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Analysis of Loss-of-Offsite-Power Events 1997–2014

Gordon R. Bower
John A. Schroeder

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Idaho National Laboratory
Risk Assessment and Management Services Department
Idaho Falls, Idaho 83415

http://www.inl.gov

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ACRONYMS

EDG	emergency diesel generator
INL	Idaho National Laboratory
LOOP	loss of offsite power
MLE	maximum likelihood estimator
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment

Introduction and Executive Summary

Commercial nuclear power plants rely on alternating current power, supplied by offsite sources via the electric grid, for their routine operation and for their 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.

This study summarizes the frequency, duration, and seasonal timing of LOOP events at commercial nuclear plants in the US for calendar years 1997-2014. Partial LOOPs, in which some but not all offsite power is lost, and LOOP events that do not result in a reactor trip, are not included.

Writing in 2003, Raughley and Lanik [7] shared their first thoughts about what was seen in five years after deregulation:

> “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.”

NUREG CR-6890, “Reevaluation of station blackout risk at nuclear power plants: analysis of loss of offsite power events,” was issued in 2005 [4], and update studies similar to the present document have been performed annually since then. The most recent such study was published by the Idaho National Laboratory (INL) in February 2015 [9].

The key findings in this year's annual update, with 18 rather than 5 years of experience since deregulation, echo Raughley and Lanik's findings:

- There is an adverse trend in LOOP frequency, driven in part by decreasing grid reliability.
- 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 analysis remains under investigation by INL staff and the results will appear in future LOOP updates.
- The engineering analysis of LOOP data shows that human errors have been much less frequent since 1997 than in the 1986 -1996 time period.

Changes from Previous Years

A major rewrite of legacy software code has begun at INL in FY2016. This presented a convenient moment to update the look of the LOOP report and incorporate some of the changes suggested in the FY2015 quality assurance review [3]. Highlights of the changes this year include the following:

- Only data from 1997 onward are used in all analysis. Previous reports have repeated the 1986-1996 frequencies verbatim year after year; these old data have been dropped in the interest of readability.
- Trends in LOOP frequencies have been changed to 10-year trends rather than 1997-present trends, to bring this product into alignment with practice in other NRC trending products. This also avoids the worst issues related to dependent grid-related events in 2003 and 2004.
- Work is still in progress on a full solution to the non-independence issue; the “multi-unit site considerations" chapter has been removed from this year's annual update, but will return in improved form in 2017.
- A more formal and more powerful statistical test has been used to assess seasonality in LOOP frequencies.

1. LOOP Frequency

Industry-average LOOP frequencies were determined for four event categories (grid-related, plant-centered, switchyard-centered, and weather-related), for both critical and shutdown operation. Table 1 reports the observed frequencies; the estimated rates are simply (\# events) / (exposure time). The observed frequencies for the period 1986-1996 have been previously reported in [1]. The raw data used for all analysis in this report is summarized below in Table 4.

Note that these are simple descriptive statistics. If one proposes to use these rates in a probabilistic risk analysis, one needs to describe the uncertainty in the estimates, and if a trend is present, one should use an estimate for the relevant year based on the fitted trend line, not the 18-year average.

Table 1. Average LOOP frequencies, 1997- 2014.

LOOP type	Critical operation:		Shutdown operation:		Combined Total	
	#LOOPs	Est. rate	#LOOPs	Est. rate	#LOOPs	Est. rate
Grid-related	18	1.08E-02	4	1.94E-02	22	1.18E-02
Plant-centered	3	1.81E-03	7	3.40E-02	10	5.36E-03
Switchyard-centered	22	1.33E-02	16	7.77E-02	38	2.04E-02
Weather-related	9	5.42E-03	8	3.89E-02	17	9.11E-03
Total	52	3.13E-02	35	1.70E-01	87	4.66E-02
Reactor-years:	1660.30		205.79		1866.09	

During critical operation, switchyard and grid LOOPs represent 42% and 35% of the total. Switchyard-centered events are also the most common type of LOOP during shutdowns at 45%. Plant- and switchyard-centered events are much more likely to occur during shutdowns, as plant management will 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, so weather-related LOOPs also show a higher frequency during shutdown periods.

Figure 1 shows year by year observed LOOP frequencies during critical operation since 1997, and the 10-year trend in LOOP frequencies. A statistically significant [1] adverse trend (higher LOOP frequencies in more recent years) is present. This trend has likely been present for some time, but was masked by the large number of dependent events in 2003 and 2004 when trending was done 1997-present instead of on a ten-year basis.

[1] Assuming each LOOP is an independent event – an assumption that is not quite true (See Section 5.)

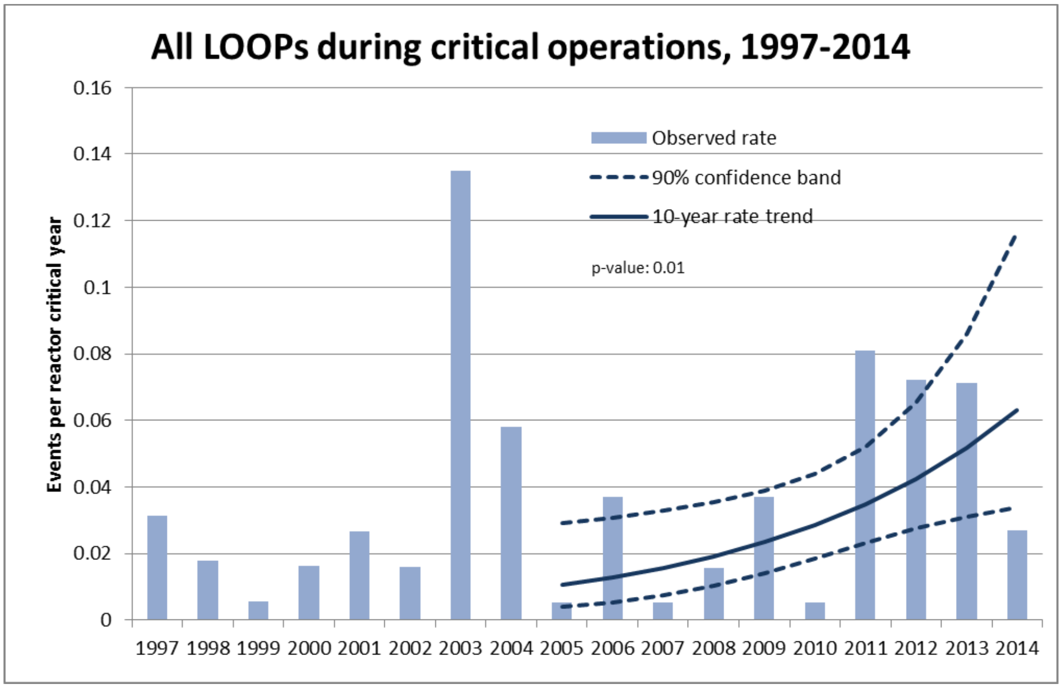

Figure 1. 10-year trend, all LOOPs during critical operation.

Figures 2- 5 show the annual frequencies and 10-year trends for each of the four types of LOOP. There have been too few plant-centered events for a well constrained rate or trend, and there has been no adverse trend in weather-related LOOPs in recent years. Several recent switchyard-centered events have occurred and fall just short of achieving statistical significance. As was reported previously [9], grid-related LOOPs showed an adverse trend 2004-2013, and researchers looking at the broader electric utility field have reported adverse trends in grid reliability over the past 10 to 15 years. No grid-related LOOPs occurred in 2014 so this year we enjoy a respite from that adverse subcategory trend.

When a weak trend is present but limited data are available, it is not unusual for aggregated data to show a significant trend while individual subgroups fail to show a significant trend. That is, we do not claim that the frequency of grid- and switchyard-centered LOOPS is constant, merely that there are inadequate data to clearly demonstrate trends in small subsets of the data.

No statistically significant 10-year trends were found in shutdown LOOP frequencies. Scanning the “Total by status: Down" column of Figure 4 shows the industry's rapid improvement in avoiding shutdown LOOPs and shortening shutdown periods in the early to mid-1990’s, since which time the annual shutdown exposure and the number of LOOPs have both been approximately constant (≈ 10 reactor-years and 1-3 LOOPs per calendar year.)

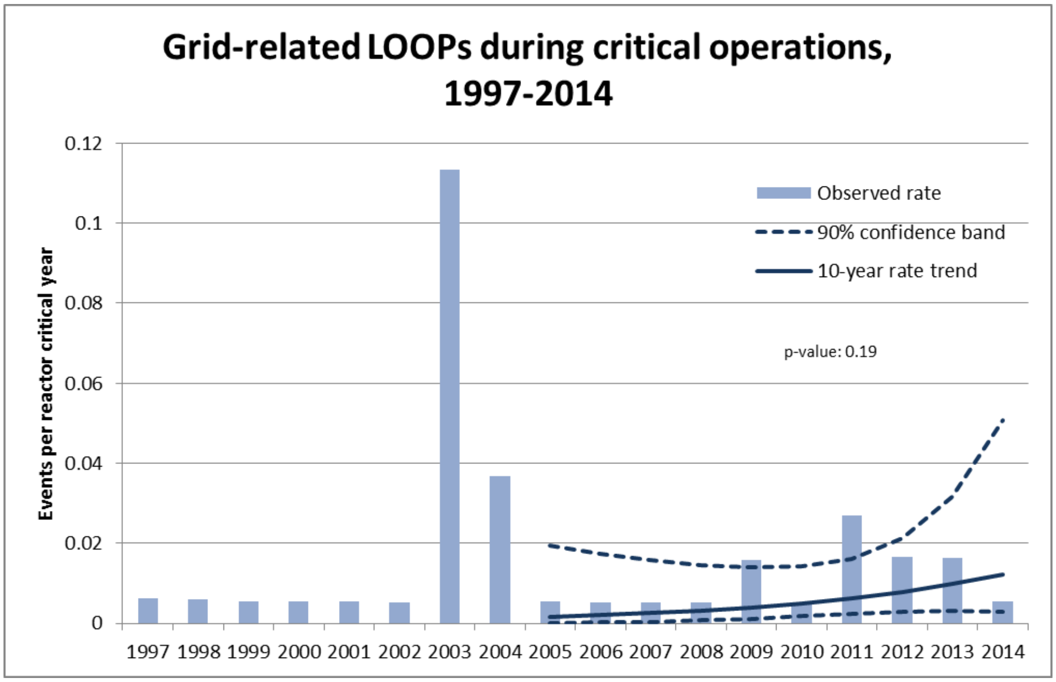

Figure 2. 10-year trend, grid-related LOOPs during critical operation.

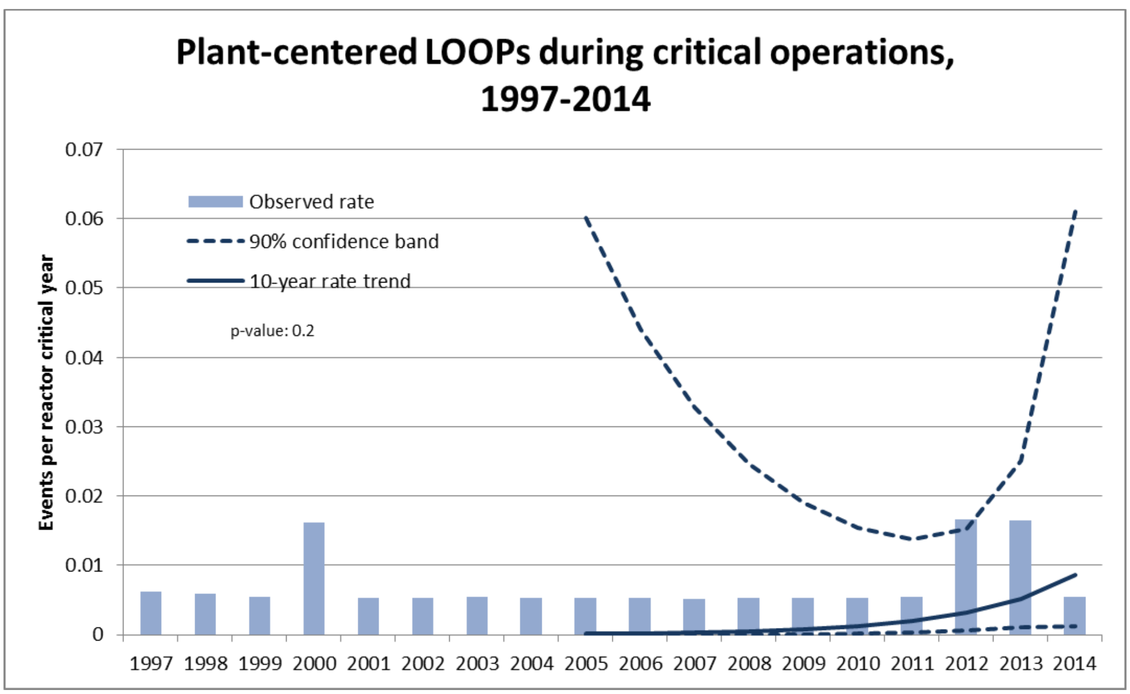

Figure 3. 10-year trend, plant-centered LOOPs during critical operation.

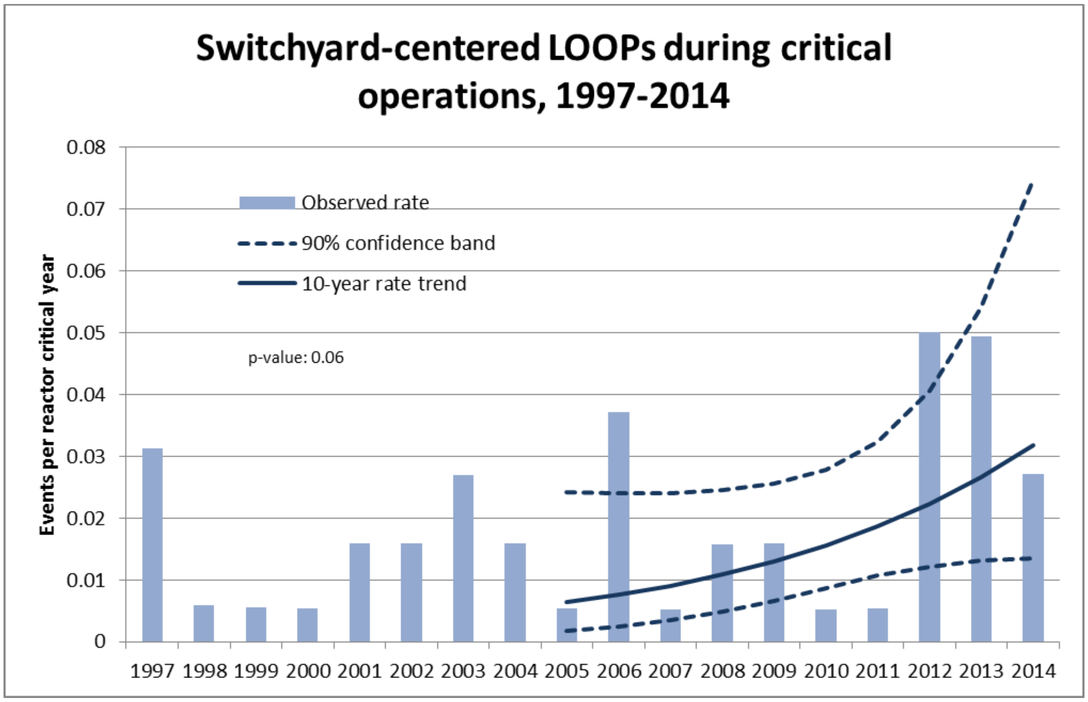

Figure 4. 10-year trend, switchyard-centered LOOPs during critical operation.

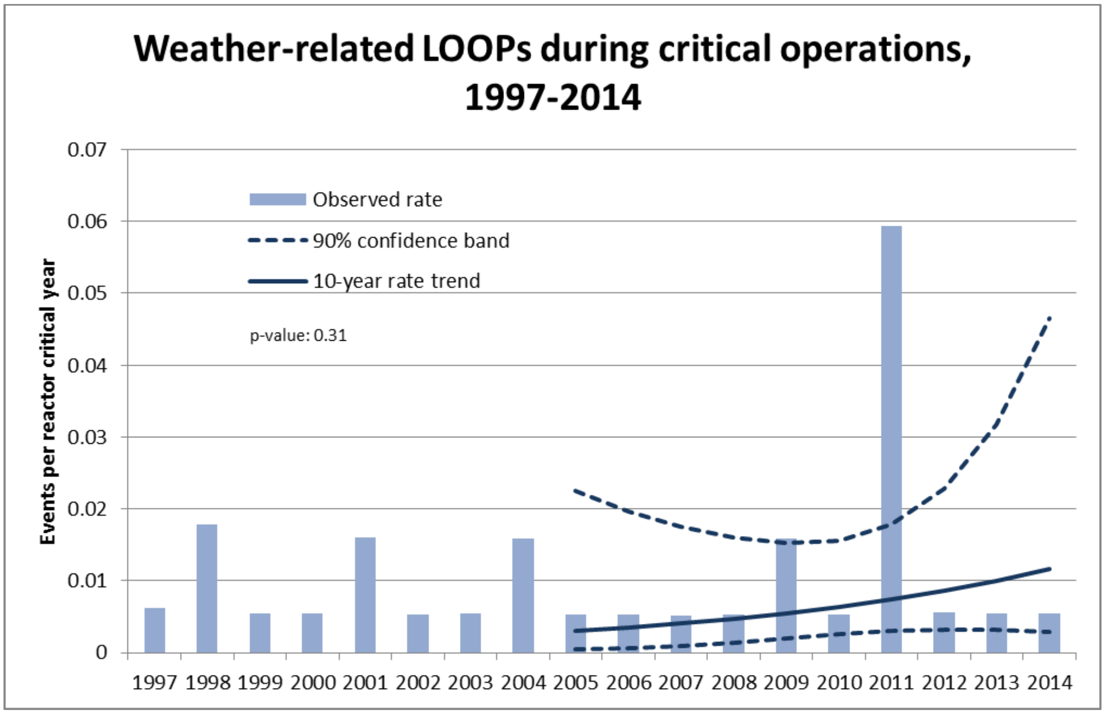

Figure 5. 10-year trend, weather-related LOOPs during critical operation.

1.1 Variation among plants

Whenever industry average data are used in the PRA for a single plant, the question arises as to whether all plants nationwide are really directly comparable to a specific plant, or whether there is significant plant-to-plant variation in incident rates. In the latter case, the shape and scale parameters of a gamma distribution are typically presented in sources such as [5].

The data are usually inadequate to tightly constrain the amount of variation among plants, except in the case of the most frequent events like general transients or individual pumps failing to start. One can either report a single-point maximum likelihood estimate for plant to plant variation (see Section 8.2 of [2]), seek expert elicitation of how much variation among plants is reasonable, or impose an arbitrary Bayesian hyperprior to prevent ($\boldsymbol{\alpha} \rightarrow \infty, \boldsymbol{\beta} \rightarrow \infty$) or ($\alpha = 0, \beta = 0$) estimates (see Section 1.3 of [3].)

Table 2 presents gamma distributions describing plant-to-plant variation in LOOP frequencies, using a $\left(\boldsymbol{\alpha} + \boldsymbol{\alpha}^{-1}\right)^{-1}\left(\boldsymbol{\beta} + \boldsymbol{\beta}^{-1}\right)^{-1}$hyperprior. For each distribution, the 5th, 50th, and 95th percentiles, as well as the mean, are tabulated. One could select numbers from Table 2 to use as priors to be updated with plant-specific information (α = alpha from table plus plant-specific events, β = beta from table plus plant-specific exposure time), but the LOOP annual update is not intended to be a substitute for proper analysis to select event frequencies for use in a PRA.

Table 3 reports the number of LOOPs during critical operation, grouped by electric reliability council. Just as variation among plants can be described as discussed above, the variation in LOOP frequencies among reliability councils can be modeled in the same way: a gamma ($\alpha = 1.75$, $\beta = 55.5$) distribution was found to best describe variation among councils. Table 3 also reports bounds on each council's mean reliability, by updating that prior with council-specific data for each council.

It is, in principle, possible to group the data in any number of ways - by season, by year, by site, by state, by proximity to the coast, by region - and characterize how much variation exists among subgroups. Doubtless such variations do exist: rolling blackouts in California, hurricanes along the Gulf Coast, and ice storms in the Northeast have all been in the news in recent years. Attempting to model all such variations is beyond the scope of the LOOP report. Modeling factors specific to a particular area properly falls in the domain of preparing PRAs for plants in that area.

Table 2. Gamma distributions describing plant to plant variation.

LOOP type	Mode	Gamma shape parameter (α)	Gamma scale parameter (β)	5%	Median	95%	Gamma mean	Simple MLE	Comments
Grid-related	Critical operation	0.98	85.0	5.59E-04	7.91E-03	3.48E-02	1.15E-02	1.08E-02	1
Plant-centered		0.27	109.4	1.07E-07	5.15E-04	1.18E-02	2.49E-03	1.81E-03	2
Switchyard-centered		1.25	69.2	1.51E-03	1.35E-02	5.00E-02	1.80E-02	1.33E-02	1
Weather-related		0.60	96.6	5.63E-05	3.23E-03	2.23E-02	6.17E-03	5.42E-03	1
Grid-related	Shutdown	0.37	14.7	1.39E-05	8.11E-03	1.07E-01	2.49E-02	1.94E-02	2
Plant-centered		0.34	9.0	1.31E-05	1.15E-02	1.68E-01	3.84E-02	3.40E-02	3
Switchyard-centered		0.76	8.9	2.00E-03	5.22E-02	2.82E-01	8.55E-02	7.77E-02	1
Weather-related		0.44	9.3	8.78E-05	1.89E-02	1.89E-01	4.71E-02	3.89E-02	1

1. MLE is homogeneous. The data rule out the possibility of wide variations among plants.
2. Essentially no constraint on whether variation among plants exists, due to sparse data.
3. MLE predicts some variation among plants. The amount of variation possible is relatively well constrained.

Table 3. LOOP frequencies by reliability council, 1997-2014.

Reliability Council	#LOOPs	Critical years	Gamma shape parameter (α)	Gamma scale parameter (β)	5%	Median	95%	Gamma mean	Simple MLE
East Central	3	119.06	4.75	174.5	1.04E-02	2.53E-02	5.05E-02	2.72E-02	2.52E-02
Florida	0	65.91	1.75	121.4	2.14E-03	1.18E-02	3.57E-02	1.44E-02	0.00E+00
Texas	1	75.04	2.75	130.5	5.30E-03	1.86E-02	4.54E-02	2.11E-02	1.33E-02
Mid-America	8	274.66	9.75	330.1	1.59E-02	2.85E-02	4.66E-02	2.95E-02	2.91E-02
Mid-Atlantic	7	182.55	8.75	238.0	1.90E-02	3.54E-02	5.93E-02	3.68E-02	3.83E-02
Mid-Continent	0	94.37	1.75	149.8	1.74E-03	9.55E-03	2.89E-02	1.17E-02	0.00E+00
Northeastern	12	177.43	13.75	232.9	3.55E-02	5.76E-02	8.74E-02	5.90E-02	6.76E-02
Southeastern	13	451.05	14.75	506.5	1.79E-02	2.85E-02	4.26E-02	2.91E-02	2.88E-02
Southwestern	3	97.69	4.75	153.2	1.19E-02	2.89E-02	5.75E-02	3.10E-02	3.07E-02
Western	5	122.54	6.75	178.0	1.75E-02	3.61E-02	6.47E-02	3.79E-02	4.08E-02

Table 4. Summary of all LOOP data, 1987-2014.

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

2. LOOP Duration and Recovery

For all LOOP events for which recovery times were available[2], the durations of the outages were modeled by lognormal distributions. A separate distribution was fitted for each LOOP type. Previous LOOP updates found that no significant differences existed in recovery times between critical and shutdown operations. The assumption has not been revisited in recent years.

The parameters of these four lognormal distributions are reported in Table 5. 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: $\mathbf{exp}(\boldsymbol{\mu}), \mathbf{exp}(\boldsymbol{\mu} + \frac{\boldsymbol{\sigma}^2}{\mathbf{2}}), \boldsymbol{and}\ \mathbf{exp}(\boldsymbol{\mu} + \mathbf{1.645}\boldsymbol{\sigma})$, respectively. These four distributions are plotted as probability-of-exceedance curves (1-*F* (*t*)) in Figure 6.

Table 5. Fitted lognormal recovery time distributions.

LOOP type	Grid-related	Plant-centered	Switchyard-centered	Weather-related
# events	21	10	35	17
Mu (μ)	0.74	0.12	0.86	2.13
Standard error of μ	0.27	0.68	0.28	0.48
Sigma (σ)	1.26	2.15	1.66	1.99
Standard error of σ	0.41	1.07	0.41	0.73
Fitted median	2.09	1.13	2.36	8.40
Fitted mean	4.61	11.35	9.33	60.68
Fitted 95th percentile	16.54	38.70	36.10	221.31

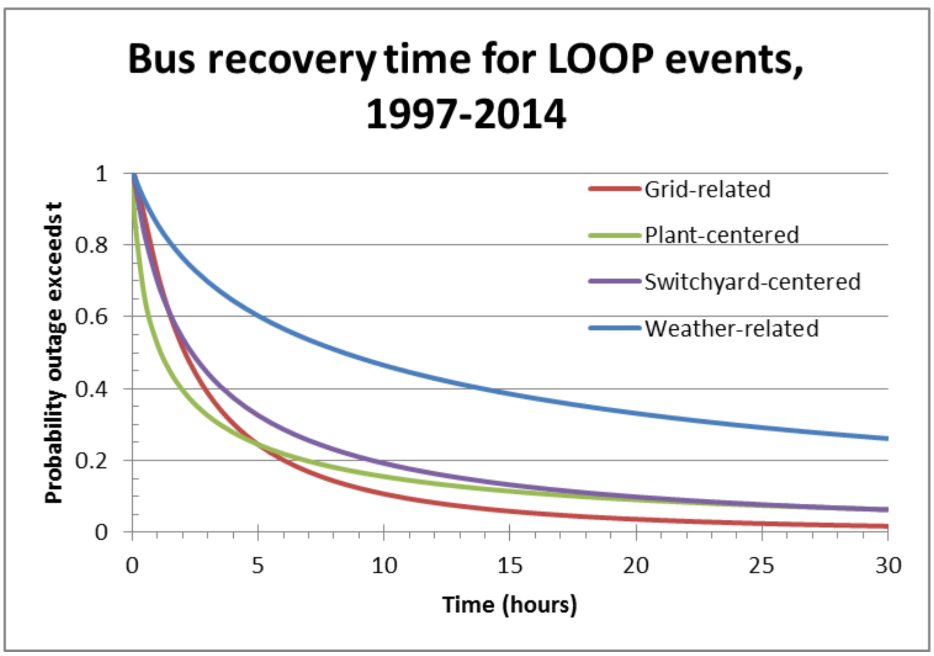

Figure 6. Fitted recovery time distributions.

[2] There are four events between 1997 and 2014 in INL's database for which duration information is not available: Seabrook, 10 August 1988; Quad Cities 1, 02 April 1991; Monticello, 17 September 2008; and Oyster Creek, 12 July 2009

The above analysis assumes that it is reasonable to pool recovery times from 1997 to the present. In fact, there is a mild but statistically significant trend toward longer recovery times in recent years. Table 6 shows the equations of best fit: the reported slopes are a measure of how much μ changes annually. The trend toward longer recovery times is most significant in groups with the largest sample sizes (switchyard-centered and grid-related LOOPs), but appears to be fairly consistent across all groups. For grid-and weather-related LOOPs this may simply be a reflection of the situation in the wider electric utility industry; for plant- and switchyard-centered LOOPs, it may be possible for plant owners to take action to reverse this trend.

Table 6. Results of loglinear regression of LOOP durations.

Subset	# events	Equation	SE of slope	p-value
All LOOPs	83	Exp(.162 x (year-2014) + 2.412)	0.032	3.17E-6
Grid-related	21	Exp(.218 x (year-2014) + 2.724)	0.054	7.48E-4
Plant-centered	10	Exp(.082 x (year-2014) + 1.052)	0.126	5.37E-1
Switchyard-centered	35	Exp(.170 x (year-2014) + 2.216)	0.038	8.44E-5
Weather-related	17	Exp(.118 x (year-2014) + 3.090)	0.096	2.38E-1
Critical operations	49	Exp(.176 x (year-2014) + 2.503)	0.044	2.44E-4
Shutdown operations	34	Exp(.148 x (year-2014) + 2.289)	0.054	9.63E-3

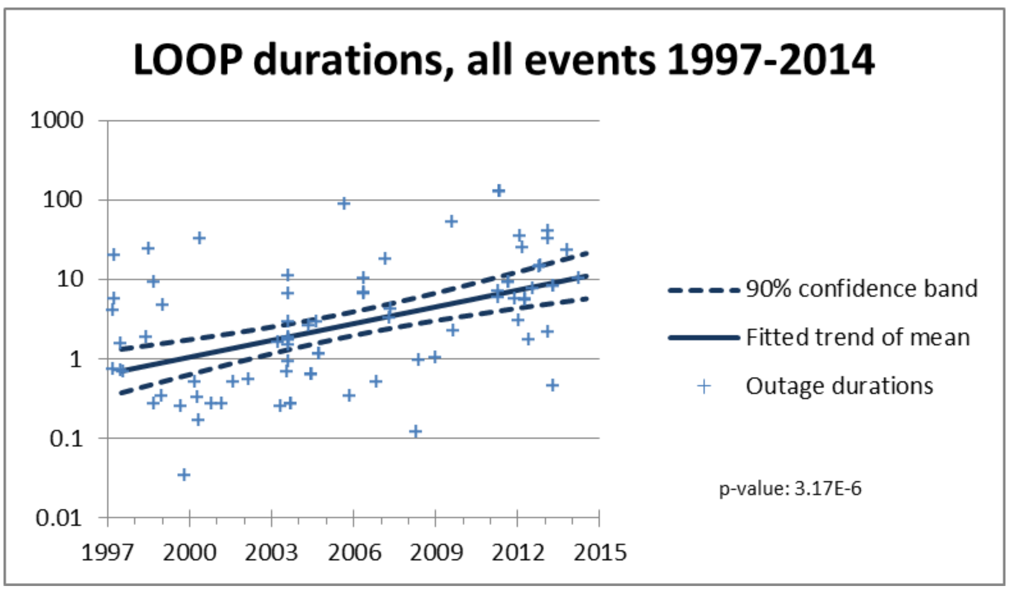

Figure 7. Trend to increasing LOOP durations (all event types).

3. 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 LOOP NUREG prepared by Atwood et al. in 1996 [1]. The topic of unreliability of EDGs is broken down into four components: probability that the EDGE is unavailable due to the component being offline (e.g. for routine maintenance) at the time of a demand; probability of failing to start on demand; probability of failing to run for the first hour after starting; and a per-hour failure probability thereafter. This topic is no longer part of the LOOP annual update, but is covered in a standalone report, the Enhanced Component Performance Study, which is periodically updated. The most recent version (currently [8]) is available for download at (http://nrcoe.inel.gov/resultsdb/CompPerf/).

As of FY2016, the topic of EDG repair times is not covered in the component study and remains part of the LOOP annual update. Lacking data on repairs performed under actual emergency conditions, this question is approached by examining how many hours of unplanned unavailability have been reported for each EDG from 2005 to 2014 in the Mitigating Systems Performance Index (MSPI) data.

Atwood et al. fitted a Weibull distribution to the repair time data, and the Weibull distribution continues to be the best fitting common distribution to the data set as a whole. For the 2005-2014 data, the distribution of best fit is a Weibull with shape parameter 0.703 and scale parameter 19.552. The probability of exceeding any given time can be calculated in Microsoft Excel 2010 with the formula "=1-WEIBULL.DIST (*t*, 0.703, 19.552, TRUE)." Exceedance probabilities for selected recovery times have been tabulated in Table 7.

Also reported in Table 7 are the actual fractions of the 1093 raw observations in the MSPI database that exceed the specified time. Note that the correspondence between fitted and observed distributions is very good at short to moderate times, but is less good at very long repair times. 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.

Table 7. Probability of exceeding selected EDG repair times.

Recovery time (hr)	Weibull model	Observed data
1	0.884	0.903
2	0.818	0.843
3	0.765	0.800
4	0.721	0.751
5	0.682	0.700
6	0.647	0.656
11.4	---	0.500
11.61	0.500	---
12	0.492	0.476
24	0.315	0.271
36	0.215	0.189
48	0.152	0.126
57.75	---	0.100
64	0.100	---

4. Seasonal variation in LOOP frequency

Raughley and Lanik called attention in 2003 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." [7] They did not perform a formal statistical test [3] 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 or addressing the basis for choosing May to September as “the five summer months.”

That arbitrary grouping, highlighting the increased stress on the grid during summer air-conditioning season, may not be appropriate for all purposes: the hurricane season, for instance, runs through late summer into early winter, so any effect of hurricanes on the weather-related LOOPs will not be discovered by this grouping. In practice, no simple pattern emerges in the weather-related LOOPs (different types of adverse weather happen at different times of the year), but a significant clustering of switchyard-based events in the January to May time period exists and was being hidden by the previous summer/non-summer grouping.

Table 8. LOOP events 1997-2014, counted by month, type, and plant status.
* - The northeast blackout of 14 August 2003 affected 8 plants simultaneously.

	Critical Operations				Shutdown operations			
Month	Grid	Plant	Switchyard	Weather	Grid	Plant	Switchyard	Weather
Jan	0	0	2	0	0	0	1	0
Feb	0	0	4	0	0	0	1	1
Mar	0	0	0	1	0	1	4	0
Apr	0	2	3	5	1	2	3	1
May	0	1	7	0	1	1	1	0
Jun	3	0	1	1	1	0	0	0
Jul	2	0	2	0	0	0	0	0
Aug	10*	0	2	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

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 whether points are distributed uniformly around a circle (wind directions, fracture orientations) that adapts readily to testing whether seasonal treads exist. [6]

Applying the Rayleigh Test to the count data in Table 8, statistically significant seasonality is present for grid-related LOOPs during critical operations ($\boldsymbol{p = .0005}$) and for switchyard-centered LOOPs

[3] A simple 2-sample z-test on the proportions gives $p < .03$, 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.

during critical operations($\boldsymbol{p} = .\mathbf{010}$). Driven by those two subgroups, the distribution of LOOPs as a whole shows a significant seasonality.

For the purposes of the above analysis, the blackout of 14 August 2003 was treated as a single event rather than counting it eight times (so 3, rather than 10, August critical grid-related LOOPs were counted.) There is room for further refinement of the methodology (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, etc.) and for giving formal estimates of when the peak time is and the strength of the seasonality, but for FY2016 we simply introduce the Rayleigh test as the recommended method of assessing seasonality.

5. Dependence among LOOP events

The analysis in Section 4 counted each plant that experienced a loss of offsite power, and the trending and distribution-fitting treated these data as if each LOOP were an independent event. This is not quite true - most spectacularly demonstrated on 14 August 2003, when a large power blackout affected 9 plants (8 critical and 1 in shutdown) at 7 sites. There were 7 occasions between 1986 and 1996, and 12 occasions between 1997 and 2014, when more than one plant was affected by the same incident. Those twelve occasions contributed fully 33 of the 87 events counted in Table 1 (38%). This calls the simplifying assumption of treating each LOOP as independent into serious question.

In general, there is a 3-part question to be answered: what is the frequency of the underlying event? How many sites will be affected by the event? How many plants at each site will be affected by the event? The details are different for each type of LOOP:

- A weather event has some (moderately low) probability of affecting more than one site within a few hours to a few days, and (considerably higher) of affecting more than one plant at the same site.
- A grid event has some probability of affecting multiple sites, even sites hundreds of miles away (the probability of affecting 2 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 event may affect more than one plant at the same site, depending 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[4].

Previous LOOP updates included a special topic titled “multi-unit site considerations,” which attempted to calculate 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 units 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.

INL staff plan to work on a comprehensive approach to accounting for this dependence in 2016, to be ready for publication in 2017. One expected result of that analysis is a widening of the confidence bands in Figures 1-5 especially for grid-related LOOPs.

[4] The only exception to date was at Catawba on 04 April 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 LOOP.)

6. Engineering analysis of LOOP data

LOOP events can also be classified as to the cause of the failure (what type of weather event caused a weather-related LOOP, and what kind of human activity or equipment failure caused one of the other types of LOOP) to provide additional qualitative insights.

Figure 8 categorizes LOOPs due to equipment failure by failed component. From 1997 to 2014, the two largest subcategories were failed circuits and transformers. A large number of transformer failures occurred 1986-1996; 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 9 categorizes LOOPs due to human error by the type of activity in progress at the time. There have been very few LOOPs due to human error since 1997, nearly a 90% reduction compared to 1996 and before.

Figure 10 categorizes weather-related LOOPs by the type of natural disaster. Since 1997 the most common causes of weather-related LOOPs have been tornadoes and hurricanes. In 1986 -1996 the most common causes were lightning and high winds. The breakdown between critical and shutdown operations reflects the fact that tornadoes and lightning strike with little warning while hurricane paths are forecast days in advance, enabling plants to preemptively shut down before the storm arrives.

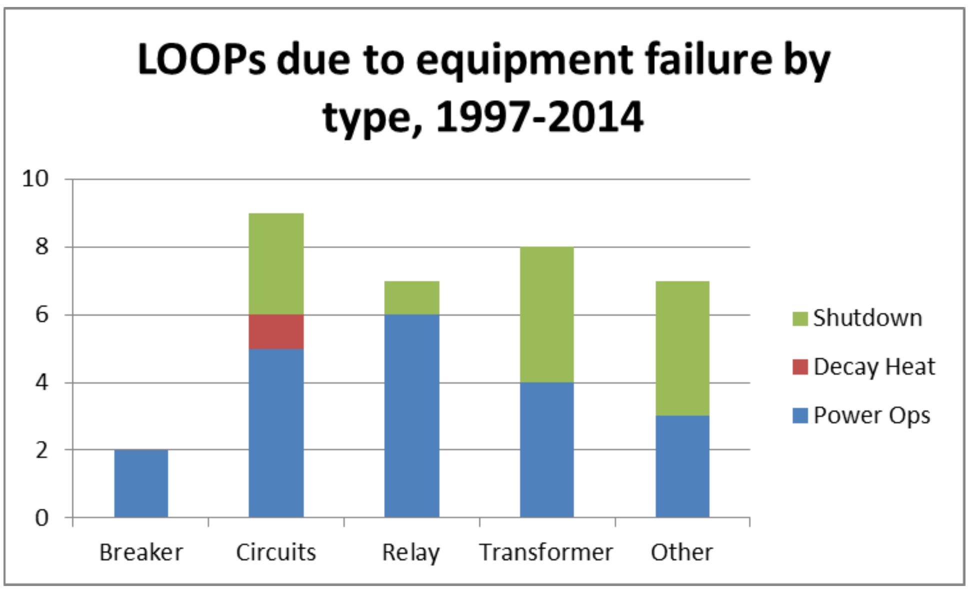

Figure 8. LOOP equipment failures by type.

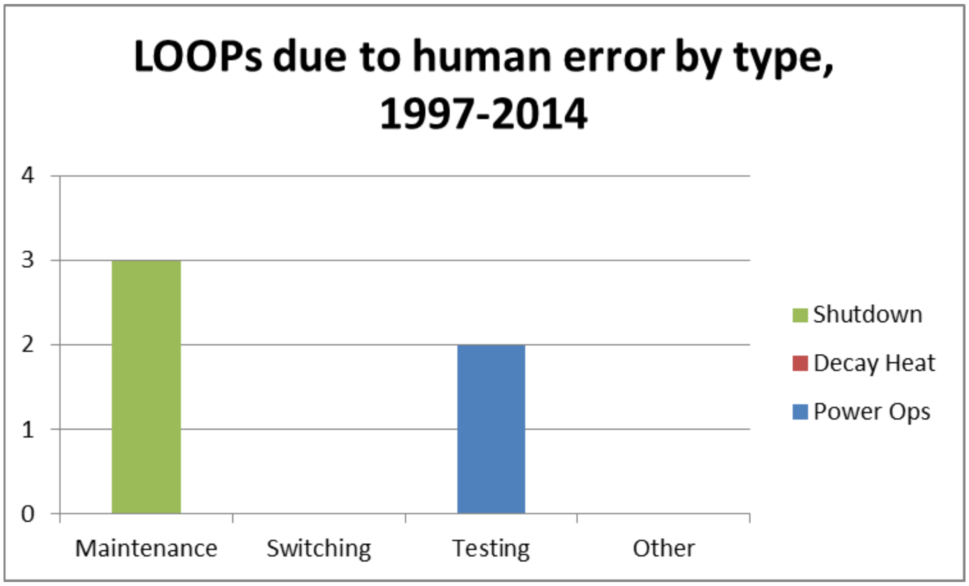

Figure 9. LOOPs due to human error by cause.

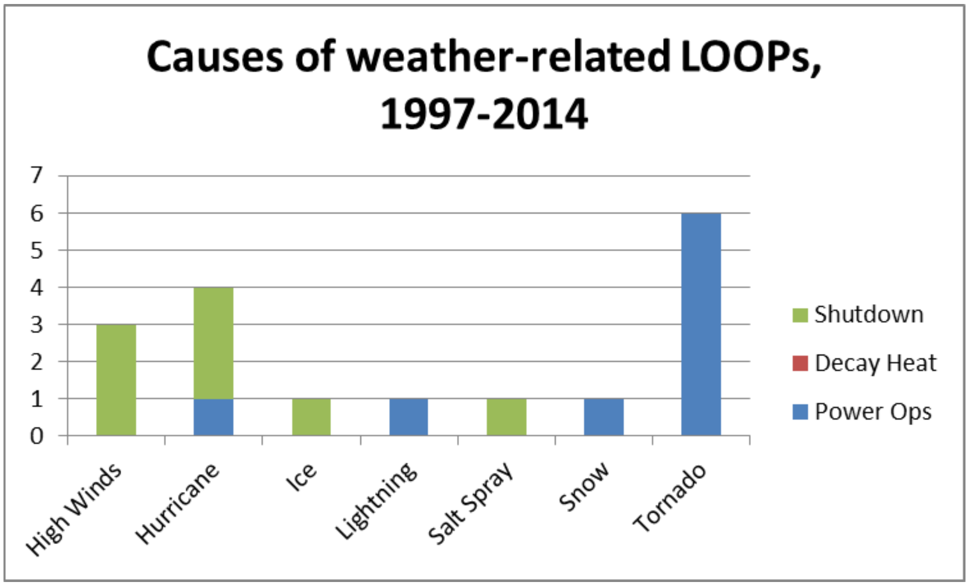

Figure 10. Weather-related LOOPS by cause.

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