Analysis of Loss of Offsite Power Events

2004 Update

The availability of alternating current (ac) power is essential for safe operation and accident recovery at commercial nuclear power plants. Normally, ac power is supplied by offsite sources via the electrical grid. Loss of this offsite power can have a major negative impact on a power plant's ability to achieve and maintain safe shutdown conditions. Risk analyses performed for U.S. commercial nuclear power plants indicate that the loss of all ac power contributes over 70% of the overall risk at some plants. Clearly, loss of offsite power (LOOP, also referred to as LOSP) and subsequent restoration of offsite power are important inputs to plant probabilistic risk assessments (PRAs). These inputs must reflect current industry performance in order for PRAs to accurately estimate the risk from LOOP initiated scenarios.

This study is a statistical and engineering analysis of LOOP frequencies and durations at commercial nuclear reactors in the U.S. LOOP data for 1986–2004 were collected and analyzed. The data cover both critical (at power) and shutdown operations at these plants. Partial LOOP events, in which not all offsite power lines to the plant are lost or not all offsite power to safety buses is lost, are not covered in this report.

1. LATEST VALUES AND TRENDS

LOOP industry frequencies were determined for four LOOP event categories: plant centered, switchyard centered, grid related, and weather related. In addition, these frequencies were subdivided into results for critical and shutdown operation. Table 1 summarizes these results (plant-specific LOOP frequencies are presented in Reference 1).

Table 1. Plant-level LOOP frequencies.

		Plant-Level LOOP Frequency				
Mode	LOOP Category	Data Period	Events	Reactor Critical or Shutdown Years	Mean Frequency[a]	Frequency Units[b]
Critical operation	Plant centered	1997–2004	1	724.3	2.07E−03	/rcry
	Switchyard centered	1997–2004	7	724.3	1.04E−02	/rcry
	Grid related	1997–2004	13	724.3	1.86E−02	/rcry
	Weather related	1997–2004	3	724.3	4.83E−03	/rcry
	All	1997–2004	—	—	3.59E−02	/rcry
Shutdown operation	Plant centered	1986–2004	19	383.2	5.09E−02	/rsy
	Switchyard centered	1986–2004	38	383.2	1.00E−01	/rsy
	Grid related	1986–2004	3	383.2	9.13E−03	/rsy
	Weather related	1986–2004	13	383.2	3.52E−02	/rsy
	All	1986–2004	—	—	1.96E−01	/rsy

a. The mean is a Bayesian update using a Jeffreys prior. Mean = (0.5 + events)/(critical or shutdown years).
b. The frequency units are per reactor critical year (/rcry) or per reactor shutdown year (/rsy).

For critical operation, grid-related LOOPs contribute 52% to the total frequency of 3.6E−2 per reactor critical year (/rcry), while switchyard-centered LOOPs contribute 29%. The remaining two categories of LOOPs have frequency contributions of 13% (weather related) and 6% (plant centered). For shutdown operation, switchyard-centered LOOPs contribute 51% to the total frequency of 2.0E−1 per reactor shutdown year (/rsy), while plant-centered LOOPs contribute 26%.

The August 14, 2003, grid disturbance that resulted in LOOPs at nine plants is included in the frequency estimates in this report. No other event of this magnitude has occurred from 1968 through 2004. We cannot predict how often this type of event might occur in the future. If the August 14, 2003, event is an outlier and will not be repeated in the near future, then the grid-related frequency presented in this report is an overestimation. (If that event had not occurred, the overall LOOP frequency for critical operation would have been 2.5E−2/rcry rather than 3.6E−2/rcry.) However, if such events continue to occur, then the frequency presented in this report may be an underestimation.

1.1 Trends

Trend plots for all four LOOP event categories and all LOOPs combined during critical operation are presented in Figure 1 through Figure 5. These figures show trends over two periods: 1986–1996 and 1997–2004. For plant-centered and switchyard-centered LOOPs, industry performance has improved considerably since 1986–1996. The corresponding trend analyses indicate p-values close to 0.05, which is a typical statistical measure indicating existence of a significant[1] trend. Therefore, the baseline period for determining industry frequencies representative of current performance is 1997–2004. As indicated in Figure 1 and Figure 2, the industry performance over this recent period is constant. In contrast, for grid-related LOOPs, performance has worsened recently because of 2003 and 2004, as indicated in Figure 3. The 2003 and (perhaps 2004) data are considered potential outliers. (Future industry performance will indicate whether 2003 and 2004 are actually outliers or are the start of an increasing trend as indicated in the figure.) Again, the baseline period for grid-related LOOPs is 1997–2004, to capture this more recent industry performance. Finally, for weather-related LOOPs, Figure 4 indicates no significant trend over the entire period covered, 1986–2004. However, the period 1986–1996 shows no events during 1986–1992, but several during 1993–1996. The resulting analysis indicates an increasing trend that is close to being significant (a p-value of 0.1). Therefore, the baseline period used is 1997–2004 in order to capture the more recent events. Figure 5 presents the trend plot for all LOOPs combined. There is a downward trend that is close to being significant (p-value of 0.052) in the combined LOOPs during critical operation over the period 1986–1996. There is no significant trend over the period 1997–2002. However, 2003 resulted in a large jump in the number of LOOPs because of the single August 14, 2003, grid blackout that resulted in LOOPs at nine plants (eight of which were in critical operation). Over the entire 1997–2004 period, an increasing trend is shown, resulting from 2003 and 2004 data.

The industry mean frequency of LOOP events during critical operation (including momentary LOOPs) is 3.6E−2/reactor critical year, or 3.6E−2/rcry. This frequency is the sum of four contributions: 2.1E−3/rcry for plant-centered LOOPs (5.8%), 1.0E−2/rcry for switchyard-centered LOOPs (28.8%), 1.9E−2/rcry for grid-related LOOPs (51.9%), and 4.8E−3/rcry for weather-related LOOPs (13.5%).

[1] 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).

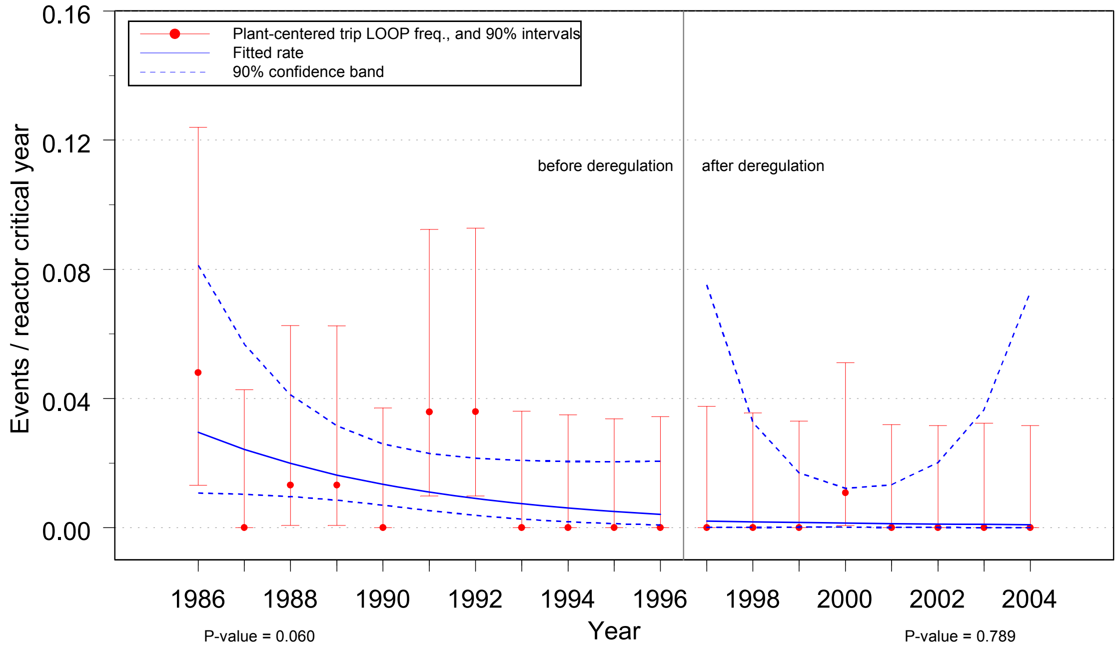


Figure 1. Trend plot of LOOP frequency for 1986–1996 and 1997–2004. Plant-centered LOOPs: trend plot of industry performance during critical operation.

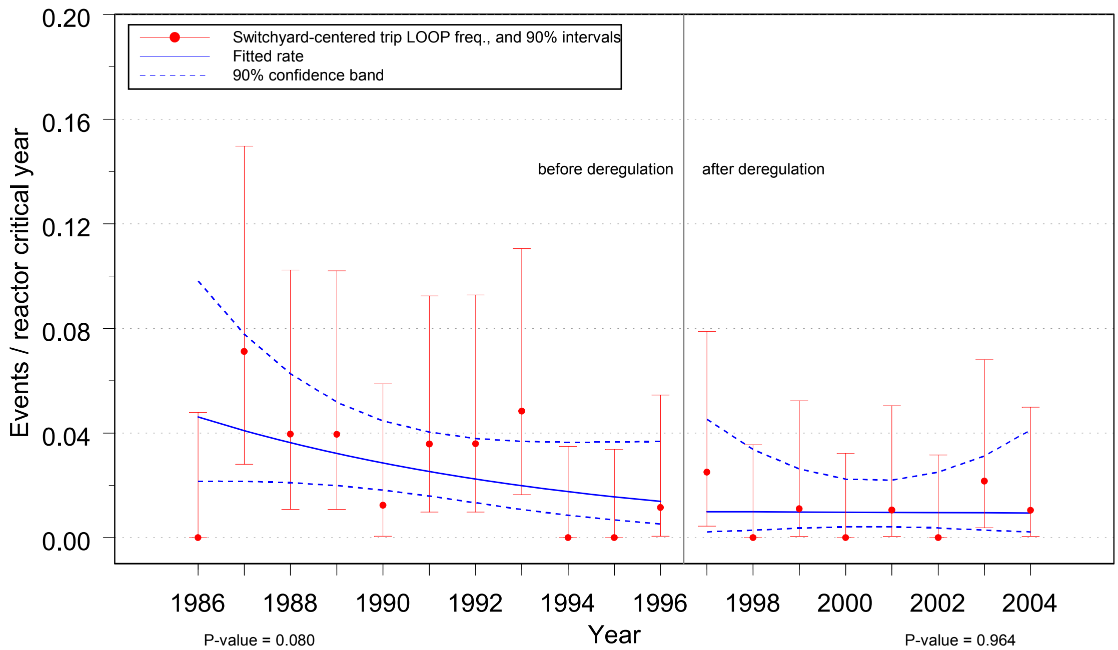
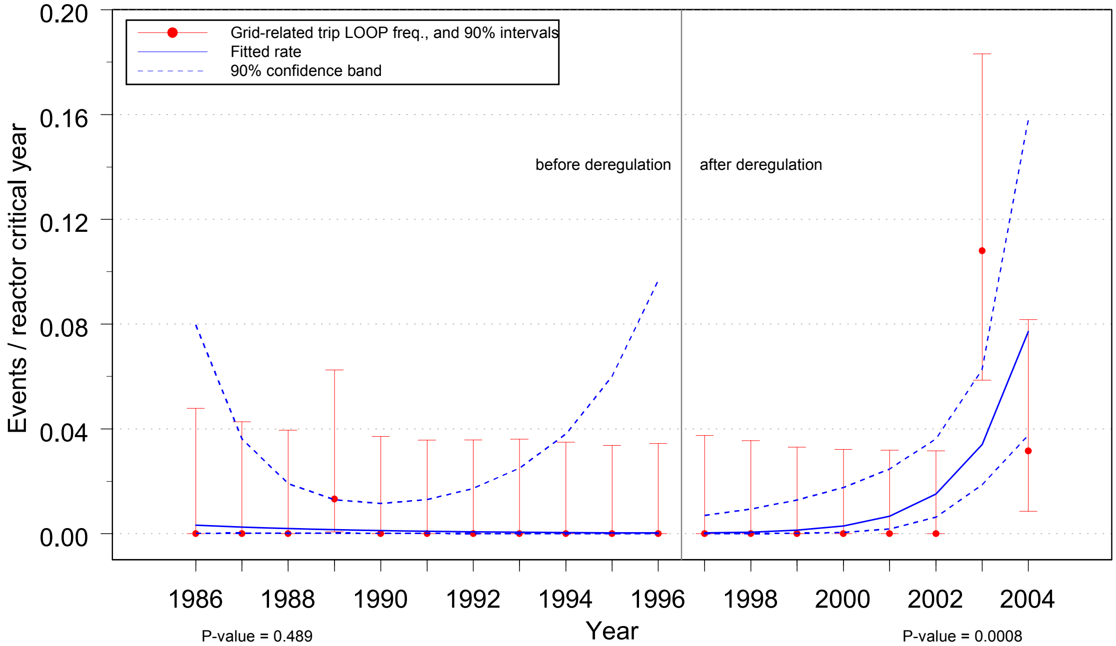


Figure 2. Trend plot of LOOP frequency for 1986–1996 and 1997–2004. Switchyard-centered LOOPs: trend plot of industry performance during critical operation.



Note: *The confidence interval for 2003 does not account for the dependence of the events and is, therefore, too narrow (by an undetermined amount).*

Figure 3. Trend plot of LOOP frequency for 1986–1996 and 1997–2004. Grid-related LOOPs: trend plot of industry performance during critical operation.

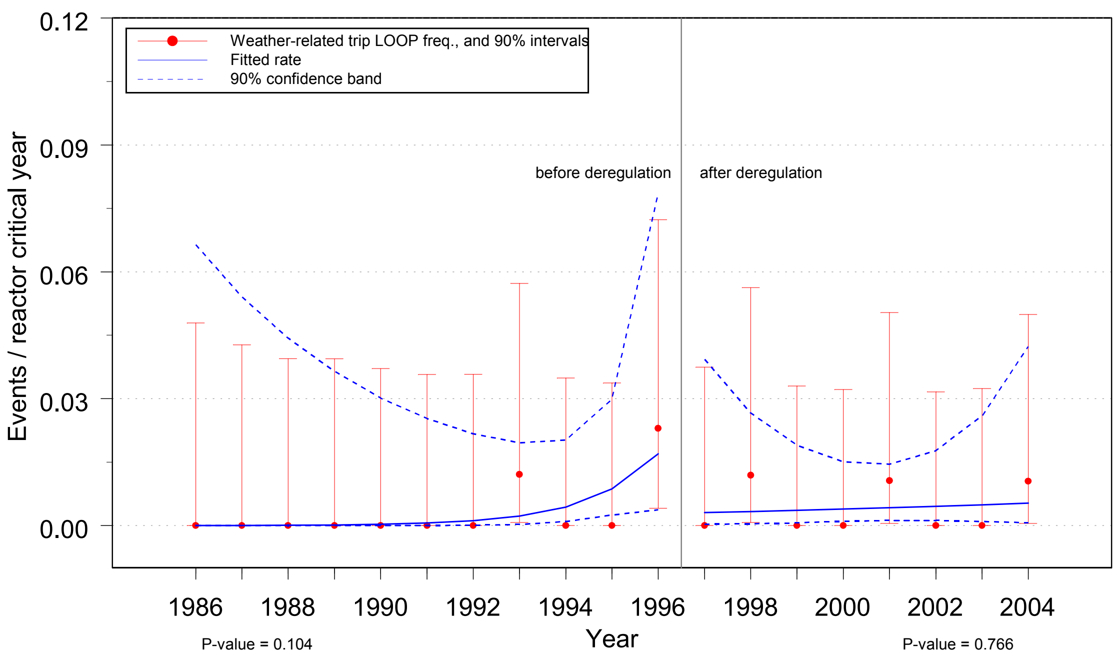
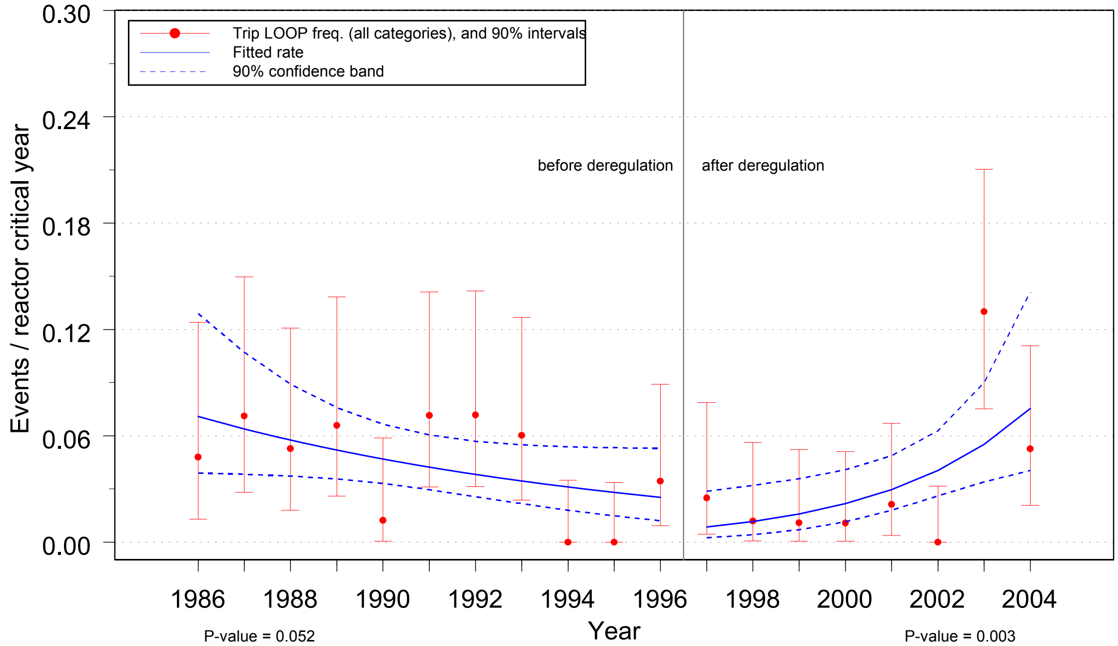


Figure 4. Trend plot of LOOP frequency for 1986–1996 and 1997–2004. Weather-related LOOPs: trend plot of industry performance during critical operation.



Note: *The confidence interval for 2003 does not account for the dependence of the events and is therefore too narrow (by an undetermined amount).*

Figure 5. Trend plot of LOOP frequency for 1986–1996 and 1997–2004. All LOOPs combined: trend plot of industry performance during critical operation.

Distributions for the industry LOOP frequencies in Table 1 are presented in Table 2. Presented are the 5%, median, mean, 95%, error factor (95%/median), and shape (α) and scale (β) parameters for the gamma distributions. For categories with limited data (nine or fewer events), the distribution was assumed to follow the constrained noninformative distribution (CNID) defined in the article "Constrained Noninformative Priors in Risk Assessment" [Reference 2]. The CNID has an error factor of 8.4 for gamma distributions. For categories with 10 or more events, empirical Bayes analysis was used to search for variability in the data using several grouping schemes: plant, site, various geographical areas, various electrical grid areas, year, and others. In cases where the empirical Bayes analyses identified more than one grouping with significant variability, a judgment call was made concerning which set of results to use. (See Appendixes B and C of Reference 1 for more information.) The 13 grid events during critical operation (Table 1) include eight resulting from a single grid disturbance on August 14, 2003, and three resulting from a single grid disturbance on June 14, 2004. This extreme dependence between events violates assumptions inherent in the empirical Bayes analysis, so the CNID was used as a default for this category. The uncertainty in the grid-related frequency might be larger than indicated by the CNID. Finally, the 13 weather events during shutdown (Table 1) include several dependencies, so the CNID was also used as a default for that category.

To determine the distributions for the overall LOOP frequencies for critical and shutdown operation, simulation was used. Results were then fit to a gamma distribution using a maximum likelihood estimate. For critical operation, the overall mean frequency of 3.6E−2/rcry has a lower bound (5%) of 4.6E−3/rcry and an upper bound (95%) of 9.2E−2/rcry. The error factor for this gamma distribution is 3.2. For shutdown operation, the overall mean frequency of 2.0E−1/rsy has a lower bound of 4.5E−2/rsy, an upper bound of 4.3E−1/rsy, and an error factor of 2.5.

Table 2. Plant-level LOOP frequency distributions.

Mode	LOOP Category	Plant-Level LOOP Frequency Distribution[a] 5%	Median (50%)	Mean	95%	Error Factor	Gamma Shape Parameter (α)	Gamma Scale Parameter (β, years)	Source[b]
Critical operation (1997–2004)	Plant centered[c]	8.14E−06	9.42E−04	2.07E−03	7.96E−03	8.44	0.50	241.43	CNID
	Switchyard centered[c]	4.07E−05	4.71E−03	1.04E−02	3.98E−02	8.44	0.50	48.29	CNID
	Grid related	7.33E−05	8.48E−03	1.86E−02	7.16E−02	8.44	0.50	26.83	CNID
	Weather related	1.90E−05	2.20E−03	4.83E−03	1.86E−02	8.44	0.50	103.47	CNID
	All	4.57E−03	2.87E−02	3.59E−02	9.19E−02	3.21	1.58	44.02	Simulation
Shutdown operation (1986–2004)	Plant centered[d]	8.42E−05	2.00E−02	5.09E−02	2.06E−01	10.31	0.43	8.45	EB (site)
	Switchyard centered[d]	7.66E−03	7.41E−02	1.00E−01	2.83E−01	3.82	1.19	11.84	EB (site)
	Grid related	3.59E−05	4.16E−03	9.13E−03	3.51E−02	8.44	0.50	54.74	CNID
	Weather related	1.39E−04	1.60E−02	3.52E−02	1.35E−01	8.44	0.50	14.19	CNID
	All	4.48E−02	1.70E−01	1.96E−01	4.33E−01	2.54	2.50	12.77	Simulation

a. The frequency units for 5%, median, mean, and 95% are per reactor critical year (/rcry) or per reactor shutdown year (/rsy).

b. CNID—constrained noninformative distribution, EB—empirical Bayes distribution, simulation—sum of 4 categories simulated and fit to gamma

c. For risk studies that combine the plant-centered and switchyard-centered LOOPs, the gamma distribution has $\alpha = 0.50$ and $\beta = 40.10$. The mean of this distribution is 1.25E−2/rcry.

d. For risk studies that combine the plant-centered and switchyard-centered LOOPs, the gamma distribution has $\alpha = 0.995$ and $\beta = 6.589$. The mean of this distribution is 1.51E−1/rsy.

1.2 LOOP Duration and Recovery

Probability of exceedance versus duration curves were generated for each of the four LOOP categories: plant centered, switchyard centered, grid related, and weather related. No significant differences exist between the critical operation and shutdown operation data within the distinct LOOP categories, so curves were generated combining both types of data. In addition, no significant differences exist within each LOOP category between the 1986–1996 and 1997–2004 data periods, so the entire 1986–2004 period is applicable.

The lognormal density and cumulative distribution functions used in this report are the following:

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

$$F(t) = \Phi\left[\frac{\ln(t)-\mu}{\sigma}\right] \quad (2)$$

where

t = offsite power recovery time

μ = mean of natural logarithms of data

σ = standard deviation of natural logarithms of data

Φ = error function.

The values that should be used for these equations are shown in Table 3. The definitions of the lognormal μ and σ parameters in Equations 1 and 2 are those found in Microsoft® Excel and the curve fitting software described in Appendix B of Reference 1.

Table 3. Lognormal fit parameters.

	Plant Centered	Switchyard Centered	Grid Related	Weather Related	Combined Plant and Switchyard Centered[a]
p-value	>0.25	>0.25	>0.25	>0.25	>0.25
Mu (μ)	−0.760	−0.391	0.300	0.793	−0.512
Sigma (σ)	1.287	1.256	1.064	1.982	1.278
Curve Fit 95% (h)	3.88	5.34	7.77	57.60	4.90
Curve Fit Mean (h)	1.07	1.49	2.38	15.77	1.36
Curve Fit Median (h)	0.47	0.68	1.35	2.21	0.60
Curve Fit 5% (h)	0.06	0.09	0.23	0.08	0.07
Error Factor (95%/median)	8.31	7.89	5.76	26.07	8.19

a. For plant risk models that combine the plant-centered and switchyard-centered LOOPs, this column should be used.
b. The LaCrosse and two Pilgrim events were excluded from these analyses. See Appendix A, Table A-1 of Reference 1 for more information.

The mean duration of a plant-centered LOOP is 1.7 h (curve fit to 1.07), and the mean duration for grid-related LOOPs is 2.4 h (curve fit to 2.38). The corresponding curves are presented in Figure 6. Statistical analyses indicated that the critical operation and shutdown operation LOOP data were similar for each LOOP category, so the duration information in Figure 6 is applicable to both types of operation.

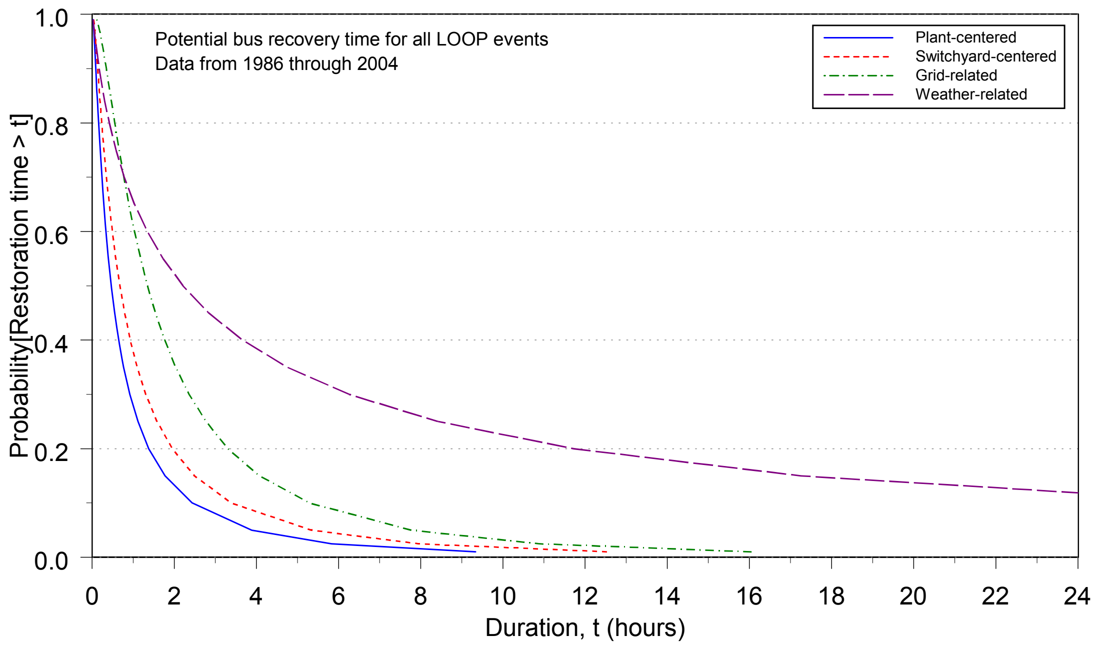
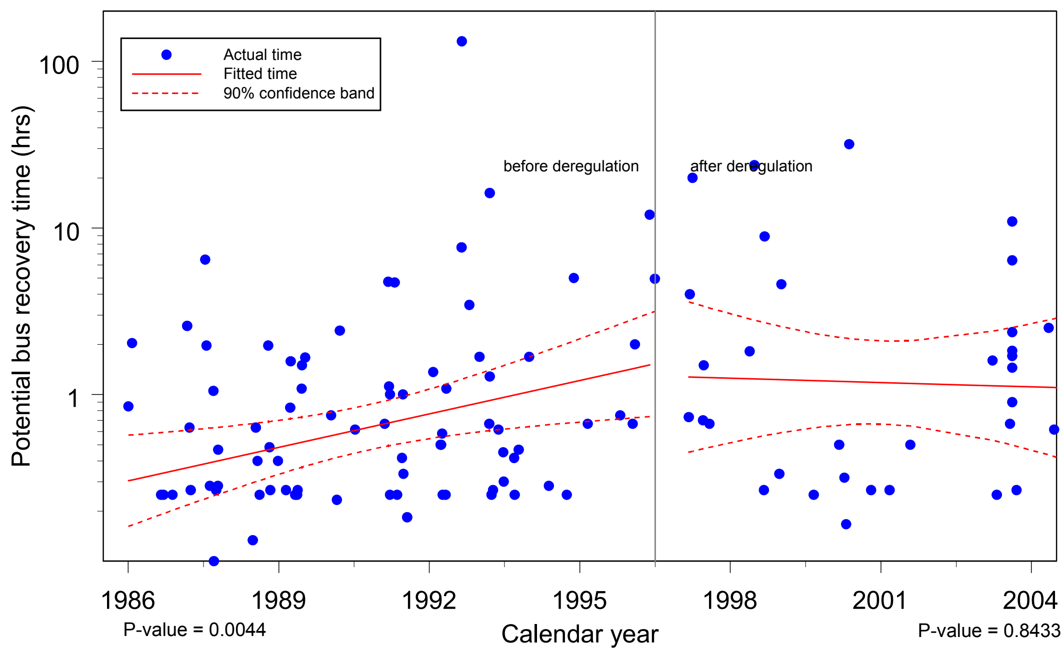


Figure 6. Probability of exceedance versus duration curves.

LOOP duration data for critical and shutdown operation over the entire period 1986–2004 were used to generate probability of exceedance versus duration curves for each of the four LOOP categories. Statistical analyses indicated that within each category, there was not a statistically significant difference between the 1986–1996 data and the 1997–2004 data. However, if all of the LOOP data are combined, a statistically significant increasing trend in durations is observed over the period 1986–1996. In contrast, the 1997–2004 duration data do not exhibit a significant trend. The results of this trending analysis are presented in Figure 7. Finally, if the entire period 1986–2004 is considered, there is no statistically significant trend in LOOP durations.



Note: *The increasing trend over 1986–1996 is statistically significant (p-value for the slope is 0.004), while the slightly decreasing trend over 1997–2004 is not statistically significant (p-value for the slope is 0.843).*

Figure 7. Trend plot of LOOP duration for 1986–1996 and 1997–2004 for critical and shutdown operation.

1.3 Seasonal Effects

NUREG-1784 (Reference 3) indicated that more recent LOOPs (switchyard centered and grid related) occur mostly during the five summer months (defined in that document as May through September). The LOOP data used for the present study were reviewed to determine if this seasonal effect exists within the four categories of LOOPs. Higher summer frequencies were found for all four categories for critical operation, but not for shutdown operation. This study analyzes each LOOP category over the periods 1986–1996 and 1997–2004 in order to identify seasonal differences between the two periods. Results for critical and shutdown operation are presented in Table 4. The results indicate no major seasonal effects on the shutdown overall LOOP frequency for either period. However, the critical operation LOOPs over the more recent period, 1997–2004, indicate a large seasonal difference in the overall LOOP frequency. This seasonal difference for the more recent period for critical operation results mainly from grid-related and switchyard-centered LOOPs. All three grid disturbance events (August 14, 2003, event contributing eight LOOPs; September 15, 2003, event contributing two LOOPs; and June 14, 2004, event contributing three LOOPs) occurred during the summer months. In addition, six switchyard-centered LOOPs occurred during the summer months, while only one occurred during the non-summer months.

Table 4. Plant-level LOOP events by season.

		1986–1996				1997–2004				
		Summer		Non-summer		Summer		Non-summer		
Mode	LOOP Category	Events	Mean Frequency[a]	Events	Mean Frequency[a]	Events	Mean Frequency[a]	Events	Mean Frequency[a]	Frequency Units[b]
Critical operation	Plant centered	5	1.45E−02	6	1.31E−02	1	4.80E−03	0	1.21E−03	/rcry
	Switchyard centered	11	3.02E−02	12	2.52E−02	6	2.08E−02	1	3.64E−03	/rcry
	Grid related	1	3.94E−03	0	1.01E−03	13	4.32E−02	0	1.21E−03	/rcry
	Weather related	2	6.57E−03	1	3.02E−03	2	8.01E−03	1	3.64E−03	/rcry
	All	19	5.52E−02	19	4.23E−02	22	7.69E−02	2	9.71E−03	/rcry
	Reactor Critical Years (rcry)	380.5	—	496.7	—	312.2	—	412.1	—	—
Shutdown operation	Plant centered	6	6.37E−02	8	4.81E−02	1	4.50E−02	4	6.31E−02	/rsy
	Switchyard centered	11	1.13E−01	20	1.16E−01	1	4.50E−02	6	9.12E−02	/rsy
	Grid related	1	1.47E−02	0	2.83E−03	2	7.51E−02	0	7.01E−03	/rsy
	Weather related	2	2.45E−02	7	4.25E−02	3	1.05E−01	1	2.10E−02	/rsy
	All	20	2.16E−01	35	2.10E−01	7	2.70E−01	11	1.82E−01	/rsy
	Reactor Shutdown Years (rsy)	102.0	—	176.6	—	33.3	—	71.3	—	—

a. The mean is a Bayesian update using a Jeffreys prior. Mean = (0.5 + events)/(critical or shutdown years).
b. The frequency units are per reactor critical year (/rcry) or per reactor shutdown year (/rsy).

2. ENGINEERING ANALYSIS OF LOOP DATA

This section reviews the LOOP events from an engineering perspective. The objective is to provide additional qualitative insights with respect to the LOOP events. Events were segregated according to specific causes. A breakdown of the equipment failures is presented in Figure 8, in which transformers dominate the results. Figure 9 presents a breakdown of human error events, in which maintenance activities contribute the largest fraction. Finally, Figure 10 shows the breakdown of weather-related LOOP events.

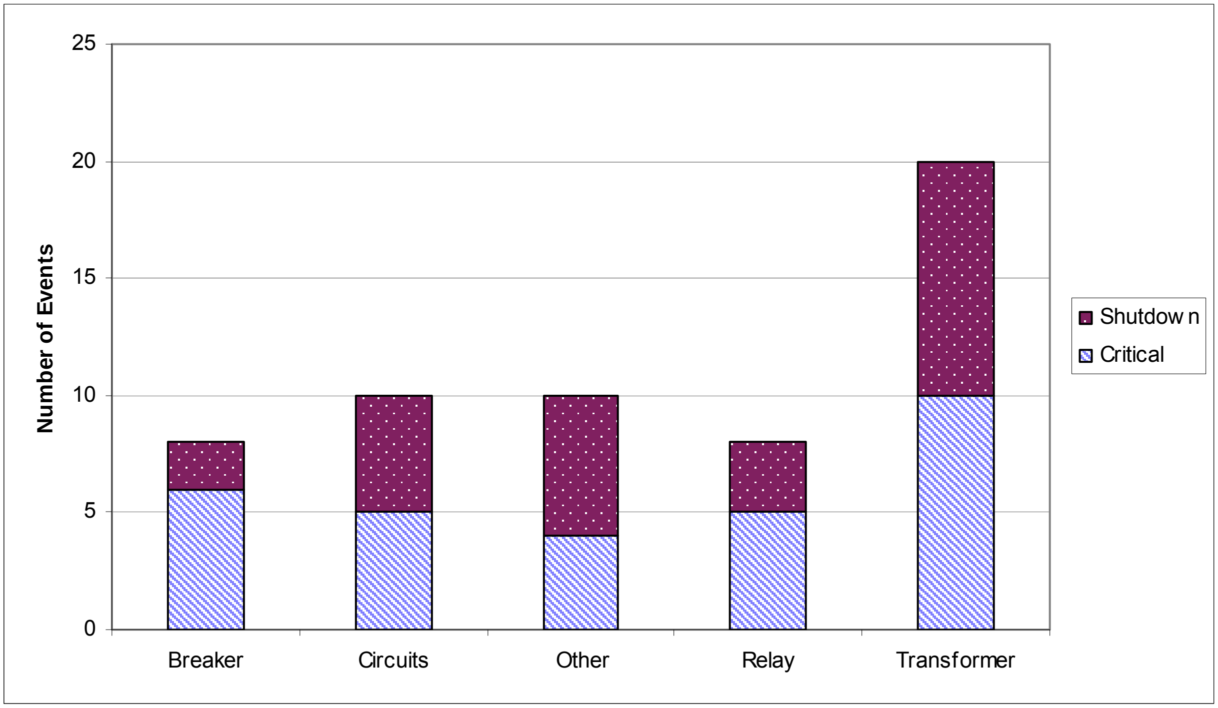


Figure 8. LOOP due to equipment failure by cause, 1986–2004.

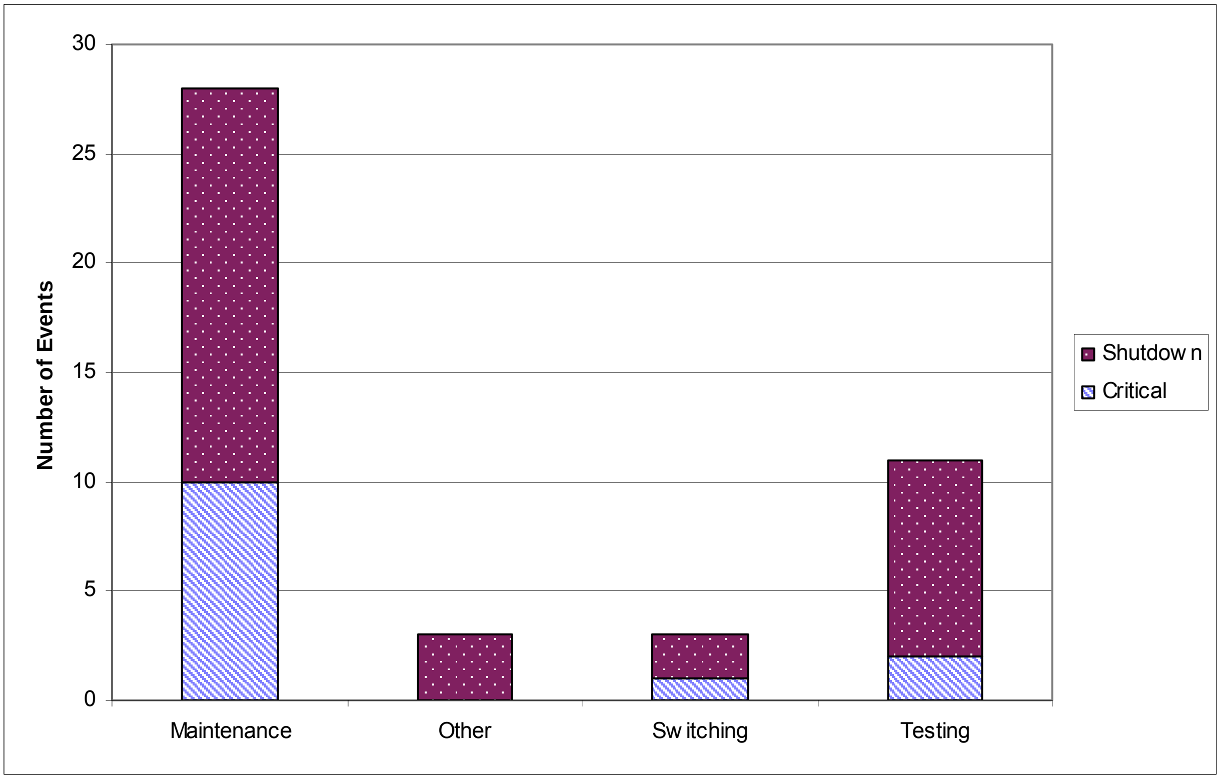


Figure 9. LOOP due to human error by type, 1986–2004.

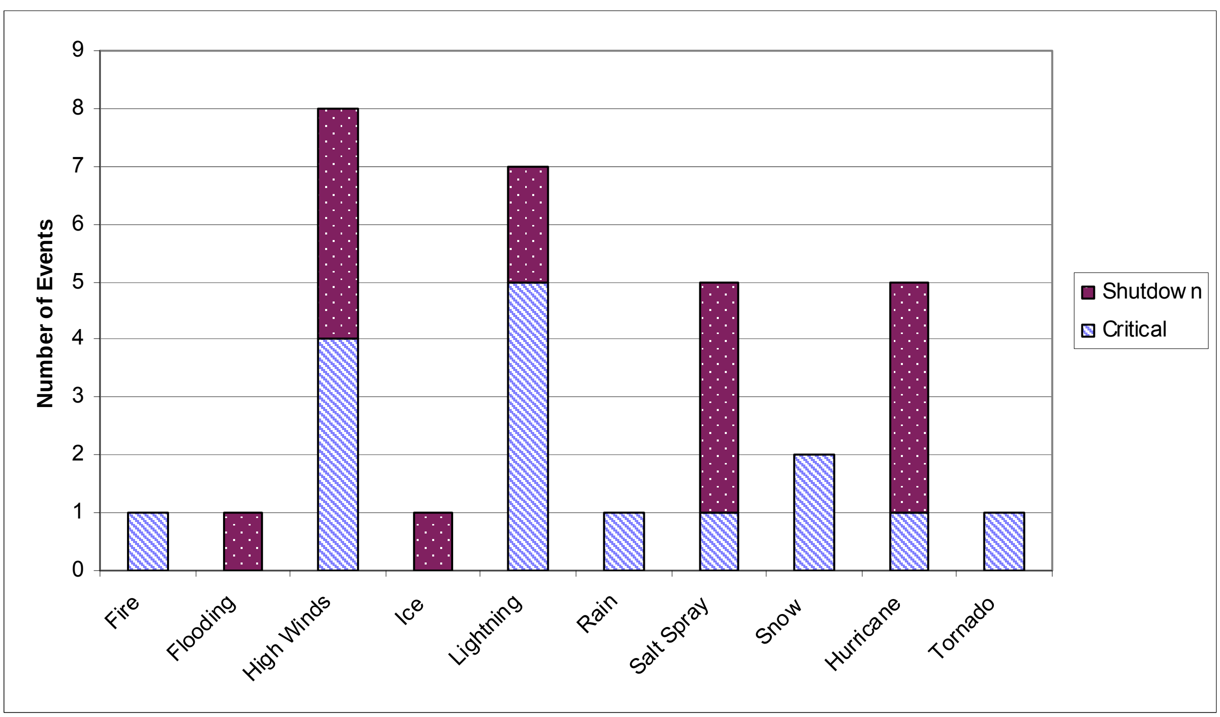


Figure 10. LOOP due to weather by cause, 1986–2004.

3. REFERENCES

1. S.A. Eide et al., *Reevaluation of Station Blackout Risk at Nuclear Power Plants*, U.S. Nuclear Regulatory Commission, NUREG/CR-6890, December 2005.
2. C. L. Atwood, "Constrained Noninformative Priors in Risk Assessment," *Reliability Engineering and System Safety*, Vol. 53, 1996, pp. 37–46.
3. W. S. Raughley, and G. F. Lanik, *Operating Experience Assessment—Effects of Grid Events on Nuclear Power Plant Performance*, U.S. Nuclear Regulatory Commission, NUREG-1784, December 2003.