 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.

There is room for further refinement of the methodology, such as

- Considering the actual date rather than just the month of each event
- Avoiding double-counting other dependent events
- Weighting each month according to how many critical and shutdown reactor hours were logged in that month.

Other improvements being considered are giving formal estimates of (a) when the peak time is and (b) the strength of the seasonality. For now, we simply introduce the Rayleigh test as the recommended method of assessing seasonality.

# 6. MULTI-PLANT LOOP EVENTS

The analysis in Section 5 counts each plant that experienced a loss of offsite power, and the trending and distribution-fitting as if each LOOP were an independent event. 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 1997–2015 when more than one plant was affected by the same incident. Those 12 occasions contributed 25 of the 90 events counted in Table 1 (27%). 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:

- What is the frequency of the underlying event?
- How many sites were affected by the event?
- How many plants at each site were affected by the event?

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 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 plants 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, even at the same site.[a]

Previous LOOP updates included a special topic titled "multi-plant site considerations."[b] Under this topic, the authors calculated the conditional probability of all plants at a multi-plant site experiencing a LOOP given that at least one plant at the site was affected. This partially addressed the "how many plants at one site?" question (it was not clear whether the same kind of analysis was appropriate for 2- and 3-plant sites) but left the "how many sites simultaneously?" question unanswered.

Among the 180 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 10. 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.

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a. 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.)

b. There are 100 currently operating nuclear power plants: 24 single-plant sites, 32 dual-plant sites, and 3 triple-plant sites. For LOOP purposes, Fitzpatrick/Nine Mile Point 1 is considered a dual-plant site and Nine Mile Point 2 is a single-plant site. Five three-plant sites are used for LOOP purposes (starting with the data in 1988): Browns Ferry, Oconee, Palo Verde, San Onofre, and Hope Creek/Salem.

*Table 10. Multi-plant LOOP events for 1987–2015.*

| Event | Site | Date | # of Plants at Site | # of Plants 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 11 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 plants and many of the LOOP events are not independent. INL staff plan to work on a comprehensive approach to account for this dependence. One expected result of that analysis is a widening of the confidence bands in Figures 1–8, especially for grid-related LOOP events.

*Table 11. 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 of the Plants 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 mean is a Bayesian update using a Jeffreys prior: Mean = (0.5 + events)/(1 + total events). The beta distribution is a constrained noninformative prior distribution.

# 7. ENGINEERING ANALYSIS OF LOOP DATA

LOOP events can be classified by the cause of the failure to provide additional qualitative insights. (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 2015, the two largest subcategories were failed circuits and transformers. A large number of transformer failures occurred from 1986 to 1996; previous LOOP annual updates, 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.

Figure 10 categorizes LOOP events from human error by the type of activity in progress at the time. There have been very few LOOPs from human error since 1997, nearly a 90% 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 1986 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.

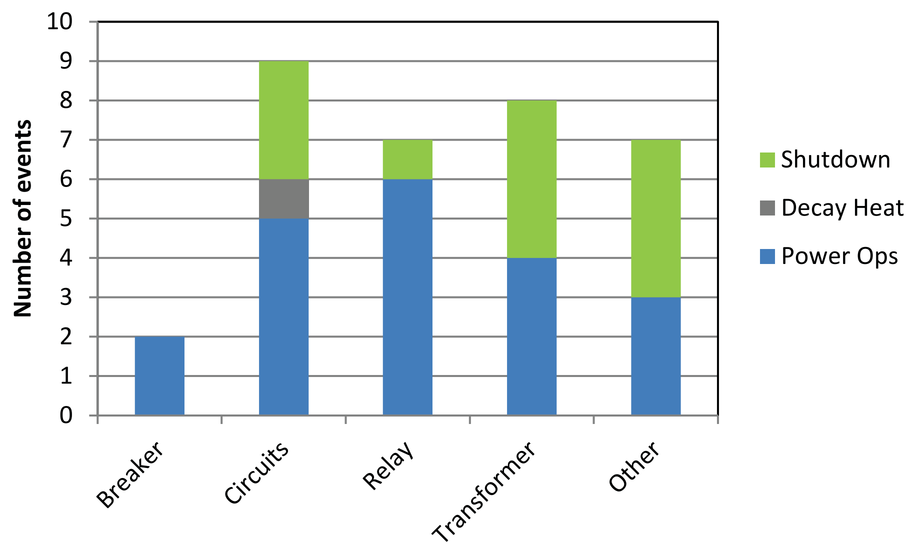


*Figure 9. Failed components causing LOOP events from equipment failures.*

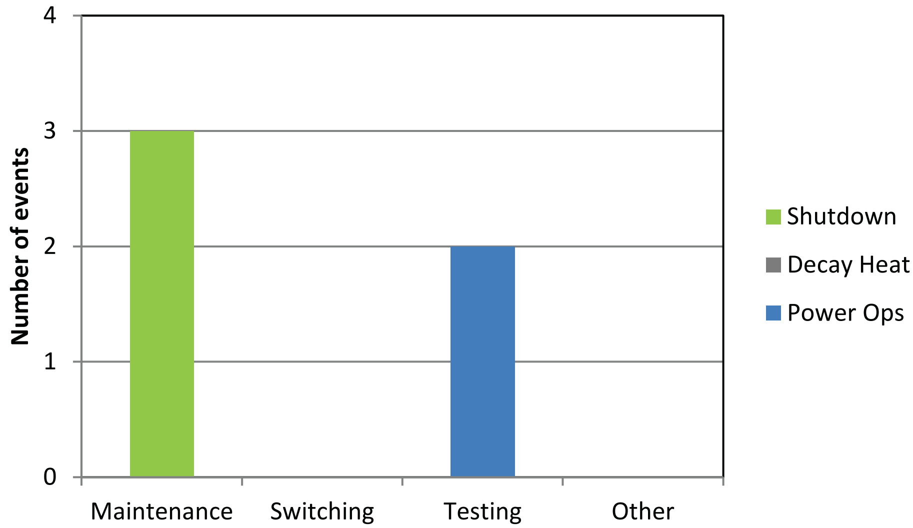


*Figure 10. Activities causing LOOP events from human error.*

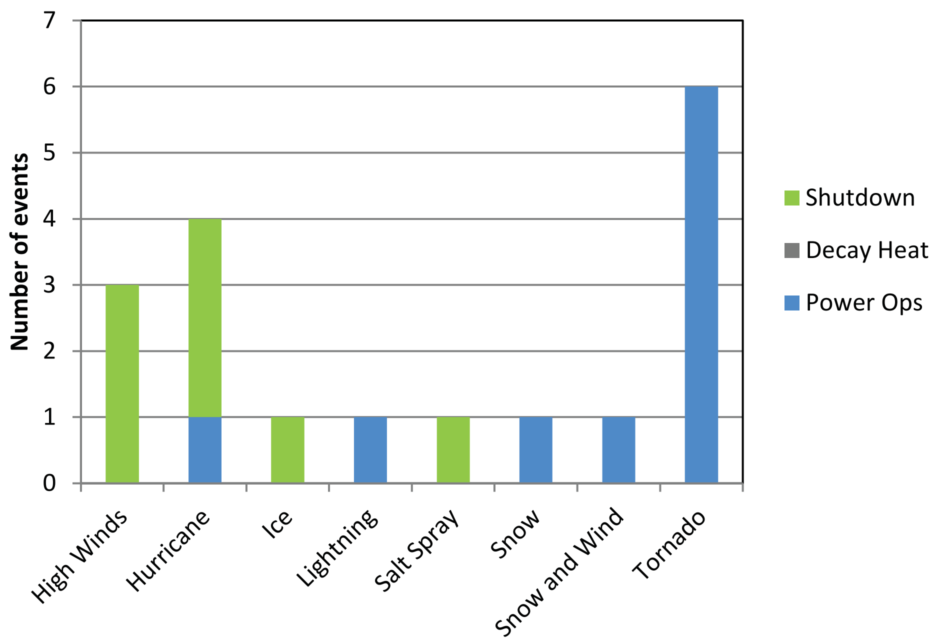


*Figure 11. Natural disasters causing LOOP events from weather.*

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# Appendix A
# LOOP LER Listing

# Appendix A
# LOOP LER Listing

*Table A-1. Critical plant-centered LERs.*

| Plant Name | LER | CY | Event Date |
|---|---|---|---|
| Diablo Canyon 1 | 2752000004 | 2000 | 5/15/2000 |
| Catawba 1 | 4132012001 | 2012 | 4/4/2012 |
| Turkey Point 4 | 2512013002 | 2013 | 4/19/2013 |

*Table A-2. Shutdown plant-centered LERs.*

| Plant Name | LER | CY | Event Date |
|---|---|---|---|
| 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 |
|---|---|---|---|
| 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 |
| Millstone 2 | 3362008004 | 2008 | 5/24/2008 |
| 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 |
| 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 |

*Table A-4. Shutdown switchyard-centered LERs.*

| Plant Name | LER | CY | Event Date |
|---|---|---|---|
| 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 |
| 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 |
| 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 |
| FitzPatrick | 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 |
|---|---|---|---|
| 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 |
| FitzPatrick | 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 |
|---|---|---|---|
| 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 |
|---|---|---|---|
| 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 | 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 |