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Evaluation of Loss of Offsite Power Events at Nuclear Power Plants: 1980 – 1996

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ABSTRACT

It is recognized that the availability of AC power to commercial nuclear power plants is essential for safe operations and accident recovery. A loss of offsite power (LOSP) event, therefore, is considered an important contributor to total risk at nuclear power plants. In 1988, the NRC published NUREG-1032 to report on an evaluation of the risk from actual LOSP events that had occurred at nuclear power plants within the United States up through 1985. This report documents a similar study whose primary objective was to update the LOSP model parameters, frequency and recovery time, using power plant event data from 1980 – 1996. An additional objective is to re-examine the engineering insights concerning LOSP events.

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EXECUTIVE SUMMARY

In 1988, NUREG-1032 estimated loss of offsite power (LOSP) frequency and duration, and the reliability of emergency diesel generators at commercial nuclear power plants in the United States. One primary objective of the present study is to update the LOSP model parameters, frequency and duration, for the time period 1980 – 1996, inclusive. These parameters are needed to estimate the risk of LOSP and station blackout (SBO) scenarios. The other primary objective is to re-examine the engineering insights from NUREG-1032, using the more recent data.

The present project includes LOSP events occurring at commercial nuclear power plants during 1980 through 1996, after the power plant unit's full power license date. For this study, LOSP was defined as simultaneous loss of electrical power to all unit safety buses, requiring the emergency power generators to start and supply power to the safety buses. For events that occurred during power operation, this report distinguishes between initiating events and non-initiators. At most power plants, a LOSP event causes the reactor to trip, but some designs permit the unit to continue operating at power, with the safety buses supplied by the emergency power generators. Also, in some of the events the reactor trip preceded the LOSP. For this study, the event was considered an initiating event if the LOSP caused the reactor to trip or if both the LOSP and the reactor trip were part of the same plant transient, resulting from the same root cause. It was not an initiating event if either no reactor trip occurred, or the cause of the reactor trip did not directly cause the LOSP event, but the reactor trip subsequently caused the LOSP event. All events included in this study are LOSP events, but only the initiating events were used in the frequency analysis.

Because one objective of this study was to produce results for use in risk analyses, the time to recovery was defined as the time until offsite power could have been restored to at least one safety bus from an alternate transformer source by use of approved licensee procedures. Often this coincided with the actual reported duration of the LOSP event, but sometimes it was shorter because a secondary source of offsite power was available but not used.

The LOSP events were grouped into three categories: plant-centered, grid-related, and caused by severe weather. They were also grouped according to the unit condition at the time of the event, either at power operation or in a shutdown. Finally, because about 15% of the events had very short recovery times, the events were classed as *momentary* if the recovery time was less than 2 minutes, and *sustained* if the recovery time was 2 minutes or more. For operating units, the frequency of LOSP initiating events was estimated. The non-initiators were not used in this estimate, even though those events might have been initiators had they occurred at other power plants. The frequencies were estimated separately for momentary and sustained events. For shutdown units, the frequency of LOSP events was estimated using all events. That is, the distinction between initiating events and non-initiators was not made for shutdown events; some of the shutdown events included in the analyses might not have caused a trip if they had occurred while the unit was at power. Again, the frequencies were estimated separately for momentary and sustained events. Finally, for each category of event, the times to recovery (for sustained events) were characterized. The unit condition, operating or shutdown, had little effect on the duration of the event, so it was ignored.

The analysis used various models, depending on what the data showed. For example, the frequencies of plant-centered LOSP event are presented in terms of units (individual power plants), but the frequencies of severe weather LOSP events, as well as all recovery times, are in terms of sites. Between-unit or between-site variation is modeled in some cases, and between-year variation in one case. Based on the data in each case, the most appropriate model was used rather than force-fitting all the data sets into a single model. Tables ES-1 through ES-3 summarize the quantitative results of this study.

Table ES-1. Summary statistics on frequencies of plant-centered events at 116 units, with 1188.8 unit critical years and 455.5 unit shutdown years (allocation of 1980 time into critical and shutdown time is estimated).

	Initiating Events during Power Operation	**Events during Shutdown**
Number of events, by unit (= momentary + sustained)	50 (= 4 + 46) (15 non-initiators not counted for frequency analysis)	80 (= 11 + 69)
Frequency of initiating events at power or of all events during shutdown (= momentary and sustained, excluding momentary events at Pilgrim, an outlier)	0.04 (= 0.003 + 0.04) per unit critical year	0.18 (= 0.02 + 0.16) per unit shutdown year
90% uncertainty interval on above frequency of sustained events. See report for unit-specific estimates.	0.006 to 0.1	0.01 to 0.45
Maximum number of events at any unit	3	5
Avg. number of events per unit	0.43	0.69

Table ES-2. Summary statistics on frequencies of grid-related and severe-weather events, by site. This includes initiating events during power operation and all events during shutdown, at 74 sites in 1065.2 site calendar years.

	Grid-Related	**Severe Weather**
Number of LOSP events, by site (= momentary + sustained)	4 (= 1 + 3), with one 2-unit event (1 non-initiator at power not counted for frequency analysis)	17 (= 7 + 10), with five 2-unit events (All events at power were initiating events.)
Frequency of events (= momentary and sustained, excluding momentary events at Pilgrim, an outlier)	0.004 (= 0.001 + 0.003) per site calendar year	0.011 (= 0.002 + 0.009) per site calendar year
90% uncertainty interval on frequency of sustained events. See report for site-specific estimates.	NA (data too sparse)	1.E–8 to 0.05
Maximum number of events at any site	2	7 (at Pilgrim)
Average number of events per site	0.05	0.2

Table ES-3. Summary statistics on sustained times to recovery.

	Plant-Centered	Grid-Related	Severe Weather
Number of sustained events with reported recovery times, by site	102	4	9
Number of events with no reported recovery times, by site	9	0	1
Mean time to recovery (min)	85.4	203	1258
Median time to recovery (min)	29	160	270.5
Minimum and maximum times (min)	2, 1675	130, 360	37, 7929
90% uncertainty interval on recovery time (based on fitted models)	2.8 to 314 min.	87 to 398 min.	23 to 5009 min.

The major technical findings concerning frequencies are summarized here.

- NUREG-1032 found that plant-centered events accounted for the majority of the losses of offsite power. This study supports that finding, with plant-centered events clearly dominating LOSP frequency during power operation, as well as during non-power modes of operation. Events induced by severe weather are much less frequent, and grid-related events are still less frequent.

- LOSP frequency for plant-centered events is significantly higher during shutdown modes of operation than during power operation, by a factor of about four. The difference is present for both sustained and momentary events, and would be present even if non-initiating events at power were combined with the initiating events in the analysis. For severe-weather events and grid-related events, too few events occurred to obtain any firm conclusion.

- For plant-centered sustained initiating events at power, no statistically significant unit-to-unit variability in LOSP frequency was found. A decreasing trend in time was not statistically significant, based on the 1980 – 1996 data. Therefore no trend was modeled. The annual event counts showed larger-than-expected scatter around the mean, caused in part by dependence between units.

- For plant-centered sustained events during shutdown, significant statistical variability was found among the units. Therefore, a population variability distribution was developed. Data at individual units were used to update this overall distribution, yielding unit-specific estimated frequencies.

- The majority of plant-centered LOSP initiating events at power were caused by equipment faults (58%), with a smaller portion being induced by human error (23%). During shutdown modes, the opposite holds, with human errors being the major contributor (58%). The percentages are similar if only sustained events or only momentary events are considered.

- Plant-centered initiating events per year have become less frequent since the time period studied by NUREG-1032. A clear downward trend can be seen in the frequency from 1969 through 1996. No effect was found in the data that could be related directly to the Station Blackout Rule (10 CFR 50.63), which was published in June 1988.

- The LOSP frequency from grid-related events in the period covered by this report, 1980 – 1996, was very small. During this period, there were only five site events that could be classified as grid-related, and two may have been dependent. This is less frequent than found in NUREG-1032 by a factor of about 10. No grid-related events occurred in the 1990s, in spite of the occurrence of several widespread losses of power to the public.

- During the time period of this study, there was only one LOSP event with total and sustained voltage loss to all safety buses due to a grid disturbance. A fire near Turkey Point caused a grid failure that resulted in both units experiencing a LOSP event.

- The frequency of LOSP sustained events due to severe weather exhibited statistically significant site-to-site variability. This is to be expected, as some power plants, merely because of their geographic location, will tend to have increased exposure to severe weather. Site-specific estimates were obtained, to the extent possible from the small number of recorded events.

- Analysis of SBO risk was outside the scope of this study. However, 16 SBO events were identified during the data review in which a power plant unit had no AC electrical power from any source for up to 1 hour. Only two of these events occurred during power operations, and the longest of these two events lasted 11 minutes, which is well below the minimum coping time specified in U.S. NRC Regulatory Guide 1.155. The duration of each event was small and the need for accident mitigation system powered from emergency AC power was not present in the events.

- For momentary events, Pilgrim Nuclear Power Station was an outlier, having 8 of the 24 momentary events. Therefore, Pilgrim events were excluded from all industry analyses of momentary events.

The next set of conclusions concerns recovery times:

- For sustained plant-centered events, the events in which the reactor did not trip following the LOSP had longer recovery times than did the trip events and the shutdown events. No statistically significant difference could be seen between the sustained recovery times for trip and shutdown events. Therefore, the analysis of sustained recovery times was based on only the trip and shutdown events, which were combined.

- As found by the NUREG-1032 study, the sustained recovery times were significantly longer for severe-weather events than for plant-centered events. Too few grid-related events occurred during the period of this report to permit comparison of their recovery times with plant-centered or severe-weather recovery times.

- NUREG-1032 defined unit design classes I1, I2, and I3, which were believed to have increasing recovery times. No such effect was seen in the 1980-1996 data. The sustained recovery times showed no pattern, and the fractions of events that were momentary did not differ much between design classes.

FOREWORD

This report provides information relevant to loss-of-offsite power (LOSP) frequency and recovery times for power and shutdown operations. It summarizes the event data used in the analysis. The results, findings, conclusions, and information contained in this study, the initiating event update study, and related system reliability studies conducted by the Office for Analysis and Evaluation of Operational Data are intended to support several risk-informed regulatory activities. This includes providing information about relevant operating experience that can be used to enhance plant inspections of risk-important systems and information used to support staff technical reviews of proposed license amendments, including risk-informed applications. In the future, this work will be used in the development of risk-based performance indicators that will be based to a large extent on plant-specific system and equipment performance.

Findings and conclusions from the loss-of-offsite power update at 116 United States commercial pressurized water reactors and 74 sites based on 1980-1996 operating experience are presented in the Executive Summary. The results of the quantitative analysis and engineering analysis are presented in Sections 3 and 4, respectively. This report also provides an indication of how performance varies among plants and the measurable magnitude of that variation. The report provides a mechanism for identifying individual licensee event reports (LERs) that are the source for the calculation of the LOSP frequencies and nonrecovery distributions. For convenience, the risk-important information that would be useful in support of risk-informed regulatory activities involving the loss-of-offsite power is summarized in Table F-1. Users of this information are cautioned to be aware of the uncertainty in quantitative results when drawing inferences about industry performance trends and plant-specific variations in performance.

The application of results to plant-specific applications may require a more detailed review of the relevant LERs cited in this report. This review is needed to determine if generic experiences described in this report and specific aspects of the loss of offsite power events documented in the LERs are applicable to the design and operational features at a specific plant or site. Factors such as site location, climate, switchyard configuration, and test and maintenance practices would need to be considered in light of specific information provided in the LERs.

In addition, it may be appropriate to obtain and review more recent LERs to bring plant-specific insights on performance and the potentially important dominant contributors to a more current state. A search of the LER database can be conducted through the NRC's Sequence Coding and Search System (SCSS) to identify the LOSP events that occurred after the period covered by this report. SCSS contains the full text LERs and is accessible by NRC staff from the SCSS home page (http://scss.ornl.gov/). Nuclear industry organizations and the general public can obtain information from the SCSS on a cost recovery basis by contacting the Oak Ridge National Laboratory.

The Office for Analysis and Evaluation of Operational Data plans to periodically update the information in this report as additional data become available.

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Table F-1. Summary of risk-important information specific to loss of offsite power.

Failure information from the 1980-1996 operating experience used to estimate system unreliability (event summaries, failure modes, and LER references)	Appendix C Tables C-1 through C-4[a]
Summary of loss-of-offsite power (LOSP) frequency and recovery times	Section 3.4 Tables ES-1, ES-2, ES-3, 3-7, 3-8
Comparison of LOSP frequency and recovery times with NUREG-1032 results	Section 3.5, B-5 Tables 3-9, 3-10, 3-11 Figures 3-8, 3-9, B-21
Industry frequencies and recovery times for plant centered LOSP initiating events	Section 3.1.1 Tables 3-1, 3-7, 3-8, B-4, B-8 Figure 3-1
Industry and plant-specific frequencies and recovery times for plant-centered shutdown LOSP events	Section 3.1.2 Tables 3-2, 3-7, 3-8, B-4, B-8 Figures 3-2, B-3
Industry and plant-specific frequencies and recovery times for grid-related LOSP initiating events and shutdown events	Section 3.2 Tables 3-4, 3-7, 3-8, B-4
Site-specific frequencies and recovery times for weather related LOSP initiating events and shutdown events	Section 3.3 Tables 3-5, B-4 Figure B-4
Distributions for LOSP frequencies	Section B-2 Table 3-7
Distributions for recovery times	Sections B-3, B-4 Table 3-8
Proximate causes of LOSP events	Section 4.2 Figures 4-1, 4-2
Major equipment failures involved in LOSP events	Figures 4-3, 4-4, 4-5
Human contribution to LOSP events	Figures 4-6, 4-7, 4-8
Engineering insights related to recovery times	Section 4.3

a. Other documents such as logs, reports, and inspection reports that contain information about plant-specific experience (e.g., maintenance, operation, or surveillance testing) should be reviewed during plant inspections to supplement the information contained in this report. These sources will provide updated information on plant operating experience including failure events and demands captured in plant logs that are not reportable in LERs.

ACRONYMS

AC	alternating current
AEOD	Office for Analysis and Evaluation of Operational Data
ASP	Accident Sequence Precursor
EDG	emergency diesel generator
IN	information notice
INEEL	Idaho National Engineering and Environmental Laboratory
LER	Licensee Event Report
LOSP	loss of offsite power
MLE	maximum likelihood estimate
NRC	Nuclear Regulatory Commission
NSAC	Nuclear Safety Analysis Center
PRA	probabilistic risk assessment
QA	quality assurance
SCSS	Sequence Coding and Search System
SBO	station blackout
UDI	Utility Data Institute

Evaluation of Loss of Offsite Power Events at Nuclear Power Plants: 1980 - 1996

1. INTRODUCTION

It is recognized that the availability of alternating current (AC) power to commercial nuclear power plants is essential for safe operations and accident recovery. Unavailability of AC power can have a major negative impact on a power plant's ability to achieve and maintain a safe shutdown condition. Early probabilistic risk assessment (PRA) studies determined that the loss of AC power can be an important contributor to total risk at nuclear power plants. The United States Nuclear Regulatory Commission (USNRC) initiated a study to estimate the frequency of total loss of offsite power (LOSP), with coincident failure of all on-site AC power sources, based on actual Unites States commercial power plant events. That study covered data from 1968 through 1985, and the results were published in NUREG-1032[1] in 1988.

The present report updates a portion of NUREG-1032. One primary objective of this study is to update the LOSP model parameters (frequency and recovery time), based on commercial power plant operating data from 1980 through 1996. These parameters are needed to estimate the risk of LOSP and station blackout (SBO) scenarios, although the estimation of such risk is beyond the scope of this study. The present study analyzes events during shutdown, as well as events during power operation, although NUREG-1032 only considered events during operation. The second primary objective of this study is to re-examine the engineering insights from NUREG-1032, using the more recent data. This study does not evaluate emergency diesel generator (EDG) reliability; for such an assessment, see Grant, et al.[2] Instead, the present study is restricted to the LOSP events themselves. Table 1-1 summarizes the comparison between these three reports.

Table 1-1. Comparison of related reports.

	NUREG – 1032	**LOSP Study**	**EDG Reliability Study**
LOSP at power	1968 – 1985	1980 – 1996	-
LOSP during shutdown	-	1980 – 1996	-
Engineering insights	1968 – 1985	1980 – 1996	-
EDG reliability	1968 – 1985	-	1987 – 1993

The current study uses event data reported for individual power plants, called units. This is to distinguish between events that affect all power plant units at a single site, and the events that affect only one power plant unit. Throughout this report, the terms power plant unit and unit refer to a single power plant (e.g., Salem Unit 1), and site refers to a site that may include multiple power plant units (e.g., Salem site includes Salem Unit 1 and Salem Unit 2). Some of the events affected multiple units at a site. For example, when a hurricane affected a two-unit site, there were two unit events but only one site event.

The main body of this report contains a full description of the scope of the study, a summary of the quantitative results of the analyses, engineering insights, and the major conclusions of the study. The insights include a discussion of possible design features that might affect vulnerability to LOSP. The appendices provide more details about the analysis methods, analyses results, and the data included in the analyses.

2. SCOPE OF STUDY

The scope of this project was to identify LOSP events, to use statistical analysis to characterize the frequencies and recovery times of such events, and to characterize the events from an engineering perspective. The time period considered was January 1980 through December 1996. The study analyzed only events that occurred after a licensee received its full power license so that events early in a unit's learning experience would be excluded.

For this report, LOSP is defined as simultaneous loss of electrical power to all unit safety buses, requiring the emergency power generators to start and supply power to the safety buses. All Class 1E EDGs, the Keowee hydro units at Oconee, and the gas turbine generator at Millstone 1 are considered emergency generators for this study. NUREG-1032 included events that resulted in a loss of power to the non-vital buses as well as the safety buses, but the present study does not.

For events that occurred during power operation, this report distinguishes between initiating events and non-initiators. At most units, LOSP causes the reactor to trip, but some unit designs allow continued operation at power following a complete LOSP event, with the safety buses supplied by the emergency power generators. The data review identified 11 at-power events during which the reactor did not trip following the LOSP event. In addition, in several cases the reactor trip preceded the LOSP event. For this study, the event was considered to be an initiating event if the LOSP caused the reactor to trip or if both the LOSP and the reactor trip were part of the same plant transient, resulting from the same root cause. It was not an initiating event if either no reactor trip occurred, or the cause of the reactor trip did not directly cause an LOSP event, but the reactor trip subsequently caused the LOSP event. This report provides estimates of the frequency of initiating events, not the frequency of all LOSP events that occurred at power.

2.1 Data

The operating experience data used in this report are primarily based on Licensee Event Reports (LERs) residing in the Sequence Coding and Search System (SCSS) database. The search criteria initially identified approximately 4500 events involving some electrical failure that occurred from 1980 through 1996. The information encoded in the SCSS database was used only to select LERs to be reviewed for event screening and classification. Engineers that formerly held commercial nuclear power plant senior reactor operator licenses reviewed these 4500 LER abstracts and identified approximately 1400 LERs involving partial or complete losses of offsite power. Information from these LERs was supplemented with the following sources of information to ensure that all appropriate events were included in the study: Nuclear Safety Analysis Center (NSAC)[3] reports, the EDG reliability study,[2] NUREG-1032,[1] the USNRC Office for Analysis and Evaluation of Operational Data (AEOD) Grid Performance report,[4] the Engineering Evaluation of Loss-of-Offsite Power due to Plant-Centered Events (AEOD March 1993),[5] the Accident Sequence Precursor (ASP) database,[6] the Initiating Event Report,[7] and an Electric Power Research Institute study on Losses of Offsite Power.[8] A total of 176 events were identified as meeting the criteria specified for this study (complete LOSP) and coded as LOSP events. Three of these were excluded from the analysis because they occurred before receipt of the full power license. Those three events were coded and are included in the electronic database, but they do not appear in the data tables of Appendix C.

It should be noted that a loss of offsite power, by itself, does not require a licensee to submit an LER; therefore, some events identified do not have an LER number. Those events without an LER number were identified from review of the above-mentioned comparison data sources.

Because one objective of this study was to produce results for use in risk analyses, the time to recovery was defined as the time until offsite power could have been restored to at least one safety bus from an alternate transformer source by use of approved licensee procedures. Often this coincided with the actual reported duration of the LOSP event. Sometimes, however, the LER or the NSAC[3] report stated that offsite power "could have" been restored earlier if it had been needed. If electrical power from a secondary transformer source could have been restored following existing approved procedures, the stated time to restore the alternate source, or an estimate thereof, was entered as the time to recovery; events in this category are identified in Tables C-1 through C-3 with a 'C' in the Recovery Time column. Licensees frequently operate on emergency power sources longer than necessary due to procedural or operational requirements. Engineering judgment had to be used in estimating some recovery times. Two event reports gave vague information, so that the recovery time could only be estimated roughly, based on LER discussion of other plant activities. The recovery time was completely missing and could not be estimated for only 12 of the 173 events used in the analysis.

The event data used in the analyses are summarized in Appendix C, along with the operating and shutdown times that were used in the analyses. Appendix C also contains a detailed description of the data coding. Table C-6 lists the units included in the data analyses.

2.2 Analysis

For this study, the LOSP event was considered an *initiating event* if the loss of offsite power (electrical transient) caused the reactor to trip or if both the LOSP and the reactor trip were part of the same plant transient, resulting from the same root cause. Additionally, some shutdown events were classified as initiating events if the licensee preemptively shut the unit down in anticipation of the LOSP event (e.g., severe weather events), but the LOSP event would have caused a reactor trip if the unit had been at power. It was not an initiating event if either no reactor trip occurred, or the cause of the reactor trip did not directly cause the LOSP event, but the reactor trip subsequently caused the LOSP event. An event can fail to be an initiating event for either of the following two reasons:

- For most units operating at power, an LOSP event results in a unit trip. The specific design of some units, however, permits the unit to continue operating at power while the emergency generators supply power to the safety buses, although a technical specification shutdown is still required within a specified time. The data set contains 11 such events, when the unit continued to operate throughout the entire loss of offsite power. In general, the result of an LOSP event, trip or not, depends both on the severity of the event and on the design of the unit.

For events at power, the frequency of initiating events was considered an important parameter to estimate, but the frequency of non-initiators was not. For shutdown units, the distinction between initiating events and non-initiators was not made; some of the shutdown events used might not have caused a trip if they had occurred while the unit was at power. In general, however, the distinction between LOSP events and LOSP initiating events pervades the analysis.

A second distinction made is between *momentary* and *sustained* events. In about 15% of the LOSP events, offsite power was recovered, or could have been recovered following approved licensee procedures, in less than 2 minutes. This report calls those events momentary. To characterize the recovery times, the analysis distinguished between momentary and sustained events. Therefore, the frequencies are also given separately for the two classes of events.

The LOSP events were grouped into several categories. Following the precedent of NUREG-1032, the events were classified as plant-centered, grid-related, or caused by severe weather. In addition, they were grouped according to whether the unit was operating or shut down. These distinctions were used in the statistical analysis whenever they corresponded to clear differences in the frequencies or recovery times. The distinction between events during power operation and during shutdown was very important for the frequency of plant-centered events, but was not clear enough to model for grid-related or severe-weather event frequencies. Finally, for each event category, the sustained times to recovery were similar for trip events and shutdown events. Therefore, the recovery times were characterized based on the combined data.

Additional analyses were performed to compare the results of this study with the results presented in NUREG-1032. Specific comparisons were for frequency of occurrence, length of recovery time, and the effects of unit design characteristics on LOSP event details.

3. SUMMARY OF QUANTITATIVE RESULTS

This section of the report discusses the results obtained from statistical analyses of the LOSP frequency and recovery time data. For details of the statistical techniques employed, refer to Appendix A. For detailed quantitative results, see Appendix B. This section is organized around the classification scheme developed for NUREG-1032. Thus, the results are presented separately for plant-centered, grid-related, and severe-weather events, in Sections 3.1 through 3.3. Since events that occurred during shutdown modes of operation are also included in the present study, some of the results are separated further into operating and shutdown categories. This is beyond the scope of NUREG-1032, which only considered events during power operation. Section 3.4 of this report provides summaries of the estimates from Sections 3.1 through 3.3. Section 3.5 provides some comparisons with the results of NUREG-1032.

The analysis uses various models, depending on what the data showed. For example, frequencies of plant-centered LOSP events are presented in terms of units (individual power plant units), but the frequencies of severe weather events, as well as all recovery times, are in terms of sites. Between-unit or between-site variation is modeled in some cases, and between-year variation in one case. A time trend was considered for each set of data, but is modeled only in Section 3.5. The choice of a model is made with care, always based on what the data show. For a full discussion, see Appendices A and B. The diversity of models results from examining diverse data sets. The most appropriate model was used in each case, rather than force-fitting all the data sets into a single model.

3.1 Plant-Centered Events

Per the definition used in NUREG-1032, plant-centered events are those "in which the design and operational characteristics of the plant [unit] itself play the major role in the cause and duration of the loss of offsite power." Plant-centered failures typically involve hardware failures, design deficiencies, human errors, and localized weather-induced faults such as lightning.

NUREG-1032 found that such plant-centered events accounted for the majority of the losses of offsite power. The current study supports that finding, with plant-centered events dominating the LOSP frequency during power operation and during shutdown. The events used in the analysis are listed in Table C-1 of Appendix C. They are summarized in Table C-6 of Appendix C.

3.1.1 Frequency of LOSP Events During Power Operation

The frequency of plant-centered initiating events was clearly smaller during power operation than the frequency of LOSP events during shutdown (see Section B-1 of Appendix B). This was true both for momentary and sustained events. Engineering reasons for this are discussed in Section 4. Therefore, the results for the two unit conditions are presented separately here and in Section 3.1.2. Table 3-1 below summarizes the results of the initiating events during power operation. Critical hours for 1980 were estimated. The source of the outage and critical times for 1981 - 1996 are discussed more fully in Section A-1.3 of Appendix A.

Table 3-1. Summary statistics on frequencies: plant-centered LOSP initiating events during power operation.

Number of unit initiating events (= momentary + sustained)	50 (= 4 + 46)
Number of non-initiators (LOSP events at power when reactor did not trip, or when trip caused LOSP)	15
Total unit-years of criticality (critical time is estimated for 1980)	1188.8
Frequency of initiating events (= frequency for momentary events + frequency for sustained events). Momentary events at Pilgrim would have been excluded, had they occurred.	0.04 per unit critical year (= 0.003 + 0.04)
90% uncertainty interval on frequency of sustained events. This is not a simple confidence interval, but instead accounts for the large observed variation from year to year.	0.006 to 0.1
Minimum and maximum number of initiating events at any unit	0, 3
Number of units with 0, 1, 2, and 3 initiating events, respectively	74, 35, 6, 1
Average number of initiating events per unit	0.43

LOSP, per the definition established for this study, results in a loss of power to all safety (vital) buses and a signal for all available emergency AC generators to start and power their respective buses. This definition is slightly different from the one established for NUREG-1032, in that NUREG-1032 also included events that resulted in loss of power to the non-vital buses. The event is an *initiating event* if, in addition, a reactor trip results. Of the 65 plant-centered LOSP events at power, 11 were not initiating events because the reactor remained at power. Four plant-centered events were not initiating events because the trip preceded, and caused, the LOSP; the trip was generally independent of the resultant electrical transient. Following the precedent of NUREG-1032, frequencies are estimated only for initiating events.

There were too few momentary events to allow more than a very simple analysis. The more numerous sustained events required a more thorough analysis, summarized here.

No statistically significant unit-to-unit variability was found in the frequency of plant-centered sustained LOSP initiating events during operation; whatever variability exists is too small to be clearly evident in the 17 years of data. When an attempt was made to account for it anyway, the resulting model assigned exactly the same frequency to every unit.

Figure 3-1 shows that the slight downward trend in time was not statistically significant. However, significant year-to-year variability was seen, beyond what is expected under the usual Poisson model. A partial explanation of this extra-Poisson scatter is dependence between units — in several cases a single site event caused simultaneous LOSP at both units of the site. This dependence increases the variability in the annual count of events. Therefore, a single generic estimate was found, with an uncertainty that accounts for the extra-Poisson variation. Section 3.4 and Table B-4, Appendix B, present the corresponding gamma distribution, which can be used for a PRA at a particular unit. No sharp change in frequency was found in the data that could be related directly to the Station Blackout Rule (10 CFR 50.63), which was published in June 1988.

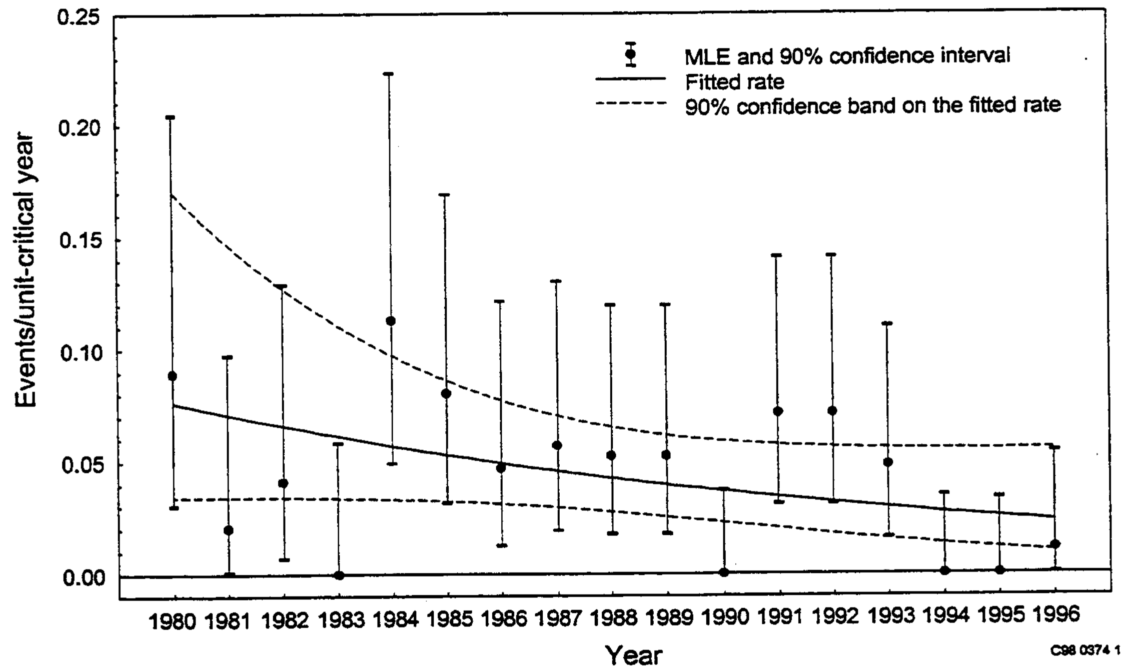

Figure 3-1. Frequency of plant-centered LOSP sustained initiating events during operation. When the extra-Poisson scatter is accounted for, the trend is not statistically significant (p-value = 0.11).

The trend in Figure 3-1 is not statistically significant and is not modeled for the frequency calculation. Section 3.5.1 presents a statistically significant trend, covering the years 1969-1996. Some reasons for the difference—insignificant trend in later years and very significant trend with early data—are explained in that section.

3.1.2 Frequency of LOSP Events During Shutdown

Although NUREG-1032 did not examine events that occurred in non-power modes of operation, this study includes analyses of shutdown events. The definition of LOSP is the same as that used above for power operation, but now the issue of initiating events does not arise: any loss of power to all safety buses that challenged the emergency power sources is counted, whether or not it would have caused a trip from power at that particular unit.

Table 3-2 summarizes the results for plant-centered events that occurred while the reactor was shut down.

The frequency of plant-centered events is significantly higher during shutdown than during power operation. Section 4 discusses possible engineering reasons for this. Unlike events that occur with the unit at power, there is statistically significant variability in the sustained LOSP event frequency from one unit to another during shutdown. The analysis method used for this study accounts for this variability, as discussed below. Variability between years was not modeled because it was not statistically significant.

Table 3-2. Summary statistics on frequencies: plant-centered LOSP events during shutdown.

Number of unit events (= momentary + sustained)	80 (= 11 + 69)
Total unit shutdown years (shutdown time is estimated for 1980)	455.5
Frequency of events (= frequency for momentary events + frequency for sustained events). This excludes 3 momentary events at Pilgrim, an outlier.	0.18 per unit shutdown year (= 0.02 + 0.16)
90% uncertainty interval on frequency of sustained events (This is not a simple confidence interval, but instead accounts for the large observed variation among units. Unit specific intervals vary.)	0.01 to 0.45
Minimum and maximum number of events at any unit	0, 5
No. of units with 0, 1, 2, 3, 4, 5 events, respectively	69, 27, 13, 3, 2, 2
Average number of events per unit	0.69

Using the methods explained in Appendix A, the population variability for sustained events was modeled by a gamma distribution, with shape parameter equal to 1.13 and scale parameter equal to 7.13 years (see Section 3.4 or Table B-4 of Appendix B). This gives a prior mean frequency of 0.16 per unit shutdown year, essentially the same as the simple estimate 69/455.5. The distribution has a 5th percentile of 0.01 per unit shutdown year and a 95th percentile of 0.45 per unit shutdown year.

This distribution was updated using each unit's specific data, yielding a wide range of posterior mean frequencies. The smallest was 0.05/plant-shutdown-year (90% interval from 0.003 to 0.16) at Browns Ferry 1, which experienced no events in about 13.5 shutdown years. The largest was 0.5/plant-shutdown-year (90% interval from 0.2 to 1.1) at La Crosse, which experienced 4 sustained events in approximately 2.3 shutdown years. A generic estimate is provided in Section 3.4, and the unit-specific frequencies are given in Table B-4 of Appendix B.

No statistically significant trend was seen in the frequency of plant-centered shutdown events over time. This is illustrated in Figure 3-2 below.

The events were examined by cause (human error, equipment problem, external environment), separately for events at power and events during shutdown. For trip events during power operation, whether initiators or not, equipment problems were the dominant cause, with 25 of the 45 sustained events (59%) and 5 of the 6 momentary events (82%). For events during shutdown, on the other hand, human errors were the dominant cause, with 39 of the 68 sustained events (57%) and 6 of the 8 momentary events (75%). This difference between trip events and shutdown events is statistically significant, both for sustained and momentary events. Details are given in Section B-1 of Appendix B.

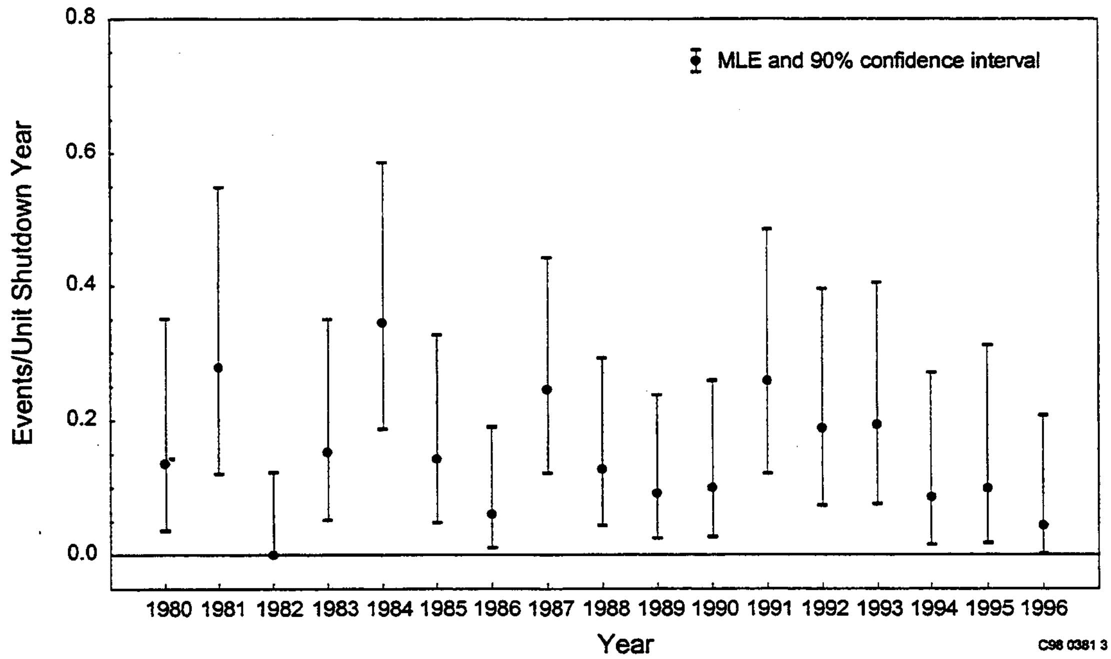

Figure 3-2. Frequency of plant-centered LOSP sustained events during shutdown. No trend is fitted, because it is not close to statistically significant. The confidence intervals for each year do not account for between-unit variation.

3.1.3 Sustained Time to Recovery

This section considers only the recovery times that were 2 minutes or longer. For the events at power, only the trip events were used, because the recovery times when the unit continued operating were significantly longer. A possible explanation of this is that the unit personnel will tend to act very carefully and deliberately, to prevent a trip, when the plant is operating on emergency power. Recovery times for the non-initiating events were combined with recovery times for the initiating events, because the recovery times appeared similar. The recovery times for trip events and shutdown events did not differ by a statistically significant amount, as shown in Section B-3.1 of Appendix B. Therefore, the trip events and shutdown events were all analyzed together.

When a single event caused LOSP at more than one unit at a multiple-unit site, the recovery times were typically similar or identical. Therefore, the recovery times were averaged, and the analysis was by site event rather than by unit event. Table 3-3 summarizes the results. Figure 3-3 shows a histogram of the recovery times.

Table 3-3. Summary statistics on times to recovery: plant-centered LOSP trip or shutdown events with recovery times ≥ 2 minutes.

Number of site events with reported recovery times	102
Number of site events with no reported recovery times	9
Mean time to recovery	85.4 min.
Median time to recovery	29 min.
Minimum and maximum times	2 min., 1675 min.
90% uncertainty interval on time to recovery (based on fitting a lognormal distribution to the recovery times)	2.8 to 314 min.

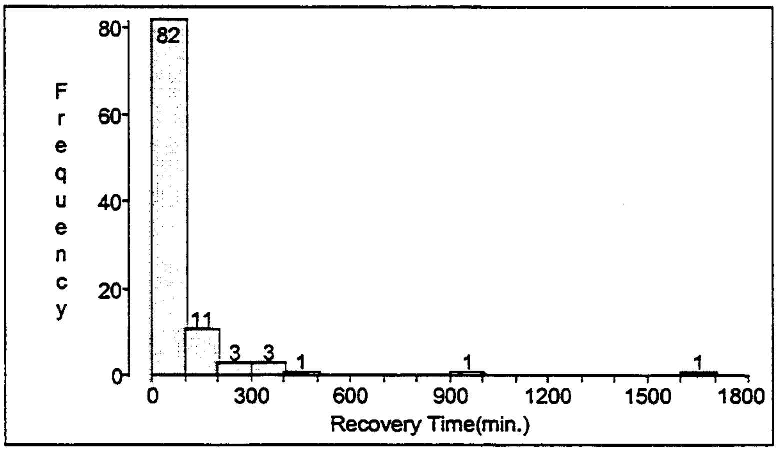

Figure 3-3. Histogram showing recovery times (minutes) for plant-centered trip and shutdown events with recovery times ≥ 2 minutes. This plot does not show 11 momentary events and 9 events with unknown recovery times. For any event at multiple units, only one site-average recovery time is counted.

A lognormal distribution fit the sustained recovery times well. The fitted mean and standard deviation of ln(recovery time) were $\mu = 3.39$ and $\sigma = 1.435$, so that the corresponding lognormal distribution had median 29.6 minutes and error factor 10.6. Percentiles of this lognormal distribution are given in Section 3.4 and in Table B-8 of Appendix B. Figure 3-4 shows the fitted recovery curve and the empirical recovery curve. The recovery curve at time *t* is defined as the probability that the recovery time exceeds *t*.

Section B-4.1 of Appendix B considers the possibility of a time trend in the recovery times. A slight trend is found, with p-value 0.03. However it is not modeled here for three reasons. The evidence for a trend is very sensitive to one or two reported times (one of which is known to be conservative), it is not strongly supported by engineering considerations, and the magnitude of the trend is small, a factor of 3.6 increase in the median in 17 years. Figure 3-5 shows plots of the logarithms of the recovery times.

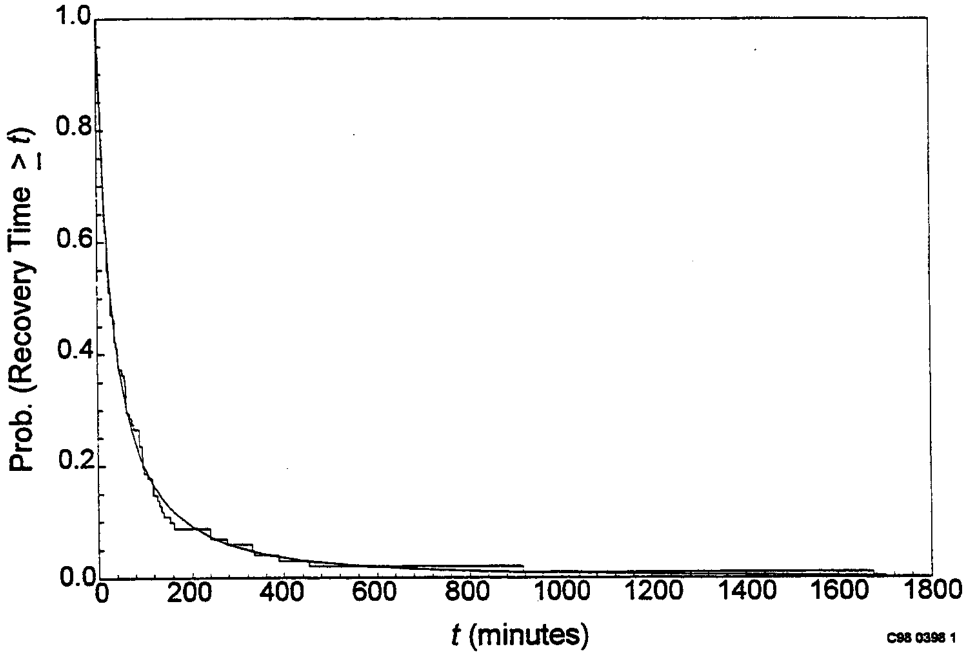

Figure 3-4. Recovery curves for recovery time (minutes) of plant-centered sustained trip and shutdown events, empirical and fitted lognormal.

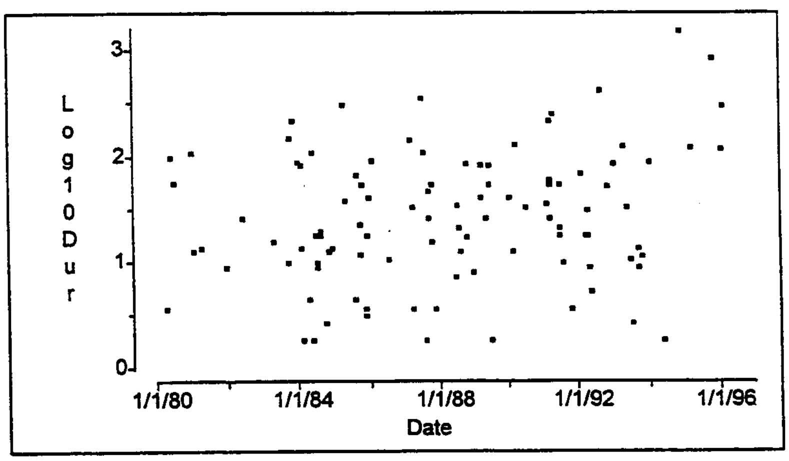

Figure 3-5. For sustained plant-centered events, plot of $\log_{10}$(recovery time) against event date. A slight upward trend is statistically significant (p-value = 0.03), but is highly dependent on the two points in the upper right, as discussed in the text. Therefore no trend is modeled.

3.2 Grid-Related Events

Grid-related events are those in which problems in the offsite power grid cause the LOSP and impact its duration. There were only six such events from 1980 to 1996. They are listed in Table C-2 of Appendix C, and listed more briefly here in Table 3-4. Appendix C explains the meanings of the column headings, which are also the LOSP database field names.

Table 3-4. Grid-related LOSP events.

LER	Unit Name	Event Date	Status	Cause	Initiator	Recovery Time (min)
25185011	Turkey Point 3	05/17/85	S	Fire	-	156
25185011	Turkey Point 4	05/17/85	T	Fire	1	125
31281034	Rancho Seco	06/19/81	S*	Load (brownout)	-	360
31281039	Rancho Seco	08/07/81	S*	Load (brownout)	-	180
33184028	Duane Arnold	07/14/84	T*	Equip	1	1.0
39589012	Summer	07/11/89	T*	Equip	0	130

Each of the events listed in Table 3-4 has unique characteristics: the Turkey Point events constituted a single site event; the Rancho Seco events may be dependent; the Duane Arnold event was a momentary event; in the Summer event a unit trip caused the grid disturbance and the subsequent LOSP. This uniqueness, and the small number of events identified during the data review, make it difficult to perform any meaningful statistical analysis. Therefore no statistical analysis is presented here, although a few summaries are given in Appendix B, and in Section 3.4.

As discussed in Section 4.1.2 below, grid-related LOSP events have become rare. None have occurred in the 1990s. Only the Turkey Point events, which are both from one initiating event, were total and sustained voltage loss to all safety buses at a unit/site from grid-related causes during the time period 1980 through 1996.

3.3 Severe-Weather Events

Severe weather is defined to be weather with forceful and non-localized effects. This is the same as the NUREG-1032 use of the term. A loss of offsite power was classified as a severe-weather event if the weather was widespread, not just centered on the site, and capable of major disruption. An example is storm damage to transmission lines, as opposed to debris blown into a transformer. This does not mean that the event actually resulted in widespread damage, as long as the potential was there. For example, a tornado might affect one unit at a site and miss the other. Because of a tornado's potential to affect both units, it would still be counted as a severe-weather event. Lightning strikes, though forceful, are normally localized to one unit, and thus coded as plant-centered, as they were in NUREG-1032. Examples of severe weather include hurricanes, tornadoes, snow, and ice storms. The frequency of LOSP from such events is lower than from plant-centered causes, but the recovery time, for sustained events, is typically longer. The events included in the analysis are listed in Table C-3 and are summarized in Table C-6 of Appendix C.

3.3.1 Frequency

The frequency of severe-weather initiating events during power operation appeared to be marginally smaller than the frequency of severe-weather LOSP events during shutdown. However, it was difficult to say whether the difference was statistically significant, because of the small data size, some possible dependence between events, and between-site variation. Although several ways of analyzing the data were considered, ultimately they were analyzed without distinguishing between events during operation and during shutdown. Every severe weather event at a multiple-unit site affected all the units at the site. That is, severe-weather events are considered most naturally as site events, not as unit events. Therefore, the frequencies were estimated as events per site calendar year.

Table 3-5 below summarizes the results for site events.

Table 3-5. Summary statistics on frequencies: severe-weather LOSP events.

Number of site initiating events and shutdown events (= momentary + sustained)	17 (= 7 + 10), with 5 2-unit events
Number of non-initiators (LOSP events at power when reactor did not trip, or trip caused LOSP)	0
Total site-calendar-years	1065.2
Frequency of events (= momentary + sustained). Analysis excludes 5 momentary events at Pilgrim, an outlier.	0.011 (= 0.002 + 0.009) per site calendar year
90% uncertainty interval on frequency of sustained events. (This models between-site variation. Site-specific intervals vary.)	1.E–8 to 0.05
Minimum and maximum number of initiating events at any site	0, 7
Number of sites with 0, 1, 2, 3, 4, 5, 6, and 7 events, respectively. (Pilgrim is the unit with 7 events, 5 of which were momentary.)	65, 7, 0, 1, 0, 0, 0, 1
Average number of events per site	0.2

For sustained events, variation between sites was statistically significant, and was modeled as follows. The population variability was modeled by a gamma distribution, with shape parameter equal to 0.205 and scale parameter equal to 22.5 site calendar years (see Section 3.4 or Table B-4 of Appendix B). This gives a prior mean frequency of 0.0091 per site calendar year, essentially the same as the simple estimate 10/1065.2 = 0.0093. The distribution has a 5th percentile of 1.E–8 and a 95th percentile of 0.05 per site calendar year. The 5th percentile is very small, and the value depends strongly on the use of a gamma distribution to model the between-site variability.

This distribution was updated using each site's specific data, yielding a wide range of posterior mean frequencies. The smallest was 5.2E–3/site-calendar-year (90% interval from 4.E–9 to 2.7E–3 at many sites that experienced no events in about 17 calendar years. The largest was 0.08/site-calendar-year (90% interval from 0.01 to 0.2) at Crystal River 3, which experienced 3 sustained events in 17 calendar years. The three Crystal River events all occurred in March, 1993. The analysis does not account for possible dependence among these three events.

No statistically significant time trend was seen in the frequency of severe-weather sustained LOSP events, although the year 1993 had a high number of events because of a single storm that affected much of the East Coast. A plot by year is given in Figure B-8 of Appendix B. The variation between years was nearly statistically significant, because of the year 1993.

3.3.2 Time to Recovery

Because the weather-related sustained recovery times did not differ significantly between power operation and shutdown, they are analyzed together here. As throughout this report, when a single event caused LOSP at more than one unit, the recovery times were typically similar or identical. Therefore, the recovery times were averaged, and the analysis is by site event rather than by unit event. The results are summarized in Table 3-6 and in Figure 3-6.

Table 3-6. Summary statistics on times to recovery: severe-weather LOSP events with recovery times ≥ 2 minutes.

Number of site events with reported recovery times	9
Number of site events with no reported recovery times	1
Mean time to recovery	1258 min.
Median time to recovery	270.5 min.
Minimum and maximum times	37 min., 7929 min.
90% uncertainty interval on time to recovery (based on fitting a lognormal distribution to the recovery times)	23 to 5009 min.

The variability among observed recovery times is very large, from 37 minutes to over 5 days. As discussed in Section B-4.2, the between-site variance is smaller than the between-event variance, and calculations of statistical significance are hampered by the small size of the data set. When site-specific estimates were found, they overlapped greatly. Therefore, any between-site differences were ignored, and only a single generic distribution is presented in this report, given in Section 3.4 and in Table B-8 of Appendix B.

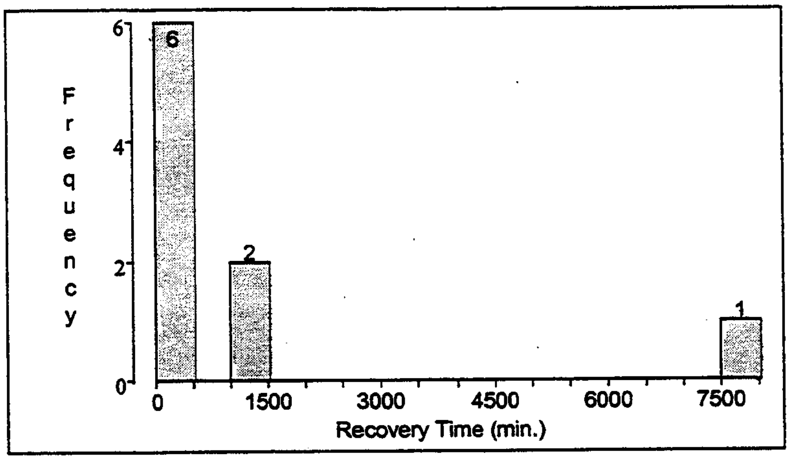

Figure 3-6. Histogram of recovery times (minutes) for sustained severe-weather LOSP events. For any event, the recovery times have been averaged for multiple units at a site, and regarded as a single time.

3.4 Summary of Estimates

Table 3-7 shows the estimates of event frequencies. Each line refers to a Bayesian distribution for the event frequency. The first three numbers in the line (columns 2 through 4) are the 5th percentile, the mean, and the 95th percentile of the frequency, in units of events per critical year or shutdown year, as relevant. Momentary events at Pilgrim are not analyzed in this report. The data in this report could be used for such an analysis. However, anyone performing a plant-specific analysis of Pilgrim should have access to more information than was available for this study, such as information about upgrades in the switchyard. It would be incorrect to analyze the Pilgrim data without such information.

Each distribution is presented as a distribution form accompanied by two parameters. Gamma distributions are shown in the form gamma(shape parameter, scale parameter), where the shape parameter is unitless and the scale parameter is in unit-critical years or unit-shutdown years. The mean of the distribution is (shape parameter)/(scale parameter), and the percentiles must be found by a computer calculation.

The frequencies of certain shutdown events showed between-unit variability. Unit-specific estimates are given in Appendix B, Table B-4 and Figures B-3 and B-4.

Table 3-8 summarizes the distributions for sustained recovery times. The percentiles and means are expressed in minutes. The format is like that of Table 3-7, except the distributions are lognormal, not gamma. For the lognormal distribution, the two parameters given are the *median*, and the error factor. The mean for each distribution is given in column 3, and the 5th and 95th percentiles in columns 2 and 4, all expressed in minutes. Both the median and the mean are given, in different columns; *do not confuse them*. The percentiles are related to the other parameters by: 5th percentile = median/(error factor), 95th percentile = median×(error factor). The mean is related by mean = $\exp(\mu + \sigma^2/2)$, with $\mu = \ln(\text{median})$ and $\sigma = \ln(\text{error factor})/1.645$.

This table also appears in Appendix B, as Table B-8.

Table 3-7. Event occurrence rates: means, percentiles, and distributions. (See text for detailed explanation.)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Plant-centered initiating events during operation				
Sustained events (46 unit events; calculated uncertainty accounts for variation above that expected for Poisson counts)				
Industry	6.39E-3	4.00E-2	9.73E-2	gamma[a](1.844, 46.12 unit crit. yrs.)
Momentary events (4 unit events, excluding Pilgrim)				
Industry	1.41E-3	3.82E-3	7.18E-3	gamma[a](4.500, 1178.6 unit crit. yrs.)
Plant-centered events during shutdown				
Sustained events (69 unit events. Unit-specific estimates given in Table B-4.)				
Industry	1.07E-2	1.58E-1	4.54E-1	gamma[a](1.127, 7.131 unit down yrs.)
Momentary events (8 unit events, excluding Pilgrim)				
Industry	9.66E-3	1.89E-2	3.07E-2	gamma[a](8.500, 448.8 unit down yrs.)
Grid-related events				
Sustained events. The 3 unit shutdown events and one initiating event consisted of only three site events at two sites. All the grid-related events are listed in Tables 3-4 and C-2. Because of the strong dependencies, the possibility of plant-specific differences, and the possibility of a trend in time, no statistical analysis is performed.				
Momentary events. One momentary event occurred in 1048 site calendar years (excluding Pilgrim).				
Industry	1.68E-4	1.43E-3	3.73E-3	gamma[a](1.500, 1048.2 site cal. yrs.)
Severe-weather events				
Sustained events (10 site events)				
Industry	1.34E-8	9.12E-3	4.67E-2	gamma[a](0.205, 22.51 site cal. yrs.)
Momentary events (2 site events, excluding Pilgrim)				
Industry	5.46E-4	2.39E-3	5.28E-3	gamma[a](2.500, 1048.2 site cal. yrs.)

a. As explained in the text, the parameters shown for the gamma distribution are the shape parameter and the scale parameter.

Table 3-8. Fitted distributions of recovery times of sustained LOSP events: means, percentiles, and distributions. (See text for explanation.)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Plant-centered events (102 site events with reported recovery times)				
Industry	2.80	82.9	313.7	lognormal[a](29.6 min., 10.6)
Grid-related events (only 4 site events with reported recovery times, two of which may be dependent. Uncertainty from lack of data is not accounted for. Interpret the results with care.)				
Industry	86.5	206.5	397.5	lognormal(185 min., 2.14)
Severe-weather events (9 site events with reported recovery times)				
Industry	23.15	1295.	5009.	lognormal(341 min., 14.7)

a. As explained in the text, the parameters shown for the lognormal distribution are the *median* and the error factor.

3.5 Comparisons with NUREG-1032

NUREG-1032 considers events from 1968 through 1985, partly overlapping the time span of this report. Although the analysis methods are somewhat different in the two reports, the overall conclusions can be compared.

3.5.1 Plant-Centered Events

NUREG-1032 only considers plant-centered initiating events that occurred during power operation. Therefore, the plant-centered shutdown events in this report cannot be compared to results from NUREG-1032. Comparisons between the two studies can be made, however, and are displayed in Table 3-9, based on Section 3.1 of this report and Table 3-1 of NUREG-1032.

Table 3-9. Plant-centered events in NUREG-1032 and present study.

	NUREG-1032	Present Study
	Frequency of Initiators	
Number of initiators	46 site initiating events	50 unit initiating events
Number of years	527 reactor critical site years	1189 reactor critical unit years
Estimated frequency	0.09 per site critical year	0.04 per unit critical year
	Time to Recovery	
Number of reported times, for site events	46	118 (trip and shutdown events, momentary and sustained)
Median recovery time	18 minutes	20 minutes

Thus, from a superficial comparison of the two studies, it can be concluded that plant-centered LOSP initiators have become less frequent but each event lasts about the same period of time. As discussed below, the change in estimated frequencies can be attributed to real changes in the unit operating histories.

Frequencies. To compare the frequencies over the combined time period of NUREG-1032 and the present study, unit calendar years were used, because unit operating data are uncertain and incomplete before 1981. As described in Section B-5.1 of Appendix B, unit calendar years were available from 1969 on. LOSP events from 1969 through 1979 were obtained from Table A-4 of NUREG-1032. Table B-9 in Appendix B displays the data used in the analyses. Figure 3-7 shows the trend. It confirms the above conclusion that plant-centered initiating events have become less frequent. The trend is statistically significant (p-value = 0.0001), and the fit is acceptable. The fraction of time when reactors are critical has increased since the late 1980s. Thus, the decreasing trend would appear slightly more pronounced if critical time were used instead of calendar time.

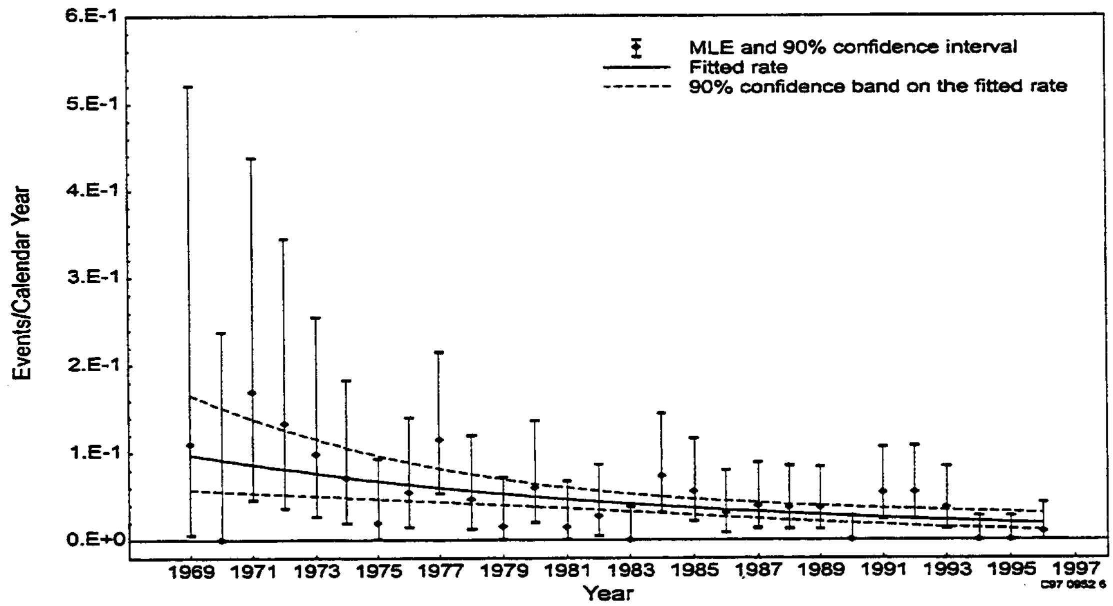

Figure 3-7. Frequency of plant-centered LOSP initiating events per unit year. The trend is statistically significant.

The present study includes 18 plant-centered initiating events in the 1980-1985 period, while 16 are listed in Table A-1 of NUREG-1032. Twelve events are included in both studies, and the other four from NUREG-1032 are classified as shutdown events using the criteria for the current study. This suggests that the present study is at least as complete as NUREG-1032. Therefore, the decreased frequency noted above apparently is not a result of incomplete data counts. The difference in the frequencies between NUREG-1032 and the current study may result partially from small differences in the definition of LOSP events between the two studies, although it was not in the scope of this study to determine the reasons for these differences.

The trend in Figure 3-1 is not statistically significant and is not modeled for the frequency calculation. The trend in Figure 3-7, on the other hand, is statistically very significant. The following considerations explain the apparent discrepancy. Most important, Figure 3-7 is based on about twice as many events as Figure 3-1, and covers 28 years instead of 17. Statistical significance measures the strength of the evidence, and the evidence for a trend becomes stronger when the data set is larger. Second, in Figure 3-7, it may be that most of the reduction in frequency came during the earlier years, in the 1970s and early 1980s. Finally, the frequency in Figure 3-1 may in fact be decreasing to some extent, as a result of upgrades at various sites and a general effort to reduce reactor scrams. However, the statistical evidence for this is far from conclusive, and it is conservative to estimate the frequency without assuming a decreasing trend.

Recovery Times. Table 3-9 shows that the median recovery time for sustained events in this report is very similar to the median recovery time for all events in NUREG-1032. Section 3.5.4 compares the frequencies of recovery times graphically.

3.5.2 Grid-Related Events

Table 3-10 gives a summary comparison between the findings of NUREG-1032 and the present report. The table shows that the frequency of grid-related initiating events has dropped by an order of magnitude between the study period of NUREG-1032 and the present study period. If the usual assumption of independence can be applied to the NUREG-1032 data, the difference is statistically very significant. The difference is also consistent with the fact that none of the grid-related events for the present study occurred in the 1990s. The recovery times for the present study tend to be longer, but the data set is quite small.

Table 3-10. Grid-related events in NUREG-1032 and present study.

	NUREG-1032	Present Study
	Frequency of Grid-Related Initiating Events	
Number of initiators	12 site initiating events	2 site initiating events
Number of site years	664 site calendar years	1065 site calendar years
Estimated frequency of initiating events	0.018 per site calendar year	0.0019 per site calendar year
	Time to Recovery	
Number of reported times for site events	12	5 (initiating and non-initiators, momentary and sustained)
Median recovery time	36 minutes	140.5 Minutes

3.5.3 Severe-Weather Events

Table 3-11 provides a summary comparison between the findings of NUREG-1032 and the present report. The differences between the two studies appear minor, explainable by the small size of the data sets and the great variability among recovery times for different events.

The final median (3.4 hours) in Table 3-11, based on modeling the momentary and sustained events, was found as follows. The Pilgrim momentary events were excluded. There were then 5 initiating site events, of which 4 were sustained. The sustained recovery times were modeled as lognormally distributed, with median 341 minutes and error factor 14.7, from Table B-8. The 37.5th percentile of this distribution is 202 minutes (= 3.4 hrs). Therefore, the probability that a recovery time is greater than 202 minutes equals:

$$\begin{aligned} \text{Prob(time} > 202) &= \text{Prob(time} > 202 \mid \text{event is sustained)} \times \text{Prob(event is sustained)} \\ &= (1 - 0.375) \times (4/5) \\ &= 0.5. \end{aligned}$$

Table 3-11. Severe-weather events in NUREG-1032 and present study.

	NUREG-1032	Present Study
	Frequency of Severe-Weather Initiating Events	
Number of initiators	6 site initiating events	7 site initiating events
Number of site years	664 site calendar years	1065 site calendar years
Estimated frequency of initiating events	0.009 per site calendar year	0.0066 per site calendar year
	Time to Recovery	
Number of reported times for site events	6	16 (initiating and non-initiators, momentary and sustained)
		11 if Pilgrim momentary events are excluded
Median recovery time	4.5 hours	1.2 hours, based on all 16 events 2.4 hours, excluding Pilgrim momentary events
	3.5 hrs. from modeling Weibull distribution	3.4 hours, excluding Pilgrim momentary events and combining models for momentary and sustained initiating events (see text)

3.5.4 Complementary Cumulative Frequency Curves

Figure 3-8, Figure A-1 from NUREG-1032, shows complementary cumulative frequency curves. For any time t, in hours, the height of the curve at t is the frequency of events with recovery times exceeding t. Because each curve was generated by fitting a parametric distribution to a portion of the data, the curve labeled 'Total' is not the exact sum of the three other curves. This is especially visible in the region around 3 hours, where the Total curve is about twice as high as the sum of the other three.

For comparison, Figure 3-9 shows the complementary cumulative frequency curves from the 1980-1996 initiating event data. Figure 3-9 uses the empirical step functions, with a jump at each observed duration. By definition, the 'Total' curve is the sum of the other three. Other than that minor difference in technique, the two figures are comparable.

There are two notable differences between the two figures. First, in Figure 3-9, the curve for grid-related events is much lower than in Figure 3-8, and is virtually negligible as a contribution to the total frequency of occurrence. Second, there are fewer short events (shorter than 1/2 hour) and about the same number of long events (longer than 3 hours) in the present study, represented by Figure 3-9. These observations are consistent with those of Section 3.5.1.

Figure 3-9 only includes initiating events during power operation, to allow direct comparison with NUREG-1032 results. Recall that for the current study the recovery times were similar for events during shutdown and operation (Section 3.1.3), and that slightly more events occurred during shutdown than during operation (Sections 3.1.1 and 3.1.2). Therefore, if *all* events had been included in Figure 3-9, the curves would be roughly twice as high as in Figure 3-9, but the qualitative relationship between the curves would remain similar to Figure 3-9.

3.5.5 Relationship between Recovery Time and Unit Design

NUREG-1032 defined three groups of units, denoted as I1, I2, and I3. This classification is based on various design factors concerning offsite power sources and the existence of automatic transfer mechanisms. The design features of I3 units are either no fast transfer to another offsite power source or no independence in the fast transfer source, in combination with limited or no independence of the incoming power lines. I2 plants automatically transfer to another offsite power source, and if that source fails one or more manual transfer paths to preferred or alternate offsite power sources exist. The I1 units are designed to automatically transfer to another offsite power source, and if that source fails there is yet another transfer to another offsite power source. For details of these groupings and design features, refer to NUREG-1032, Tables A-2 and A-3. The unit classifications used in this study are displayed in Table C-7 of Appendix C. The units not used in this study (because they experienced no LOSP events during the time period of this study) were neither classified nor listed in Table C-7.

Figures 3-10 and 3-11 show that the sustained recovery times have no statistically significant relation to design group.

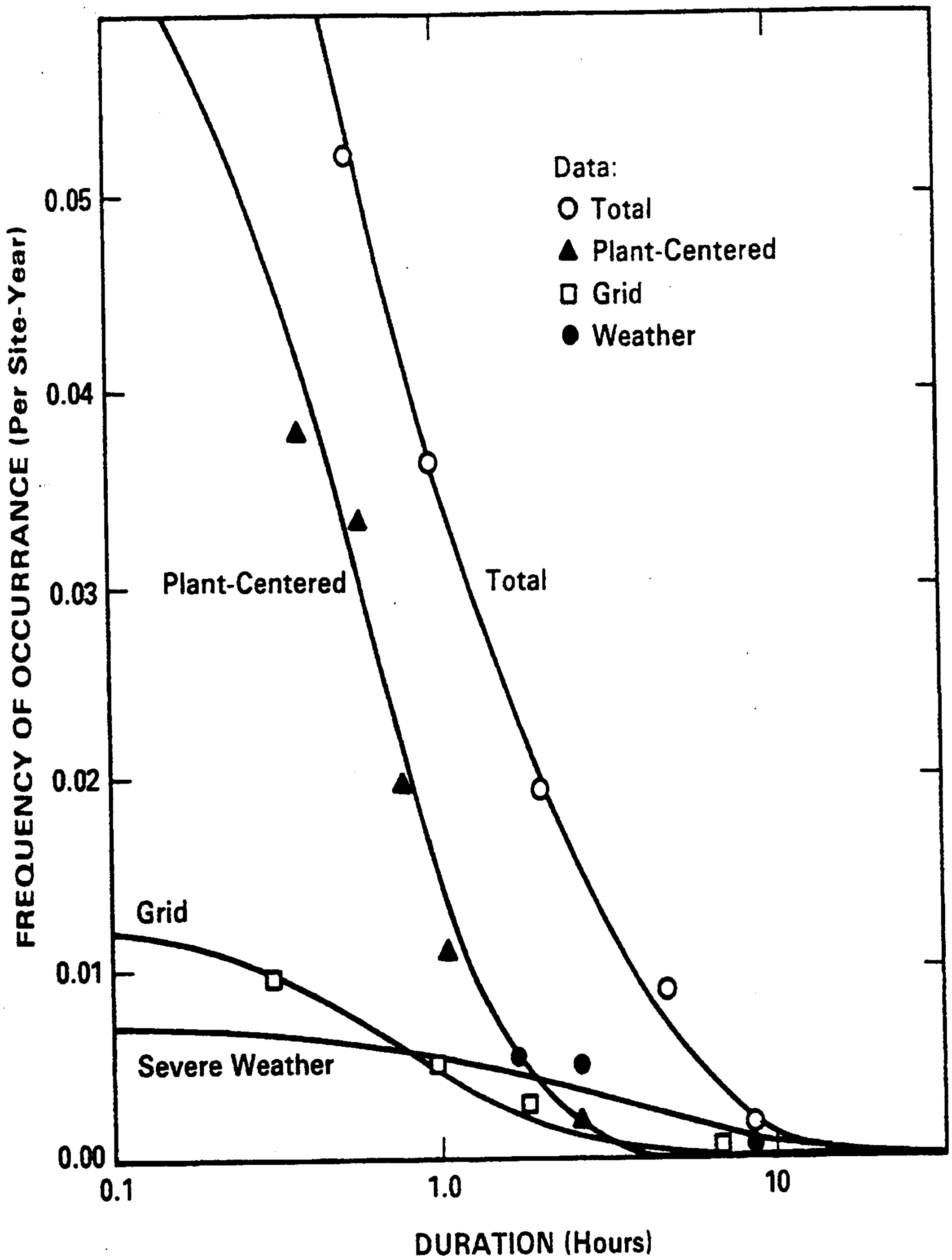

Figure 3-8. Complementary cumulative frequency curves, from NUREG-1032. Height of curve equals frequency of exceeding the time on the horizontal axis.

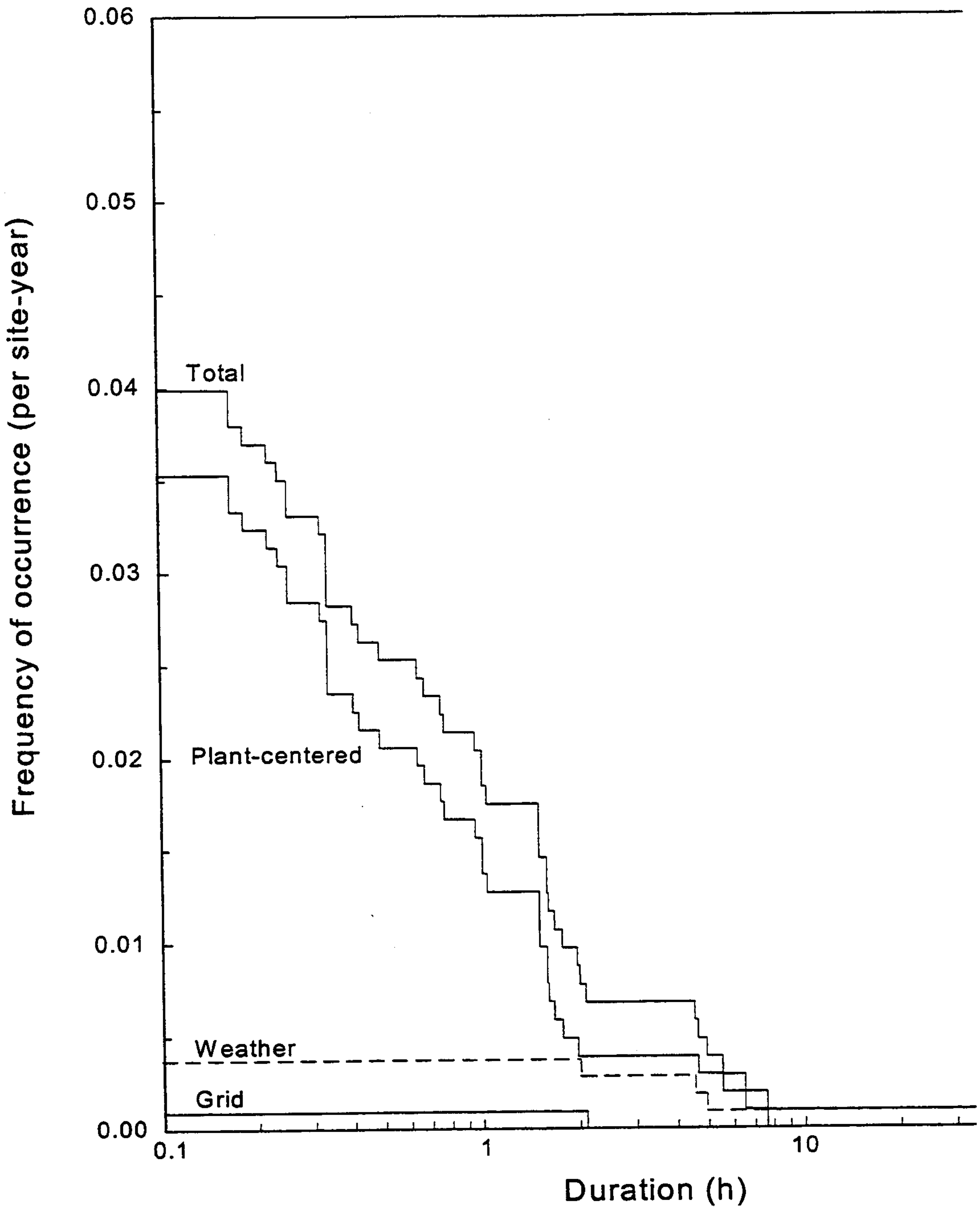

Figure 3-9. Complementary cumulative frequency curves using 1980-1996 initiating event data. Interpretation is the same as for Figure 3-8.

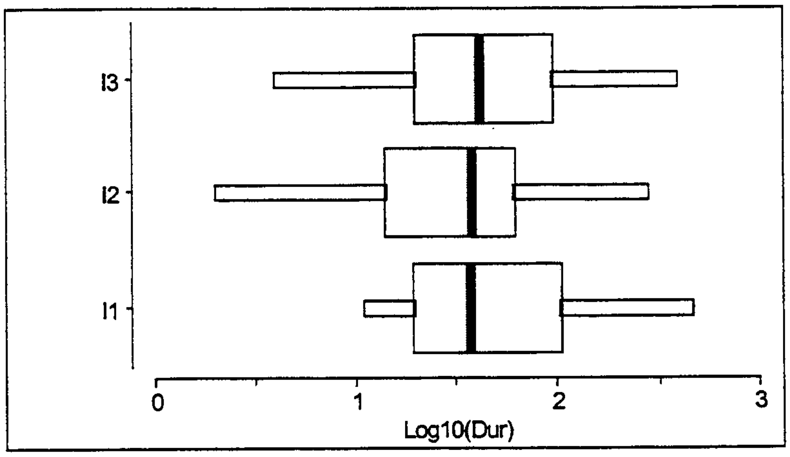

Figure 3-10. Log_{10}(recovery time), for plant-centered trip events with recovery time ≥ 2 minutes, plotted by design group. The differences are not statistically significant (p-value = 0.39).

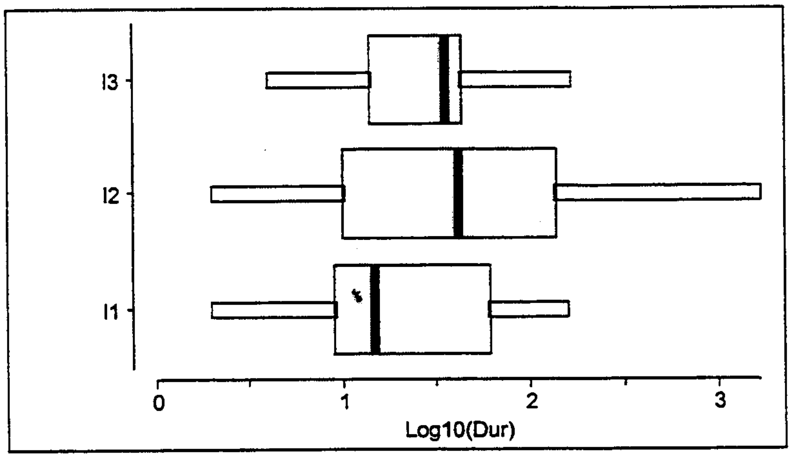

Figure 3-11. Log_{10}(recovery time), for plant-centered shutdown events with recovery time ≥ 2 minutes, plotted by design group. The differences are not statistically significant (p-value = 0.37). The difference between groups I1 and I3 is also not statistically significant (p-value = 0.35).

The design groups correspond to capability for fast transfer. Therefore, one might suppose that any difference among the design groups might be revealed in the momentary events rather than the sustained events. Table 3-12 shows that this also is not the case. Note in particular that the confidence intervals overlap greatly.

Table 3-12. Estimated probability that a random LOSP event is momentary.

Design Group	Momentary Events	All Events	Observed Fraction of Momentary Events	90%Confidence Interval on Prob(event is momentary)
Trip Events (p-value for difference between design groups = 0.46)				
I1	0	9	0.0	(0.00, 0.28)
I2	5	33	0.15	(0.06, 0.29)
I3	2	11	0.12	(0.02, 0.33)
Shutdown Events (p-value for difference between design groups = 0.40)				
I1	1	20	0.05	(0.003, 0.22)
I2	4	42	0.10	(0.03, 0.21)
I3	4	23	0.17	(0.06, 0.36)

4. ENGINEERING INSIGHTS

This section of the report discusses the results presented in Section 3 from an engineering perspective. The objective of this part of the study is to attempt to provide some insight into the quantitative results, and what unit designs or operating activities might impact either the LOSP frequencies or recovery times. The insights presented here are not the result of qualitative studies performed independently of the quantitative analyses, but are intended to complement the findings presented in Section 3.

4.1 Events by Frequency

4.1.1 Plant-Centered Events

This is the largest group of events resulting in a loss of offsite power, accounting for approximately 80% of all events. Although the total of unit outage years (shutdown) are only roughly a third of the total unit operating years, the number of plant-centered LOSP events during shutdown is approximately 50% higher than during power operation. (Details of this are displayed in Figure B-1 in Appendix B.) This is an expected result because shutdown unit conditions typically involve more vulnerable electrical unit configurations due to testing and maintenance activities. In addition, less redundancy in offsite power supplies is required by Technical Specifications while a unit is in a shutdown condition. Therefore a power plant may, and often does, have fewer incoming power feeds to its shutdown electrical line-up. For example, at Haddam Neck (LER 21393009), a testing line-up placed all shutdown power through a single incoming electrical line. The wrong breaker opened during the test because of a wiring error, and all internal plant power was lost. Such an event would have only been a partial loss of offsite power if all redundant electrical equipment had been operable.

4.1.2 Grid-Related Events

Because the power grid is not affected by whether a power plant is operating or in a shutdown condition (assuming a steady state condition, i.e., no transient that will cause grid fluctuations), all grid-related events were considered together for the engineering analysis.

The nature and small number of grid-related events indicates that losses of offsite power to a nuclear power plant due to grid disturbances are rare events and none have occurred in the 1990s (see Table 3-4). Of the six events identified in the study, two of them, at Rancho Seco, were actually electrical brownout situations, both occurring in the summer of 1981. It is suspected, but not proven, that these two events were not independent, due to the short time between the events and the similarity of the occurrences. Both the Summer event (not used for frequency analysis) and the Duane Arnold event did not involve loss of power to all unit buses; only the safety buses were affected by the grid voltage degradation. The Turkey Point events resulted from the same brush fire and thus both events are from the same initiator, implying only one natural event in time. Only the Turkey Point events, which are both from one initiating event, were total and sustained losses of all AC power to a unit/site from grid-related causes during the time period 1980 through 1996. Although investigation of the specific reasons for the low number of grid events was outside the scope of this study, it may be inferred from a comparison of the frequency between the present study and NUREG-1032 that loss of offsite power to a power plant due to grid-related failures is less likely to occur now than it was prior to 1985. Based on this experience, grid instability has not been an important contributor to LOSP frequency.

On February 27, 1998, the NRC issued Information Notice (IN) 98-07, "Offsite Power Reliability Challenges from Industry Regulation." This IN addressed an NRC concern relating to electric power deregulation that could potentially adversely affect offsite power sources. The IN identified and discussed eight grid-related disturbances. Only one event identified in the IN was classified as a LOSP event in this study (Summer, July 11, 1989). The other seven grid disturbances did not result in a LOSP at any nuclear power station.

There were two electrical grid disturbances throughout the western states on July 2, 1996 and August 10, 1996 that received national media attention. Because of this, a specific search for loss of power events on these dates was conducted. Two western states power plant events caused by this grid disturbance were reported on August 10, 1996 and none were reported on July 2, 1996. Only one event (LER 27596012) involved loss of electrical power and it was only a partial loss of power to Diablo Canyon. Both units tripped due to the major disturbance on the western transmission grid (500kV) and transferred to startup power (230kV) as per design. There is no indication that emergency diesel generators were used for power. The other event (LER 52896004) did not report a loss of power but Palo Verde units 1 and 3 tripped by automatic protective system action caused by the grid disturbance. The LER referred to the event as uncomplicated reactor trips with no ESF actuations. Unit 2 remained at 100% power throughout the disturbance. These events do not meet the criteria established for the LOSP study, and thus were not included in the data analysis. If any plant experienced grid disturbances on either of these dates, the effect on the plant electrical systems was insufficient to require the licensee to submit an LER. Due to the lack of reports on these dates, it is concluded that no plants experienced an LOSP event, as defined for this study, due to those grid disturbances.

4.1.3 Severe-Weather Events

Engineering considerations suggest that plants may be more vulnerable to LOSP during shutdown than during operation, for the same reasons as for plant-centered events. However, this assumes that the plants do not modify their shutdown electrical configurations in anticipation of approaching storms. After several analyses were tried, the following considerations led to an analysis by site, ignoring the difference between operation and shutdown.

- The difference between frequencies during shutdown and power operation is not clear.
- It is natural to consider severe-weather events as site events. Every severe-weather event at a multiple-unit site involved LOSP at all units.
- Small data sets should not be subdivided unnecessarily. For example, the three Crystal River 3 events have more influence in a set of 7 unit events during shutdown than in a set of 10 site events during both operation and shutdown. The larger data set, though still

small, provides somewhat more confidence in the fitted empirical Bayes model, and dilutes the effect of possible dependence of the Crystal River events.

The Pilgrim Nuclear Power Station experienced 13 LOSP events, 6 plant-centered and 7 from severe weather. Identifying the reason(s) for this large number is beyond the scope of this study. However, Pilgrim had a procedure for easily obtaining offsite power through an independent secondary offsite 23 kV power line. Although this procedure was rarely used, it could have been used in many events. The recovery times were coded based on what could have been done, which explains why so many of the Pilgrim events are momentary. Some Pilgrim LERs mentioned upgrades or redesigns of the switchyard; therefore, that work may have fixed some of the switchyard problems, because Pilgrim has reported no LOSP events since 1993.

Sixteen of the 22 unit events resulting from severe weather occurred at only 5 sites. These are Pilgrim, Crystal River, Brunswick, Millstone, and Turkey Point. The units at these sites have diverse designs with little similarity in electrical power supply design or redundancy. Because all five of these sites are located on the east coast, it seems clear that their proximity to the ocean and its storms is a major factor in loss of power frequency. There is no indication of why other power plant sites located on ocean shorelines have no losses of offsite power events. Investigation into the details of unit designs and their effects on weather vulnerability was outside the scope of this study.

4.2 Events by Cause

4.2.1 Proximate Cause

Figure 4-1 displays the LOSP events by overall cause. All 173 unit events used in the analyses are included in this figure.

The rest of this subsection examines the causes of plant-centered events in more detail. A classification scheme was examined that segregates events according to the cause categories used in the data classification (e.g., equipment failure, human error, extreme environment condition). The simplest breakdown of plant-centered events looks at these causes for events at power and events during shutdown, ignoring finer distinctions such as whether the event was an initiating event. Table 4-1 provides a summary of the counts. The plant-centered power operation data indicate that approximately 58% of the events are caused by equipment failures, and approximately 23% of the events are caused by human errors. Tables B-1 and B-2 show similar percentages. Conversely, the plant-centered shutdown data indicate that approximately 34% of the events are caused by equipment failures, and approximately 58% of the events are caused by human errors. This is a reasonable result. Due to the increased number of maintenance and testing activities occurring during a unit shutdown, and due to an increased number of people working at the unit during any given hour over what is the normal staff level at power operation, the exposure to human error is increased substantially during shutdown conditions.

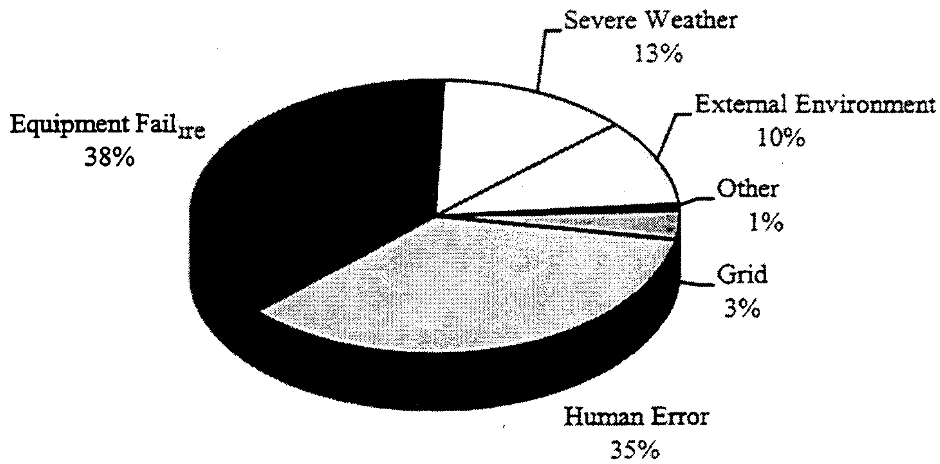

Figure 4-1. Causes of all LOSP events.

Table 4-1. Number of plant-centered events for each cause, for events occurring when reactor was at power and when reactor was shut down.

	Ext. Envir.	Equipment.	Human	Other	Total
Power	11 (17%)	38 (58%)	15 (23%)	1 (2%)	65
Shutdown	7 (9%)	27 (34%)	46 (58%)	0 (0%)	80
Total	18 (12%)	65 (45%)	61 (42%)	1 (1%)	145

Figure 4-2 shows the frequencies of the three primary causes in Table 4-1, dropping the single event with cause "other." The 144 plant-centered events, both initiators and non-initiators, are used.

Figures 4-3 through 4-5 examine the equipment failures in more detail. Figure 4-3 shows the types of equipment that failed during equipment failures. These equipment types are explained under the 'cause' bullet in Section C-1 of Appendix C.

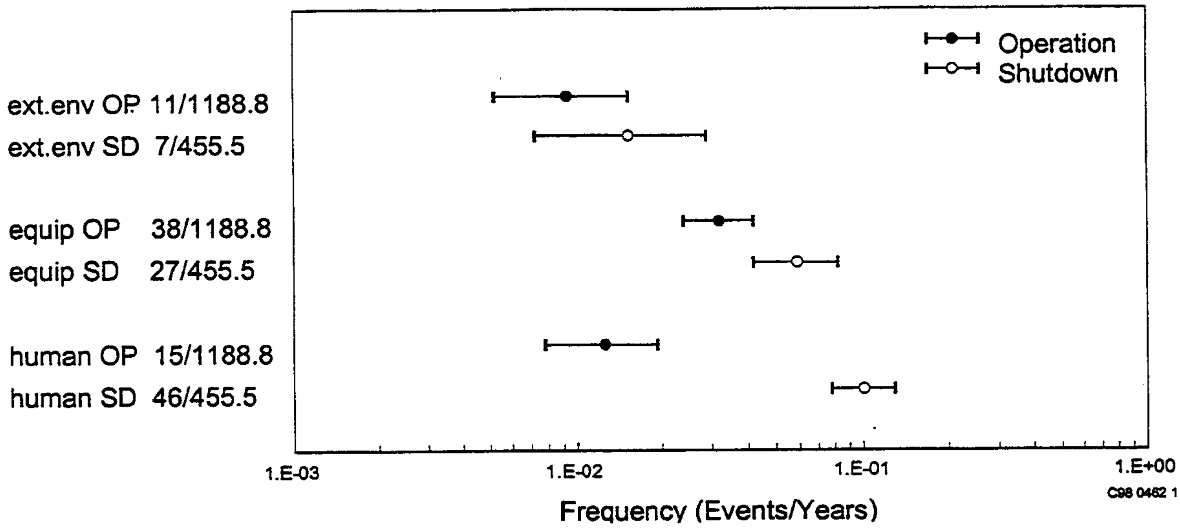

Figure 4-2. Frequencies of major causes of plant-centered events. The number of events per reactor critical year or events per reactor shutdown year is printed on the left. Maximum likelihood estimates and 90% confidence intervals are plotted.

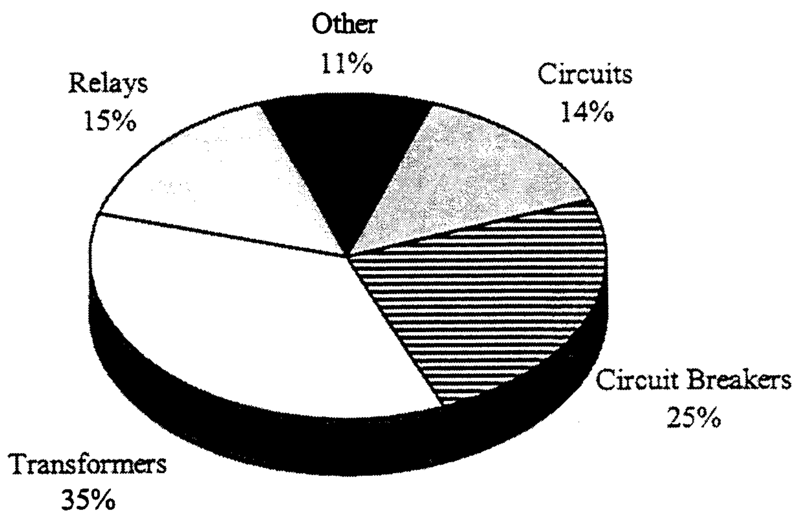

Figure 4-3. LOSP events caused by equipment failures, by equipment type.

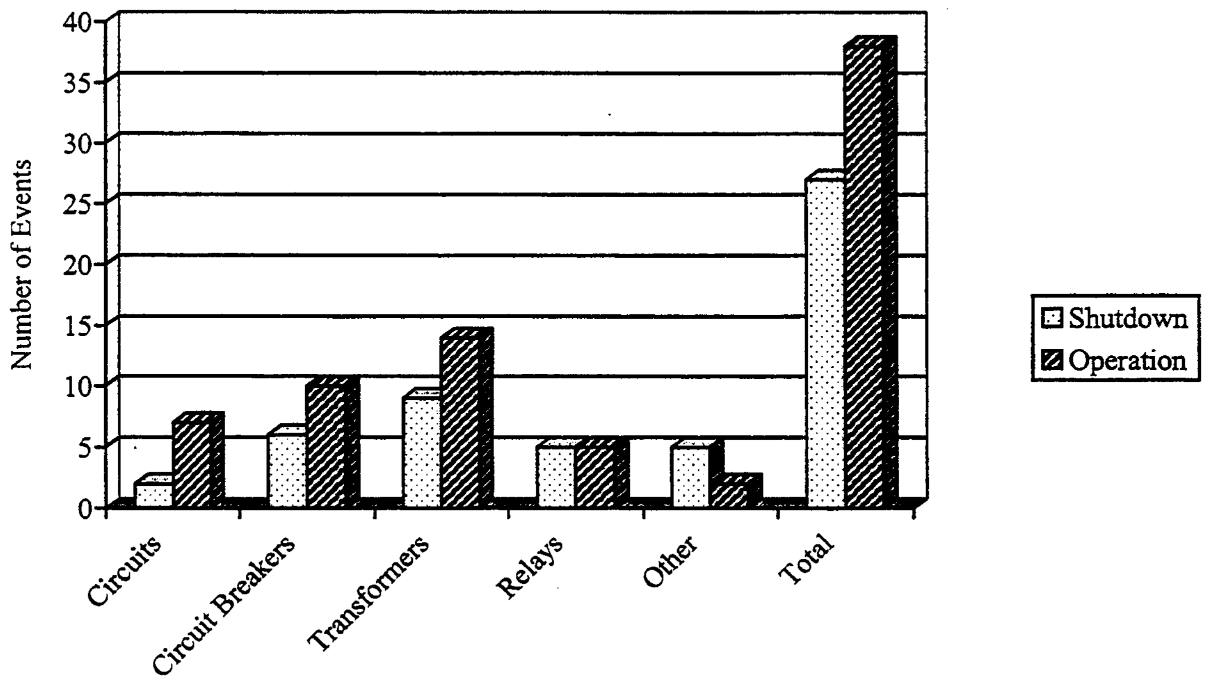

Figure 4-4. Number of LOSP events caused by equipment failures, by equipment type and unit status.

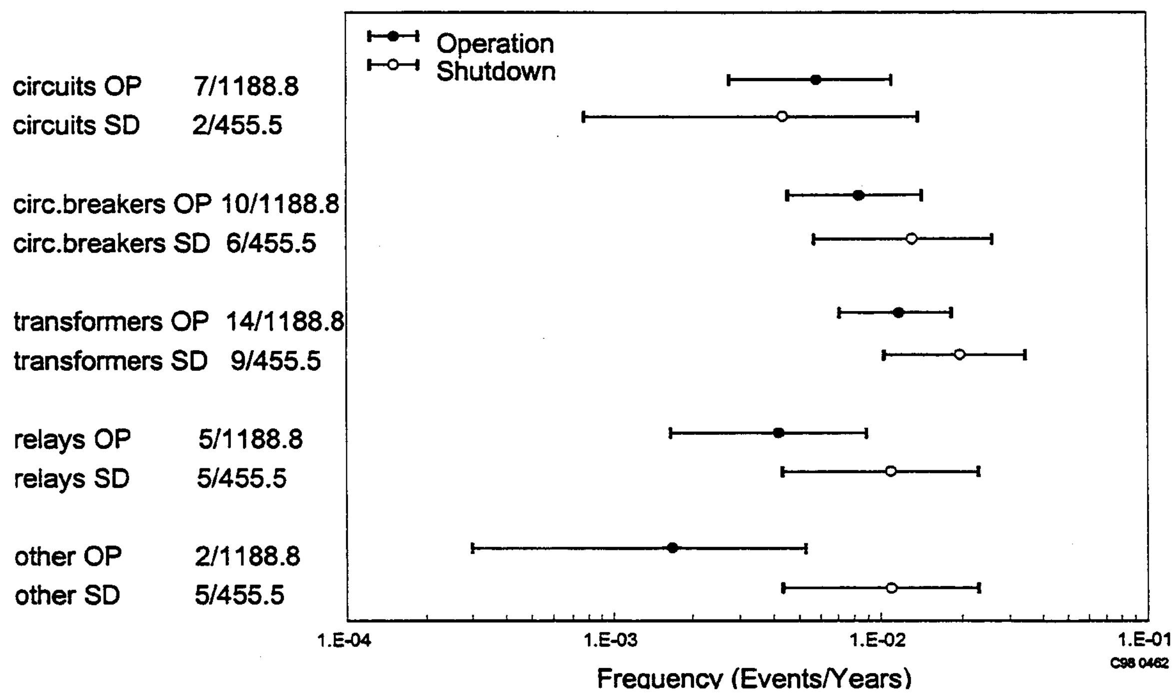

Figure 4-5. Frequencies of equipment failure types, during operation and shutdown. Maximum likelihood estimates and 90% intervals are plotted.

Figure 4-4 shows the same counts, broken into events during operation and events during shutdown. Because this figure does not show the differences between operating time and shutdown time, Figure 4-5 shows the frequencies of the different kinds of equipment failure. From Figure 4-2, the overall equipment failure frequency is higher during shutdown than during operation. However, from Figure 4-5, this difference is not attributable to any particular kind of equipment; instead, it is a general tendency for all equipment.

Figures 4-6 through 4-8 examine the human errors in more detail. Figure 4-6 shows the personnel activities at the time of the human failures. These activities are explained under the 'cause' bullet in Section C-1 of Appendix C. Figure 4-7 shows the same counts, broken into events during operation and events during shutdown. Because this figure does not show the differences between operating time and shutdown time, Figure 4-8 shows the frequencies of the different kinds of human errors. From Figure 4-2, the overall human error frequency is much higher during shutdown than during operation. Figure 4-8 shows that this strong difference is not attributable to any particular kind of activity; instead, it is a general tendency for all personnel activities.

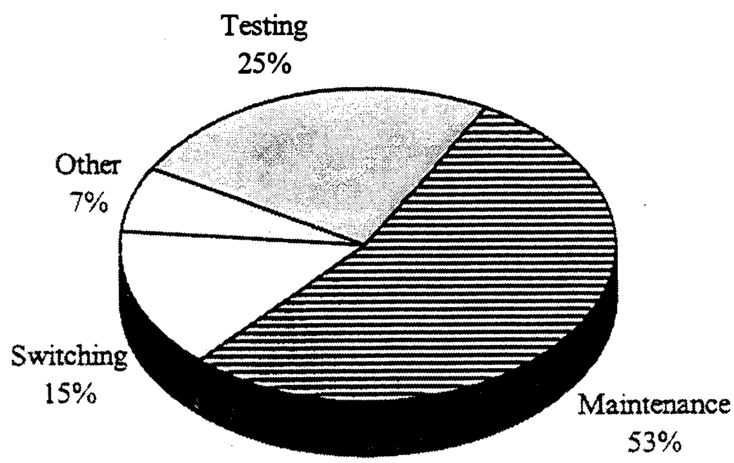

Figure 4-6. LOSP events caused by human error, by personnel activity.

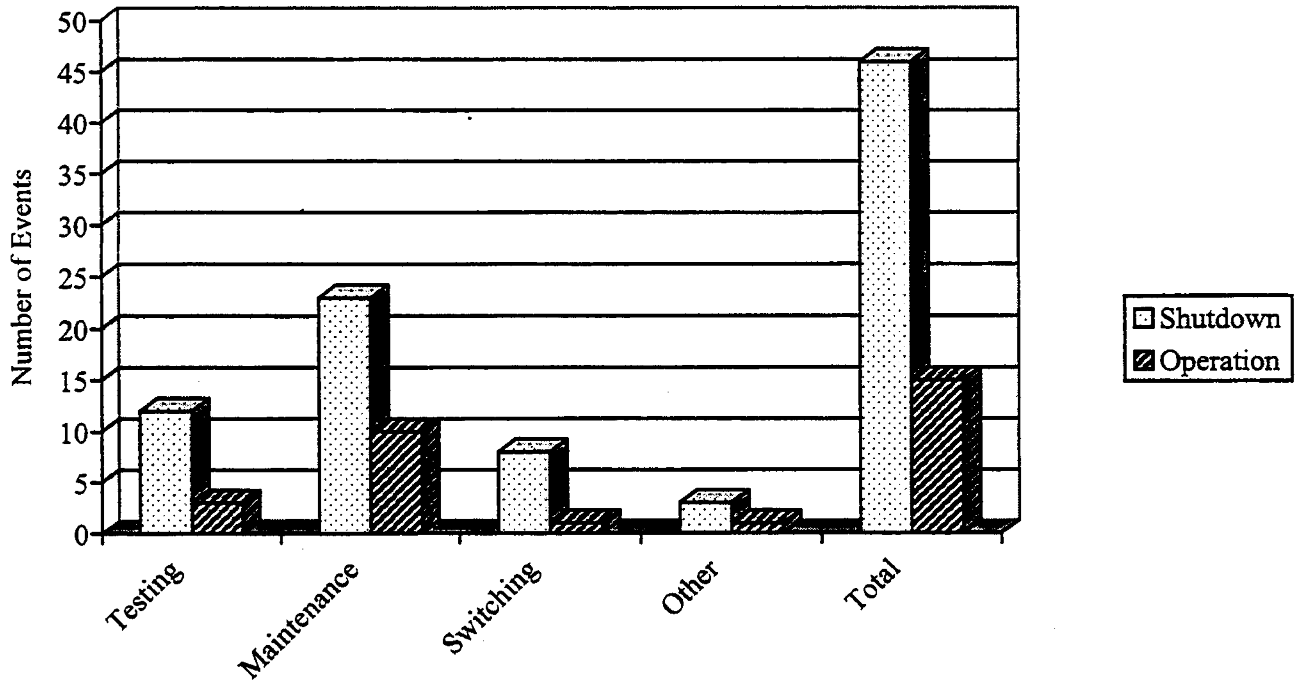

Figure 4-7. Number of LOSP events caused by human error, by personnel activity and unit status.

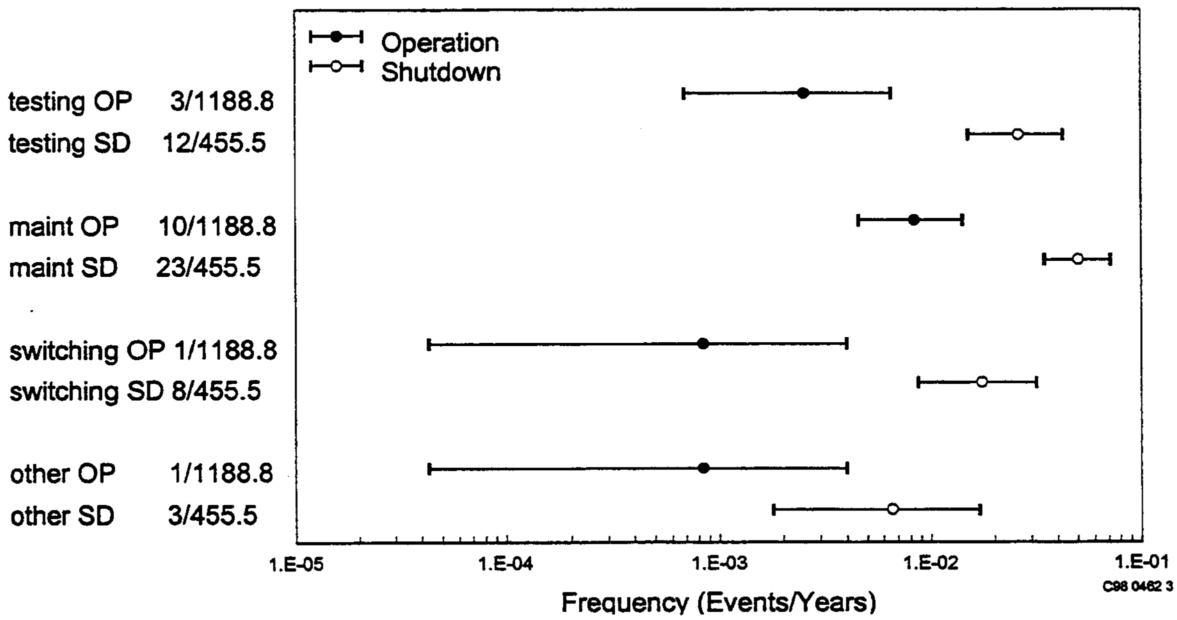

Figure 4-8. Frequencies of human error types, during operation and shutdown. Maximum likelihood estimates and 90% intervals are plotted.

4.2.2 Electrical Configuration

In order to determine the relative contribution to loss of offsite power due to unit electrical configuration, each event was reviewed to identify non-standard electrical system configurations that may have increased the vulnerability to a loss of offsite power or may have increased the recovery time. For most events, this review suggests that the total loss of offsite power might not have occurred had the unit electrical system been aligned in a normal configuration. In addition, for some events, recovery was delayed by complications resulting from a non-standard configuration. The results of this review are displayed in Table 4-2.

Table 4-2. Events with abnormal electrical configurations.

	# of Events	# Abnormal Lineup Events	Fraction of Abnormal Lineups
Shutdown	94	45	0.48
Initiating Event	69	9	0.13
Total	157*	54	0.34

* The 'Power Op' events (loss of power events that did not result in a reactor trip), trips that caused LOSP events, and pre-full power license events were excluded from these counts.

Clearly the number of unit LOSP events is greatest when the unit is shutdown and in a non-standard electrical system configuration. This is consistent with expectations because Technical Specifications limit unit electrical configurations at power, and maintenance involving non-standard electrical system supplies is necessarily performed while shutdown. It was not in the scope of this study to determine the amount of time, as a percentage of both operating and shutdown periods, that a unit might be in a non-standard electrical configuration. Such information might allow for more detailed analysis to determine the risk of specific activities or configurations.

4.3 Recovery Times

The recovery time results presented in Section 3 of this report are predictable, in that the recovery times are longer for the sustained severe weather events than for both the sustained plant-centered events and the sustained grid events. Due to the type of events that have caused the severe weather LOSP events (hurricanes with widespread damage, and other storms that affect large geographical areas), it is reasonable to expect that restoration of equipment would be a lengthy process.

The time trend indicates that recovery times (Figure 3-5) are not appreciably changing, as recorded for this study, even while LOSP frequencies are decreasing (as shown in Table 3-9 and Figure 3-7). The recovery times used for this study relate to the time that power *could have been* recovered to the first safety bus from any offsite transformer source, which is consistent with previous studies, rather than the actual reported recovery time. Thus, the contribution to risk from recovery times is unchanged.

Preliminary analysis of *actual* recovery times from LERs indicated that the more recent recovery times tend to be longer than recovery times from older events. Although the actual times were initially determined from LERs and other source reports, they were not recorded, analyzed, or reported in this study. Several factors combine that may explain the increase in *actual* recovery times:

- Through the 1980s and 1990s, nuclear power plant operators became more deliberate due to higher standards of operator performance and increased caution of licensee management, and licensee operating procedures were enhanced with greater detail, such that recovery from an abnormal event would be expected to take more time now than it did in the 1970s. What may have been estimated to take 15 minutes in earlier years of nuclear power operations may take closer to 45 minutes now.

- The data in the earlier reports may err on the optimistic side. Some events discussed in earlier reports indicate the availability of a cross-tie option to the other unit on the same site, while LERs reporting the same events do not mention either an attempt to use the cross-tie to restore power or even the existence of the option to cross-tie.

- The option to use a cross-tie to a sister unit is now considered only in extreme circumstances. There is greater concern now than before about a cascading effect to another unit.

- Review of the plant-centered events with recovery times greater than 200 minutes, all occurring after 1986, revealed that the majority of them (14 of 17) involved severe equipment failure. Licensees have become extremely conservative with respect to event recovery. Root cause investigation now takes priority over immediate repair activities, provided there is at least one emergency power source (e.g., EDG) supplying power to the safety equipment. While no engineering evaluation was performed to determine if the rate of equipment failure is increasing, the discussion of the first bullet above explains the longer time to restore power following an equipment failure.

4.4 Station Blackouts

In NUREG-1032, an SBO is defined as the complete loss of AC electrical power to the essential and nonessential buses in a nuclear power plant. Several incidents at nuclear power plants have occurred that could be classified as precursors to SBO. This study found 16 LOSP events in which an LOSP and loss of emergency AC power occurred simultaneously. However, the duration of each event was small, and the need for accident mitigation systems powered from emergency AC power sources were not present in the events.

Two of the 16 events occurred during power operation. The other 14 events occurred when the units were shutdown or during refueling, when SBO regulatory requirements are reduced and the limiting condition for operation (LCO) requirements, in terms of numbers of offsite and emergency AC power supplies available, are also reduced. All events required manual operator actions to restore power. Most losses were caused by human errors while conducting tests or maintenance activities. Each loss had minimal impact on decay heat removal.

The two events occurring at power lasted 1 minute and 11 minutes respectively. U. S. NRC Regulatory Guide 1.155[9] specifies that the minimum coping time for nuclear power plants during a SBO is at least 2 hours, which is much greater than the durations of these two events. Using average values for the LOSP frequency (0.04/unit critical year for plant-centered events), EDG failure to start probability (0.01) and a common cause alpha factor (0.03) for two EDGs failing to start, the partial sequence frequency for loss of offsite power and two emergency diesel generators failing to start equals 1.6×10^{-5} [= 0.04 $((0.01)^2 + (0.03)(0.01))$] per unit critical year. Failure to recover offsite power or the EDGs in conjunction with additional system failures would be necessary for core damage to occur. Shorter recovery times would reduce this number by about an order of magnitude. Therefore, these events do not exhibit frequency or severity characteristics that are compatible with the SBO events modeled in NUREG-1032.

Six of the 14 shutdown events occurred while the reactor was defueled, and five events occurred during refueling outages. The unit configurations when these events occurred would not exist during power operations and are therefore not representative of the expected frequency or severity of SBO events at power operations. The length of time when electrical power was lost from the safety buses ranged from 40 seconds to 67 minutes. The only increase in temperature occurred during one event in which the temperature in the spent fuel pool increased about 3 degrees. The consequences of these events on core and spent fuel cooling were minimal.

5. CONCLUSIONS

This section highlights the major technical findings of the study.

- Not all LOSP events at power cause a reactor trip, because the design of some units allow the units to operate while using emergency power. Following the precedent of NUREG-1032, this report provides estimates of the frequency of LOSP initiating events at power. This report also provides the frequency of LOSP events during shutdown, ignoring whether such an event would have caused a trip at power.

This set of conclusions concern LOSP event frequency:

- NUREG-1032 found that plant-centered events accounted for the majority of the losses of offsite power. This study supports that finding, with plant-centered events clearly dominating LOSP frequency during power operation, as well as during non-power modes of operation. Events induced by severe weather are much less frequent, and grid-related events are still less frequent.

- LOSP frequency for plant-centered events is significantly higher during shutdown modes of operation than during power operation, by a factor of about four. The difference is present for both sustained and momentary events, and would be present even if non-initiating events at power were combined with the initiating events in the analysis. For severe-weather events and grid-related events, too few events occurred to give any firm conclusion.

- For plant-centered sustained initiating events at power, no statistically significant unit-to-unit variability in LOSP frequency was found. A decreasing trend in time was not statistically significant, based on the 1980 – 1996 data. Therefore no trend was modeled. The annual event counts showed larger-than-expected scatter around the mean, caused in part by dependence between units.

- For plant-centered sustained events during shutdown, significant statistical variability was found among the units, but not among years. Therefore, a population variability distribution was developed. Data at individual units were used to update this overall distribution, yielding unit-specific estimated frequencies.

- The majority of plant-centered LOSP initiating events at power were caused by equipment faults (58%), with a smaller portion being induced by human error (23%). During shutdown modes, the opposite holds, with human errors being the major contributor (58%). The numbers are similar if only sustained events or only momentary events are considered.

- Plant-centered initiating events per year have become less frequent since the time period studied by NUREG-1032. A clear downward trend can be seen in the frequency from 1969 through 1996. No effect was found in the data that could be related directly to the Station Blackout Rule (10 CFR 50.63), which was published in June 1988.

- The LOSP frequency from grid-related events in the period covered by this report, 1980 – 1996, was very small. During this period, there were only five site events that could be classified as grid-related, and two may have been dependent. This is less frequent than found in NUREG-1032 by a factor of about 10. No grid-related events occurred in the 1990s, in spite of the occurrence of several widespread losses of power to the public.

- During the time period of this study, there was only one LOSP event with total and sustained voltage loss to all safety buses due to a grid disturbance. A fire near Turkey Point caused a grid failure that resulted in both units experiencing a LOSP event.

- The frequency of LOSP sustained shutdown events due to severe weather exhibited statistically significant site-to-site variability. This is to be expected, as some power plants, merely because of their geographic location, will tend to have increased exposure to severe weather. Unit-specific estimates were obtained, to the extent possible from the small number of recorded events.

- Analysis of SBO risk was outside the scope of this study. However, 16 SBO events were identified during the data review in which a power plant unit had no AC electrical power from any source for up to 1 hour. Only two of these events occurred during power operations, and the longest of these two events lasted 11 minutes, which is well below the minimum coping time specified in U.S. NRC Regulatory Guide 1.155. The duration of each event was small and the need for accident mitigation system powered from emergency AC power was not present in the events.

- For momentary events, Pilgrim was an outlier, having 8 of the 24 momentary events. Pilgrim was excluded from all industry analyses of momentary events.

The next set of conclusions concern recovery times:

- For sustained plant-centered events, the events in which the reactor did not trip following the LOSP had longer recovery times than did the trip events and the shutdown events. No statistically significant difference could be seen between the sustained recovery times for trip and shutdown events. Therefore, the analysis of sustained recovery times was based on only the trip and shutdown events, which were combined.

- As found by NUREG-1032, the sustained recovery times were significantly longer for severe-weather events than for plant-centered events. Too few grid-related events occurred during the period of this report to permit comparison of their recovery times with plant-centered or severe-weather recovery times.

- NUREG-1032 defined unit design classes I1, I2, and I3, which were believed to have increasing recovery times. No such effect was seen in the 1980-1996 data. The sustained recovery times showed no pattern, and the fractions of events that were momentary did not differ much between design classes.

6. REFERENCES

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8. H. Wyckoff, *Losses of Offsite Power at U.S. Nuclear Power Plants*, TR-106306, April 1996, Electric Power Research Institute.

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GLOSSARY

1032 category - The category taken from NUREG 1032 to which the event was assigned. The three categories are plant-centered, grid-related, and severe-weather.

Cause - The direct cause of the electrical transient resulting in the loss of offsite power.

Docket - Three digit docket number of the affected unit.

Grid - Interconnected grid transmission lines, outside direct power plant control.

Grid-related - Events involving failure of the offsite power grid. If such events are caused by weather or storm, they are classified as severe-weather events, not as grid-related events, even though the grid was involved.

Loss of offsite power - Simultaneous loss of electrical power to all unit safety buses, requiring the emergency power generators to start and supply power to the safety buses.

LOSP initiating event - The LOSP event was considered an *initiating event* if the loss of offsite power (electrical transient) caused the reactor to trip or if both the LOSP and the reactor trip were part of the same plant transient, resulting from the same root cause. Additionally, some shutdown events were classified as initiating events if the licensee preemptively shut the unit down in anticipation of the LOSP event (e.g., severe weather events), but the LOSP event would have caused a reactor trip if the unit had been at power. It was not an initiating event if either no reactor trip occurred, or the cause of the reactor trip did not directly cause the LOSP event, but the reactor trip subsequently caused the LOSP event.

Momentary event - An LOSP event with a recovery time of less than 2 minutes.

Plant-centered - Following the approach of NUREG-1032, plant-centered events are those in which the design and operational characteristics of the unit itself play the major role in the cause and recovery time of the loss of offsite power. Plant-centered failures typically involve hardware failures, design deficiencies, human errors, and localized weather-induced faults (e.g., lightning).

P-value - The probability that the data set would be as extreme as this, if the assumed model is correct. It is the significance level at which the assumed model would barely be rejected by a statistical test. A small p-value indicates strong evidence against the assumed model.

Recovery time - The time (in minutes) at which AC power becomes available from non-emergency generator transformer power sources to power at least one unit safety bus. Note that this may be different from the time at which the failed source was recovered, or the time at which normal power was actually restored. Put another way, time to recovery is the time to which power from a non-emergency source could be available, by using approved licensee procedures and installed equipment, if the emergency AC generators were not available to provide power.

Unless the event report states otherwise, it is assumed that a minimum of 1 minute is required for operators to restore offsite power to the safety buses even if actual offsite power is never lost.

Severe weather - Weather with forceful and non-localized effects. A loss of offsite power is classified as a severe-weather event if it was judged that the weather was widespread, not just centered on the power plant site, and capable of major disruption. An example is storm damage to transmission lines instead of just debris blown into a transformer. This does not mean that the event had to actually result in widespread damage, as long as the potential was there. For example, a tornado might affect one unit and jump past the other; because of its potential, it would still be counted as a severe-weather event. Lightning strikes, though forceful, are normally localized to one unit, and so are coded as plant-centered.

Statistically significant - having a p-value of 0.05 or smaller. For example, if a trend is statistically significant, the model with no trend would be rejected at a significance level of 0.05 or larger.

Statistically significant at the xx level - having a p-value of xx or smaller.

Sustained event - An LOSP event with a recovery time of 2 minutes or more.

APPENDIX A

METHODS OF DATA ANALYSIS

APPENDIX A

METHODS OF DATA ANALYSIS

This appendix describes the methods for the basic data characterization and the estimation of occurrence frequencies. The descriptions give details of the methods and discussion of some of the reasoning behind the choice of methods. Results of these methods applied to the current set of data are presented in Appendix B.

A-1. PRELIMINARY ANALYSIS

A-1.1 Quality Checks on Event Coding

The first Quality Assurance (QA) verification that was performed consisted of comparing the events collected for this LOSP study (including all the events that did not meet the rigorous definition of a LOSP event for this report) to other published studies that evaluated events involving losses of offsite power to the nuclear power plant sites. These studies are listed as References 1-8 of the main report (not the Appendix A references) and are summarized here:

- NUREG-1032
- EDG Power System Reliability Study report
- NSAC182/203
- AEOD Grid Performance Factors report
- Evaluation of Loss of Offsite Power due to Plant-Centered Events
- ASP database
- Initiating Events Study report
- EPRI Loss of Offsite Power report

The purpose of the comparison was to ensure that all appropriate events were included in the LOSP event analysis, and to ensure correct classification of the events. During this comparison, two events were determined to belong in the LOSP study that were not already included in the database, primarily because during the initial screening the LER abstract did not contain sufficient information for the reviewer to identify the event as pertaining to a loss of offsite power.

Additionally, the data coding performed for this study was compared to the data coding performed for the Initiating Events study (Poloski et. al. 1998) to examine the comparability of the two studies. Some differences in event coding were found, due primarily to the difference between the objectives and methodologies of the two studies. The Idaho National Engineering and Environmental Laboratory (INEEL) staff performed a comparison between the external unit events coded by the INEEL subcontractor and the internal unit events coded by INEEL staff to ensure that events were not included in the database twice. Finally, all events used in the analyses for this study were reviewed by a second engineer to verify recovery times and proper categorization of the event (i.e., with respect to shutdown/operation, grid/weather, cause, etc.).

A-1.2 Events Used for Analysis

For the years 1980 through 1996, 176 events were found in which a loss of offsite power to all safety buses and a resulting demand for emergency power occurred. Only events that caused a total loss of offsite power to all safety buses were considered.

Only events that occurred after the full power license date (and before decommissioning) were considered in the analysis, to eliminate influencing the results by the learning curve that may occur between the low power license date and the full power license date. This eliminated three events, and all consideration of the Shoreham power plant events.

Of the remaining 173 events, a distinction was made between LOSP events and LOSP *initiating* events. Initiating events are defined for this study as the LOSP events that cause a reactor trip. In eleven events occurring at power, the reactor did not trip, because of the design of that particular unit. Although a similar event would presumably have caused a trip at some power plants, these events were not considered as initiating events. In an additional five events, a unit trip caused the LOSP rather than the LOSP being the initiator. These events were also not counted as initiating events. Thus, only 157 events were used for the analysis of event frequencies, 63 initiating events at power, and 94 events during shutdown. Note that all LOSP events during shutdown were counted, even at power plants where a similar event might not have caused a trip during power operation.

For the analysis of recovery times, all 173 events were considered relevant, in principle. When the recovery time for an event was reported or could be estimated, that time was used. However, groups of events were pooled or analyzed separately based on whether their recovery times appeared similar or not.

A-1.3 Critical Hours and Shutdown Hours

The critical hours for each unit were taken from the INEEL database CRITHRS (INEEL, 1997). These hours are drawn directly from the unit monthly operating reports, submitted by the licensees to the NRC. This database gives critical hours by month, beginning in January 1984. The only recognized inaccuracy in using this database for the present report concerns the month when a unit obtained its full power license, because information was unavailable on how many of the critical hours for the month occurred after the full power license. This inaccuracy is negligible. The shutdown hours for each year were obtained by subtracting the critical hours from the calendar hours in the year (8760 hours except in a leap year, or less if the unit received its full power license during the year or was decommissioned during the year.)

For the years 1981 - 1984, the UDI database (Utility Data Institute, 1997) was used. This gives dates of all outages, and their durations in hours. To use this data, a few reported overlapping outages were consolidated, and the unit names "Connecticut Yankee" and "Genoa Two" were interpreted as "Haddam Neck" and "La Crosse," respectively. This database goes back to 1981, and lists outages that began in 1980 only if they extended into 1981. The TMI 1 outage, which began before 1980, was not listed but was inserted manually. From this information, the shutdown hours for each unit and each year from 1981 through 1983 were obtained. The critical hours were obtained by subtracting the shutdown hours from the calendar hours for each unit and year.

For 1980, the critical hours and shutdown hours were not obtained. As discussed in Section B-2 of Appendix B, 33% of the 1980 calendar hours were estimated to be shutdown hours.

Most of the frequencies presented in this report are expressed in terms of years. For this purpose, a calendar year was defined as 365 days, that is, 8760 hours. A critical year was defined as 8760 critical hours for a reactor, and a shutdown year was defined as 8760 shutdown hours for a reactor. The time period from 1980 through 1996 had 17.014 calendar years, because of the five leap years in that period. This approach seemed the simplest way to convert results in terms of hours to results in terms of years.

The critical times and shutdown times are summarized in Table C-5 of Appendix C.

A-1.4 Defining Appropriate Subsets of the Data

One major goal of the analysis is to produce estimates of event frequencies and recovery times, for use in PRA studies. For this, the data must be divided into qualitatively similar subsets. Four ways of dividing the data into subsets were considered, and used where appropriate:

1. A PRA usually considers the operating state of the unit being considered — the unit is assumed to be operating at power, or, occasionally, it is assumed to be in a shutdown condition. Therefore, the data should be examined to see if the desired quantities, that is, the event frequencies and times to recovery, differ for *operating* units and *shutdown* units.

2. NUREG-1032 (Baranowsky, 1988) classified LOSP events as *plant-centered*, *grid-related*, and caused by *severe weather*. Two reasons for this classification were that the classes involved different mechanisms, and that they seemed to have different recovery times on average. Therefore, these divisions were considered for the present study as well.

3. The events were classified according to their causes: *equipment problem*, *human error*, *external environment*, and *other*. Severe-weather events were, by definition, all caused by the external environment, but plant-centered and grid-related events could have a variety of causes. Therefore, the data were analyzed to see if the subsets of plant-centered and grid-related events deserved separate treatment. In the end these distinctions were not used, but they were considered.

4. About 15% of the events lasted only a very short time, about one minute. For many of these, it was judged that power could have been recovered in about one minute. Therefore, events for which power was recovered, or could have been recovered, in less than 2 minutes were called *momentary*. The others were called *sustained*. The recovery times could typically be characterized by a lognormal distribution for the sustained events plus a spike at one minute

for the momentary events. The easiest way to present the results was to analyze the momentary and sustained events separately.

The above conditions can be considered simultaneously, for example, plant-centered sustained events caused by human error during shutdown. The analysis of frequencies was not required to use the same data groupings as the analysis of recovery times. For example, for frequencies the plant-centered sustained events were divided into two classes, initiating events and shutdown events, because the frequencies were clearly different. For recovery times, on the other hand, plant-centered sustained trip events and shutdown events were considered as one class of events, because the recovery times did not seem to be related strongly to the shutdown/operation distinction.

A-1.5 Statistical Tools for Comparing Data Subsets

The data were evaluated to determine the most appropriate partitioning for subsequent analysis. For example, plant-centered events during shutdown could be divided into three subsets according to their causes: equipment problems, human error, or external environment. Both graphical methods and formal statistical tests were used to see whether the subsets of the data were similar enough that they could be combined. The methods are described in many statistical texts, and in the references cited below. The specific tools used are presented here, for comparing recovery times and for comparing event frequencies.

A statistical test can be used to show *statistical* significance, that is, to show whether the data give strong evidence of a difference between the subsets. A graphical comparison can be used to show *engineering* significance, that is, whether the differences among the subsets are large enough to be important in practice. Both kinds of significance were considered for the presentations of this report.

A-1.5.1 Frequencies

A frequency is a rate of occurrence, with units 1/time. If the events are independent and generated by a Poisson process with constant occurrence rate, standard analysis tools are available. Engelhardt (1994) explains these tools, which are briefly summarized here.

For a graphical comparison, the maximum likelihood estimate (MLE) and a confidence interval for the frequency, λ, were calculated for each subset. These intervals were plotted side by side to see if they overlapped.

The Pearson chi-squared test was used to test equality of the frequencies. The significance level, or p-value, was calculated using a large-sample approximation. A p-value of 0.05 is typically calculated with adequate accuracy if the number of events is at least as large as the number of subsets being compared. Engelhardt summarizes further refinements on this rough guideline.

A-1.5.2 Recovery Times

A box plot (also called a box-and-whisker plot) was constructed for the recovery times of events from each subset, and the boxes were compared to see how much they overlapped. Box plots are constructed as follows in the implementation by SAS/INSIGHT (1995). The lower quartile of a distribution is the 25th percentile, the upper quartile is the 75th percentile, and the interquartile range is defined as the distance from the lower to the upper quartile. For a distribution defined by data, one fourth of the data values lie at or below the lower quartile, and one fourth of the values lie at or above the upper quartile. The median is the 50th percentile, with half of the data values lying on each side of the median. A box plot shows a box going from the lower quartile to the upper quartile, with a line at the median. The whiskers are two lines extending out from the ends of the box. Each whisker has length up to 1.5 times the interquartile range; however if this length makes the whisker extend beyond the most extreme data value, the whisker stops at the most extreme data value. Any points beyond the whiskers are shown individually. Appendix B contains box plots, Figures B-9 through B-12 and B-22 through B-23. Because recovery times (times to recovery of offsite power) have highly skewed distributions, the box plots were calculated using $\log_{10}$(recovery time).

Box plots provide an informal graphical comparison of distributions. More formal comparisons were carried out by the statistical tests of equality of distributions, in particular the Wilcoxon and Kolmogorov-Smirnov tests for two distributions, and the Kruskal-Wallis test for two or more distributions. These tests were used to supplement the qualitative evidence of the box plots. The tests are implemented by the SAS (1990) procedure NPAR1WAY.

A-1.5.3 Non-Independence of Events and Recovery Times

The statistical techniques given above all assume that the quantities measured — event counts or event recovery times — are statistically independent. However, the event counts and recovery times are not always independent, as illustrated by the following examples. An equipment problem caused LOSP at units 2 and 3 of Peach Bottom, and the times to recovery (event recovery times) were identical (LER 27788020). A fire caused a collapse of the grid in south Florida; units 3 and 4 of Turkey Point both lost offsite power, and the recovery times were similar (LER 25185011). A hurricane caused loss of power at Millstone 1 and Millstone 2, with recovery times of similar magnitude (LER 24585018). In the cases just mentioned, the event occurrences were positively correlated, that is, the probability of LOSP at the second unit increased when the first unit lost power. The recovery times were also positively correlated, that is, the two recovery times tended to be similar in length. A possible negative correlation is seen when Rancho Seco experienced two grid instabilities within 2 months of each other (LERs 31281034 and 31281039). The second event had a shorter recovery time than the first event, possibly because of the experience acquired during the first event.

These examples illustrate that a few dependencies exist, for plant-centered events, grid-related events, and severe-weather events. The statistical analyses dealt with these dependencies as follows.

Frequencies. Consider plant-centered events first. Frequencies per site year are not calculated here. Instead, the analysis presents frequencies per unit critical year or per unit shutdown year, for three reasons. First, most plant-centered events did not involve multiple units. Therefore, an analysis of frequencies by unit is natural. Second, the frequencies are substantially different for initiating events at power and shutdown events. For a single reactor, shutdown hours and critical hours are easily defined. For a site, however, critical hours and shutdown hours are not easily defined. If one unit is shut down and one is operating for a full year, does the site have both a shutdown year and a critical year? Because of this conceptual difficulty, no attempt was made to define site critical time and site shutdown time.

The plant-centered initiating events were treated as independent, and the plant-centered shutdown events were treated as independent. This had the following effects when the standard statistical formulas were applied. Dependencies were rare; there were only 7 pairs of events out of 130 unit events, with two of those pairs involving one operating unit and one shutdown unit. There, the effect of ignoring the dependencies is small. The dependencies do exaggerate the random variability in total counts per year, however. This explains part of the extra-Poisson scatter (seen as between-year variation) when time trends are considered.

Now consider grid-related events and severe-weather events. Every event at a multiple-unit site had LOSP at all the units of the site. The data sets were too small to show clear evidence of a difference between the initiating event rate and the shutdown rate. Therefore, the events were modeled as site events, with frequencies given as site events per site calendar year.

Some dependencies remained, however. The two grid-related events at Rancho Seco may have been dependent. This possible dependence (out of three sustained site events) seems to invalidate any analysis, and no frequency analysis was performed. The three severe-weather events at Crystal River 3 all occurred within a single month, and two may have been caused by a single storm. These dependencies are not modeled in this study. However, the possible dependence of the Crystal River 3 events was one reason for combining the operating and shutdown data; the resulting larger data set helped dilute the effect of the dependencies.

Recovery Time. Although the definition of a momentary event is an event with a recovery time less than 2 minutes, most momentary events have a recovery time of about one minute. The data for sustained events were analyzed for components of variance, as follows. In the end, it was decided that the between-unit and between-site variations were not worth modeling. However, consideration of the components of variance justified the final simple analysis method.

Missing values were ignored. The distribution of log(recovery time) is more nearly symmetrical than the distribution of the recovery time itself. Because the methodology uses variances of the distributions, and because variances are better descriptors of symmetrical distributions than of highly asymmetrical distributions, the analysis was performed on log(recovery time). Natural logarithms were used.

The following model was assumed:

$$\log(\text{recovery time}) = \mu + X_{\text{site}} + X_{\text{event}} + X_{\text{resid}} \qquad \text{(A-1)}$$

where the Xs are independent random variables. That is, the log(recovery time) of a random event at a random power plant unit has an overall average value μ, plus a term that depends on the site, plus a term that depends on the particular event (the human error, equipment problem, hurricane, etc.), plus a residual random term. The residual variation is indistinguishable from variation between units, because the only way to observe different recovery times from a single event is to observe the recovery times at different units; the event itself cannot be repeated to observe its effect during the next trial. Because a single event occurs only at one site, and can affect both units at a site, event is nested within site and residual variation is nested within event. In the data analysis, event date was used as a surrogate for event.

For a recovery time from a random event at a random site and random unit, the mean is the sum of the means and the variance is the sum of the variances. One way of modeling the X terms is to assign them all mean zero, so that the overall mean is μ. The variance is

$$\sigma^2_{\text{total}} = \sigma^2_{\text{site}} + \sigma^2_{\text{event}} + \sigma^2_{\text{resid}} , \tag{A-2}$$

where each σ^2 is the variance of the corresponding X. This equality does not require normal distributions; it is a property of variances of independent random variables.

The values σ^2_{site}, σ^2_{event}, and σ^2_{resid} are called the *components of variance*. They are estimated from the data, using the SAS procedure VARCOMP (SAS 1990), with the REML (restricted maximum likelihood) estimator. REML estimation, explained by Searle et al. (1992), has become one of the most accepted methods for estimating variance components with unbalanced data. If the data contain one or more events that affect multiple units, σ^2_{resid} can be estimated. If the data contain one or more events at a single site, σ^2_{event} can be estimated. And if the data contain events from more than one site, σ^2_{site} can be estimated.

In every case analyzed, σ^2_{resid} was estimated to be a very small fraction of σ^2_{total} in Equation (A-2), at most a few percent. Therefore, it was ignored, as follows. For each event affecting multiple units, the recovery times were averaged, and this single recovery time was assigned to the site event. The distribution of recovery times was estimated using this averaged data, one recovery time for each site event. This eliminates the major dependence among the recovery times.

In addition, σ^2_{site} was always smaller than σ^2_{event}. When it was much smaller, a few percent, it was dropped from the model. When σ^2_{site} was only somewhat smaller, less than half as large as σ^2_{event}, engineering understanding was used to decide whether to drop σ^2_{site} from the model.

A-2. QUANTIFYING THE EVENT FREQUENCIES

The preceding section considered which groups of events should be analyzed together. This section of the report presents the methods used in the estimation of frequencies. Section A-3 below presents the methods used in estimation of the distribution of recovery times.

The statistical method chosen for analyzing a subset of the data depended on the complexity of the data set. A data set with only a few event occurrences must be analyzed simply. A data set with a large number of events requires more complicated modeling, so that the estimates can reflect the trends or patterns that are evident in the data. The three models used are described here, beginning with the simplest.

The assumption underlying all the models is that the events occur following a Poisson process, so that in any small time interval Δt, the probability of an event occurring is $\lambda\Delta t$. The basic properties of this model are described by Engelhardt (1994) and in many statistics books. The different models are determined by the form of λ, specifically, whether λ is constant, or dependent on the specific unit, or dependent on the calendar year. No data set was large enough to show dependence on both.

In every case, a desired result is a Bayesian distribution for the event occurrence frequency or frequencies, that can be used in PRAs. In some models, a Bayesian distribution is obtained directly, by using the data to update a prior distribution. The prior distribution either is chosen to be noninformative (not reflecting any strong prior information or belief), or is inferred from the data. In other models, classical (non-Bayesian) methods are used, and a Bayesian distribution is constructed afterwards so that the Bayesian uncertainty intervals match the classical confidence intervals. The result is a Bayesian distribution that depends on the data but not on prior information or belief.

After the models are described, a separate section explains the data-analysis methods used to decide which model is most appropriate.

A-2.1 Constant Generic Frequency

Here λ is assumed to be the same for all units and all time. This simple model is appropriate when very few events have occurred. Let n be the observed number of events in t critical hours. The Jeffreys noninformative prior distribution is updated by the data to produce a posterior distribution, which has a gamma form. The two parameters are the shape parameter, equal to $n + ½$, and the scale parameter, equal to t hours. The mean of the distribution is $(n + ½)/t$. For further explanation, see Engelhardt (1994).

A-2.2 Constant Frequencies, Differing Among Units

This model says that the ith unit has an event frequency λ_i, which is constant over time but possibly different from the frequencies of the other units. The other main assumption is that the events occur independently, at a unit and among various units. The model used was a parametric empirical Bayes model. The units were modeled as belonging to a family. Any one unit was treated as being drawn randomly from the family. The distribution of λ_i within this family was modeled parametrically, and for mathematical convenience, the distribution was assumed to be a gamma(a, b) distribution. (During any data analysis, this assumption was checked to make sure that it was consistent with the data.) Therefore, the model was that λ_i for the ith unit is generated randomly from a gamma(a, b) distribution, and that the random number of failures in the observed t_i hours (operating or shutdown hours, as appropriate) is Poisson with mean $\lambda_i t_i$.

The empirical Bayes method estimates a and b from the data. That is, the likelihood function for the data is based on the observed number of event occurrences and (operating or shutdown) hours at each unit and the assumed gamma-Poisson model. This function of a and b was maximized through an iterative search of the parameter space, using a SAS routine given by Engelhardt (1994). In order to avoid fitting a degenerate, spike-like distribution whose variance is less than the variance of the observed failure counts, the parameter space in this search was restricted to cases where b was less than the total number of observed critical hours. The a and b corresponding to the maximum likelihood were taken as estimates of the gamma distribution parameters representing the observed data for the failure mode.

The resulting distribution was then updated by the data for each unit, to produce a unit-specific distribution for λ_i. A refinement, due to Kass and Steffey (1989) was also used, which adjusted these unit-specific distributions to account for the fact that a and b were only estimated, not known exactly. The form of each adjusted unit-specific distribution was approximated by a gamma distribution, which is printed in the report. For further discussion, see Engelhardt (1994).

A-2.3 Trend in Calendar Time, with No Differences Among Units

If a trend in time was postulated, but no strong differences between units were evident, the form of the occurrence frequency was modeled as $\lambda = \exp(a + by)$ or equivalently, $\log(\lambda) = a + by$, where y denotes the calendar year. If b is negative, the trend is decreasing. This model is a *loglinear* model, and methods for analyzing data from such a model are explained by Atwood (1995) and by certain advanced texts. The SAS procedure GENMOD (SAS 1993) was used to analyze data using this model. In nearly all the cases considered in this report, either the trend was not statistically significant or the model fit badly because of one or more outlying years. Only in one case did the trend model fit the data well and show a statistically significant trend: For comparison with NUREG-1032, the data for plant-centered initiating events were extended back to 1969, and a decreasing trend was seen. For plant-centered initiating events using the 1980-1996 data, the trend was not significant, after the substantial lack of fit was accounted for.

To model a trend with lack of fit, it was assumed that the count during any year was not Poisson distributed, but instead had a negative binomial distribution. The negative binomial distribution was chosen because it is commonly used when extra-Poisson variance must be modeled. The mean count was assumed to change exponentially over time, and the coefficient of variation was assumed to be constant. This led to a three-parameter model. The three parameters were estimated by maximum likelihood, and the asymptotic distribution of the maximum likelihood estimators was used to quantify the uncertainty in the estimates.

Mathematically, this is identical to an empirical Bayes analysis with a trend in the mean; however, the interpretation is different.

The program to do this was written in SAS. The output of the program was compared to GENMOD output, both for some test data and for the plant-centered initiating event data, and the results were consistent: the three-parameter model showed a similar trend, but: (a) the three-parameter model saw less statistical significance in the trend than did GENMOD, (b) it calculated a wider confidence band around the fitted trend than did GENMOD, and (c) the increase in width of the confidence band was consistent with the size of the lack-of-fit statistic produced by GENMOD. These comparisons were just as expected.

A-2.4 No Trend, but Extra-Poisson Variation

This is similar to modeling a trend with extra-Poisson variation, as discussed above, except the trend term is constant. The count for each year is assumed to have a negative binomial distribution instead of a Poisson distribution. Mathematically, this is equivalent to a gamma-Poisson distribution, which is the distribution used in empirical Bayes modeling of Poisson counts. Thus, the desired answer can be found by formally constructing an empirical Bayes model of the between-year variation. The empirical Bayes software used for estimating the underlying gamma distribution of λ yields a distribution for λ which accounts for the extra-Poisson variation.

A-3. ESTIMATING THE DISTRIBUTION OF RECOVERY TIMES

This section of the report presents the methods used in estimation of the distribution of recovery times. Recovery times less than 2 minutes were excluded from these analyses.

A-3.1 Independent Identically Distributed Recovery Times

As explained in the recovery time portion of Section A-1.5.3, the recovery time data were analyzed for components of variance. In every case, it was concluded that only one component of variance needed to be modeled, the component corresponding to events. The recovery times from different events were then treated as independent identically distributed random values.

To characterize the distribution of the sustained recovery times, the lognormal distribution fit well. Therefore, other distributions, such as gamma and Weibull, were not considered. The lognormal parameters were estimated by treating log(recovery time) as normally distributed, and calculating the usual unbiased estimators of the mean and variance. The fit was assessed both by graphical plots and by the Shapiro-Wilk test of normality. Royston (1988) describes this test as "one of the most powerful 'omnibus' procedures for testing univariate nonnormality."

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APPENDIX B

RESULTS OF DATA ANALYSIS

APPENDIX B

RESULTS OF DATA ANALYSES

This appendix describes the results of the data analyses, using the methods presented in Appendix A. The analyses of initiating event frequencies and of recovery times are driven by different considerations, and are completely separate. Initiating event frequencies are presented first, and recovery times second.

B-1. PRELIMINARY ANALYSIS OF INITIATING EVENT FREQUENCIES

During the preliminary analysis, frequencies were analyzed by unit, not by site. Critical time and shutdown time for each unit were obtained for 1981-1996. To make use of the 1980 events, the shutdown portion of 1980 was estimated as follows. Using Table C-5, the industry percentage of shutdown time was calculated for each year. From 1981 through 1987, the percentage was between 31% and 35%, with no evident trend in those years. The average was 33%. Therefore, the shutdown time *for each unit* in 1980 was estimated as 33% of the calendar time for the unit, and the critical time was estimated as the remaining time. More accurate information could be obtained only with difficulty, by careful examination of many monthly operating reports now stored on microfiche; this was not considered an effective use of resources. Trend analyses might be especially sensitive to the 1980 shutdown or critical time. Therefore, as a check, each trend analysis was reperformed, setting the 1980 shutdown time to 31% and 35% of the 1980 calendar time, and little difference in the conclusions of the analysis was noted. Only the results using 33% are presented here.

The momentary and sustained events were analyzed separately. Eight of the 24 momentary shutdown and initiating events occurred at one power plant, Pilgrim. Therefore, Pilgrim was regarded as an outlier, with respect to momentary events. The analysis of momentary events below excludes Pilgrim. The data in this report could be used for a plant-specific analysis of Pilgrim. However, anyone performing such an analysis will have access to more information than we had, such as information about upgrades in the switchyard. It would be incorrect to analyze the Pilgrim data without such information.

To explore the frequency of initiating events, we considered those events in Tables C-1 through C-3 that had a '1' in the column 'Initiator.' This excluded the shutdown events, the power-operation events, and the five trip events for which the trip preceded the LOSP. To explore the frequency of the shutdown events, we considered those events with S or S* in the 'Status' column. Assuming homogeneous data sets of independent events, point estimates and 90% confidence intervals were calculated for the frequencies (events per critical year or events per shutdown year.) The statistical method is explained in Appendix A. These estimates and intervals are shown in Figures B-1 and B-2. The identifiers on the left show whether the events are plant-centered (P), grid-related (G), or severe-weather (W), and whether the event was a reactor trip or a shutdown event. The identifiers also show the number of events divided by the relevant number of reactor years in the 1980-1996 period.

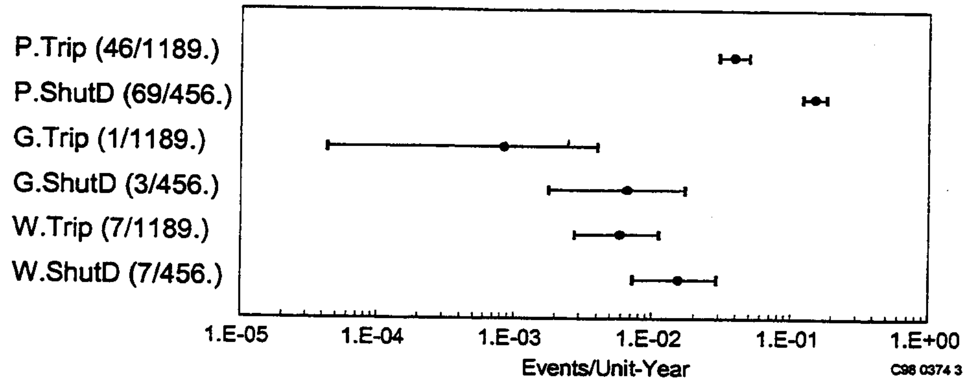

Figure B-1. Frequencies of sustained LOSP initiating events and shutdown events. Points are maximum likelihood estimates and intervals are 90% confidence intervals. Units are events per unit critical year and events per unit shutdown year, respectively.

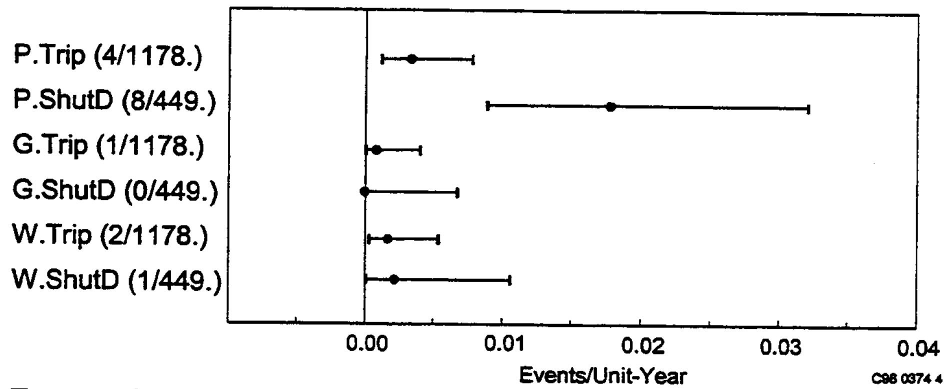

Figure B-2. Frequencies of momentary LOSP initiating events and shutdown events. The labels and symbols have the same meaning as in Figure B-1. Events at Pilgrim are excluded.

The figures show that the reactor status, operating or shutdown, clearly affects the frequencies of plant-centered events. That is, for sustained events and also for momentary events, plant-centered events have higher frequencies when the reactor is shut down than when it is operating. Section 4.1.1 discusses engineering reasons for this.

The different causes of the classes of events are tabulated in Tables B-1 and B-2. The trip events include a few non-initiators. This table demonstrates that shutdown events have a high fraction of human error causes (over 50%), whereas trip events have a high fraction of equipment causes (over 50%). The pattern holds for both sustained and momentary events. In each table, the difference between shutdown and trip events is statistically significant. One might expect that all events at power would have the same pattern of causes, whether or not the unit responded by tripping. However, the tables are not clear as to whether this is the case.

Table B-1. Number of plant-centered sustained events for each cause and plant status (including events for which recovery times not reported.)

	Equipment	Ext. Envir.	Human	Other	Total
Power, no trip	4 (44%)	4 (33%)	1 (11%)	0	9
Trip	28 (58%)	6 (13%)	13 (27%)	1 (2%)	48
Shutdown	25 (36%)	5 (7%)	39 (57%)	0	69
Total	57 (45%)	15 (12%)	53 (42%)	1 (1%)	126

Table B-2. Number of plant-centered momentary events, for each cause and plant status, excluding Pilgrim.

	Equipment	Extern. Envir.	Human Error	Total
Power, no trip	1	1	0	2
Trip	5	0	1	6
Shutdown	1	1	6	8
Total	7	2	7	16

Return now to Figure B-1. Severe-weather sustained events also show a tendency to be more frequent during shutdown than during power operation, but it is difficult to say whether the difference is statistically significant. The calculated p-value is 0.06, but the calculation assumes independent events, which is not the case for this data set. The *unit* events were dependent, but the *site* events were independent, or nearly so. Although there were 7 momentary unit initiating events and 7 momentary unit shutdown events, there were only 4 momentary *site* initiating events and 6 momentary *site* shutdown events. If site critical years and site shutdown years could be calculated, the data set for site events would presumably show a difference between the estimated initiating event rate and shutdown rate that is more extreme than in Figure B-2, although based on fewer events. Thus, the calculation of p-values is inconclusive.

Engineering considerations suggest that plants may be more vulnerable to LOSP during shutdown than during operation, for the same reasons as for plant-centered events. However, this assumes that the plants do not modify their shutdown electrical configurations in anticipation of approaching storms. After several analyses were tried, the following considerations led to an analysis by site, ignoring the difference between operation and shutdown.

- The difference between frequencies during shutdown and operation power is not clear.
- It is natural to consider severe-weather events as site events. Every severe-weather event at a multiple-unit site involved LOSP at all units.
- Small data sets should not be subdivided unnecessarily. For example, the three Crystal River 3 events have more influence in a set of 7 unit events during shutdown than in a set of 10 site events during both operation and shutdown. The larger data set, though still small, provides somewhat more confidence in the fitted empirical Bayes model, and dilutes the effect of possible dependence of the Crystal River events.

For grid-related events, to the extent that any analyses are performed, they are performed by site, for the same reasons as for severe-weather events.

In summary, this report analyzes frequencies for the following classes of events:

- Plant-centered sustained initiating unit events during power operation,
- Plant-centered sustained unit events during shutdown,
- Plant-centered momentary initiating unit events during power operation,
- Plant-centered momentary unit events during shutdown,
- Grid-related sustained site events,
- Grid-related momentary site events,
- Severe-weather sustained site events, and
- Severe-weather momentary site events.

B-2. ESTIMATION OF EVENT FREQUENCIES

First, based on the data, one must decide which model to use: whether to model a time trend and whether to model differences between units.

The analysis steps are given in Section A-2 of Appendix A. First, the possibility of differences between years was considered, and the possible presence of a time trend. Next, the data were analyzed for possible differences between units. If differences are modeled, they should not only be statistically significant; they should also be significant from an engineering standpoint, that is, large enough to have a practical effect. Therefore, when unit-specific frequencies could be estimated, the highest and lowest unit-specific rates were compared, to see if the difference was significant from an engineering perspective. Table B-3 summarizes the results of all the analyses mentioned so far.

Table B-3 mentions p-values. Moderately accurate calculation of small p-value requires at least 58 events for analysis by unit, at least 37 events for analysis by site, and at least 9 events for analysis by year. When small p-values based on fewer events are shown, they should be interpreted as extremely rough.

The conclusions on how to treat the data in the analyses are as follows. For sustained events:

- Plant-centered initiating events, during operation. Model the extra-Poisson variation between years. The trend is not statistically significant even at the 0.1 level. Present a generic estimate, with no trend. The estimate is mathematically equivalent to an empirical Bayes distribution accounting for year-to-year variation.

- Plant-centered events, during shutdown. Pool the data from all the years, and quantify between-plant variation with an empirical Bayes model.

Table B-3. Summary of data analyses for frequencies.

	Events	Betw.-year diffs?	Trend in time?	Betw.-unit or betw.-site diffs?
		Sustained events		
P-Init. **(by unit)**	46	Yes, p-val = 0.009	Minimal: p-val = 0.03 when lack of fit ignored; p-val = 0.11 when lack of fit modeled	No, p-val = 0.4
P-SD **(by unit)**	69	Minimal, p-val = 0.1	No, p-val = 0.3	Yes, p-val = 0.0000 Emp. Bayes ratio of highest to lowest = 10
G-total **(by site)**	3	Yes, p-val=0.01, but very few events, which may be dependent	Minimal, p-val=0.07, but very few events, which may be dependent	Yes, but very few events, which may be dependent
W-total **(by site)**	10	Borderline, p-val = 0.07, caused by 1993 storm	No, p-val = 0.18	Yes, p-val = 0.005, but calculation assumes independent events
		Momentary events		
P-Init. **(by unit)**	4	No, p-val = 0.6	No, p-val = 0.4	No, p-val = 0.9
P-SD **(by unit)**	11	No, p-val = 0.8	No, p-val = 0.5	Yes, p-val = 0.004, Pilgrim high
G-total **(by site)**	1	No	No	No
W-total **(by site)**	7	No, p-val = 0.8	No, p-val = 0.11, calculation influenced by Pilgrim events	Yes, p-val = 0.0000, Pilgrim high
		Momentary events, without Pilgrim		
P-Trip **(by unit)**	4	No, p-val = 0.6	No, p-val = 0.4	No, p-val = 0.9
P-SD **(by site)**	8	No, p-val = 0.7	No, p-val = 0.7	Yes, p-val = 0.016, but data set small, and emp. Bayes estimate is degenerate
G-total **(by site)**	1	No	No	No
W-total **(by site)**	2	No, p-val = 0.4	No, p-val=0.2	No, p-val = 0.85

- Grid-related events. Two of the events occurred at one power plant (Rancho Seco) in 1981. It seems oversimplified to model the high rate there as a function only of the specific power plant or only of the year; however it is difficult to construct a truly appropriate model. One other site event occurred at Turkey Point, where the grid has since been modified (P. Baranowsky, personal communication). For these reasons, present the data but do not perform a statistical analysis.

- Severe-weather site events. Pool the data from all the years, and quantify between-site variation with an empirical Bayes model.

For momentary events, treat Pilgrim separately. Obtain industry estimates with Pilgrim excluded, as follows.

- Plant-centered events. Calculate a single generic estimate for momentary initiating events during operation, and a single generic estimate for momentary shutdown events.

- Grid-related events. Calculate a single generic estimate for momentary events.

- Severe-weather events. Calculate a single generic estimate for momentary events.

Numerical values of the event occurrence rates are displayed in Table B-4. Each line refers to a Bayesian distribution for the event frequency. The first three numbers in the line (columns 2 through 4) are the 5th percentile, the mean, and the 95th percentile of the frequency, in units of events per critical year or shutdown year, as relevant.

Each distribution is presented as a distribution form accompanied by two parameters. Gamma distributions are shown in the form gamma(shape parameter, scale parameter), where the shape parameter is unitless and the scale parameter is in unit critical years or unit shutdown years. The mean of the distribution is (shape parameter)/(scale parameter), and the percentiles must be found by a computer calculation.

Table B-4. Event occurrence rates: means, percentiles, and distributions. (See text for detailed explanation.)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Plant-centered initiating events during operation				
Sustained events (46 unit events; calculated uncertainty accounts for between-year variation, above expected variation of Poisson counts)				
Industry	6.39E-3	4.00E-2	9.73E-2	gamma[a](1.844, 46.12 unit crit. yrs.)
Momentary events (4 unit events, excluding Pilgrim)				
Industry	1.41E-3	3.82E-3	7.18E-3	gamma[a](4.500, 1178.6 unit crit. yrs.)
Plant-centered events during shutdown				
Sustained events (69 unit events, between-unit variation modeled)				
Industry	1.07E-2	1.58E-1	4.54E-1	gamma[a](1.127, 7.131 unit down yrs.)
Arkansas 1	6.37E-3	1.02E-1	2.95E-1	gamma(1.087, 10.70 unit down yrs.)
Arkansas 2	6.50E-3	1.03E-1	3.01E-1	gamma(1.089, 10.53 unit down yrs.)
Beaver Valley 1	6.18E-3	9.91E-2	2.88E-1	gamma(1.085, 10.96 unit down yrs.)
Beaver Valley 2	4.36E-2	2.46E-1	5.85E-1	gamma(1.995, 8.10 unit down yrs.)
Big Rock Point	3.56E-2	1.92E-1	4.49E-1	gamma(2.075, 10.83 unit down yrs.)
Braidwood 1	4.09E-2	2.26E-1	5.33E-1	gamma(2.030, 8.98 unit down yrs.)
Braidwood 2	8.58E-3	1.33E-1	3.86E-1	gamma(1.101, 8.27 unit down yrs.)
Browns Ferry 1	3.04E-3	5.46E-2	1.61E-1	gamma(1.035, 18.97 unit down yrs.)
Browns Ferry 2	4.21E-3	7.16E-2	2.10E-1	gamma(1.058, 14.77 unit down yrs.)
Browns Ferry 3	3.12E-3	5.58E-2	1.65E-1	gamma(1.037, 18.58 unit down yrs.)
Brunswick 1	2.95E-2	1.56E-1	3.65E-1	gamma(2.099, 13.42 unit down yrs.)
Brunswick 2	3.06E-2	1.62E-1	3.80E-1	gamma(2.096, 12.90 unit down yrs.)
Byron 1	7.81E-3	1.22E-1	3.53E-1	gamma(1.098, 9.01 unit down yrs.)
Byron 2	8.62E-3	1.34E-1	3.87E-1	gamma(1.101, 8.24 unit down yrs.)
Callaway	8.40E-3	1.30E-1	3.78E-1	gamma(1.101, 8.44 unit down yrs.)
Calvert Cliffs 1	5.66E-3	9.18E-2	2.68E-1	gamma(1.079, 11.75 unit down yrs.)
Calvert Cliffs 2	5.85E-3	9.45E-2	2.75E-1	gamma(1.082, 11.45 unit down yrs.)
Catawba 1	7.22E-3	1.13E-1	3.29E-1	gamma(1.095, 9.65 unit down yrs.)
Catawba 2	7.71E-3	1.20E-1	3.49E-1	gamma(1.098, 9.12 unit down yrs.)
Clinton 1	7.48E-3	1.17E-1	3.40E-1	gamma(1.097, 9.36 unit down yrs.)
Comanche Peak 1	8.71E-3	1.35E-1	3.91E-1	gamma(1.101, 8.16 unit down yrs.)
Comanche Peak 2	9.21E-3	1.43E-1	4.13E-1	gamma(1.101, 7.72 unit down yrs.)
Cook 1	6.24E-3	9.99E-2	2.91E-1	gamma(1.086, 10.87 unit down yrs.)
Cook 2	5.66E-3	9.18E-2	2.68E-1	gamma(1.079, 11.75 unit down yrs.)
Cooper	5.77E-3	9.34E-2	2.72E-1	gamma(1.081, 11.58 unit down yrs.)
Crystal River 3	1.96E-1	4.96E-1	9.06E-1	gamma(5.042, 10.17 unit down yrs.)
Davis-Besse	5.51E-3	8.99E-2	2.62E-1	gamma(1.078, 11.99 unit down yrs.)
Diablo Canyon 1	8.56E-2	3.41E-1	7.35E-1	gamma(2.742, 8.04 unit down yrs.)
Diablo Canyon 2	8.15E-3	1.27E-1	3.67E-1	gamma(1.100, 8.68 unit down yrs.)
Dresden 2	5.41E-3	8.84E-2	2.58E-1	gamma(1.076, 12.18 unit down yrs.)
Dresden 3	5.38E-3	8.80E-2	2.57E-1	gamma(1.076, 12.23 unit down yrs.)
Duane Arnold	3.58E-2	1.93E-1	4.52E-1	gamma(2.074, 10.77 unit down yrs.)
Farley 1	3.89E-2	2.12E-1	5.00E-1	gamma(2.050, 9.66 unit down yrs.)
Farley 2	4.12E-2	2.28E-1	5.39E-1	gamma(2.027, 8.88 unit down yrs.)
Fermi 2	6.14E-3	9.85E-2	2.87E-1	gamma(1.085, 11.02 unit down yrs.)
Fitzpatrick	5.77E-3	9.33E-2	2.72E-1	gamma(1.081, 11.58 unit down yrs.)

Table B-4. Event occurrence rates: means, percentiles, and distributions. (continued)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Fort Calhoun	1.21E-1	3.84E-1	7.67E-1	gamma(3.578, 9.32 unit down yrs.)
Fort St. Vrain	5.26E-3	8.64E-2	2.52E-1	gamma(1.074, 12.44 unit down yrs.)
Ginna	6.92E-3	1.09E-1	3.17E-1	gamma(1.092, 10.00 unit down yrs.)
Grand Gulf	7.67E-3	1.20E-1	3.48E-1	gamma(1.098, 9.16 unit down yrs.)
Haddam Neck	1.57E-1	4.35E-1	8.25E-1	gamma(4.350, 10.00 unit down yrs.)
Harris	8.27E-3	1.28E-1	3.72E-1	gamma(1.100, 8.57 unit down yrs.)
Hatch 1	3.55E-2	1.91E-1	4.47E-1	gamma(2.076, 10.89 unit down yrs.)
Hatch 2	6.52E-3	1.04E-1	3.02E-1	gamma(1.089, 10.49 unit down yrs.)
Hope Creek	8.10E-3	1.26E-1	3.65E-1	gamma(1.100, 8.73 unit down yrs.)
Indian Point 2	1.14E-1	3.55E-1	7.04E-1	gamma(3.682, 10.37 unit down yrs.)
Indian Point 3	9.23E-2	2.74E-1	5.33E-1	gamma(3.929, 14.36 unit down yrs.)
Kewaunee	7.37E-3	1.16E-1	3.35E-1	gamma(1.096, 9.48 unit down yrs.)
La Crosse	1.81E-1	5.45E-1	1.07E+0	gamma(3.852, 7.07 unit down yrs.)
LaSalle 1	6.32E-3	1.01E-1	2.94E-1	gamma(1.087, 10.77 unit down yrs.)
LaSalle 2	6.65E-3	1.05E-1	3.07E-1	gamma(1.090, 10.33 unit down yrs.)
Limerick 1	8.05E-3	1.25E-1	3.63E-1	gamma(1.099, 8.78 unit down yrs.)
Limerick 2	9.24E-3	1.43E-1	4.15E-1	gamma(1.101, 7.69 unit down yrs.)
Maine Yankee	6.16E-3	9.87E-2	2.87E-1	gamma(1.085, 10.99 unit down yrs.)
McGuire 1	3.54E-2	1.90E-1	4.45E-1	gamma(2.077, 10.93 unit down yrs.)
McGuire 2	3.91E-2	2.14E-1	5.03E-1	gamma(2.049, 9.60 unit down yrs.)
Millstone 1	3.42E-2	1.83E-1	4.28E-1	gamma(2.083, 11.39 unit down yrs.)
Millstone 2	3.01E-2	1.60E-1	3.73E-1	gamma(2.097, 13.14 unit down yrs.)
Millstone 3	6.92E-3	1.09E-1	3.17E-1	gamma(1.092, 9.99 unit down yrs.)
Monticello	7.85E-2	3.01E-1	6.40E-1	gamma(2.862, 9.52 unit down yrs.)
Nine Mile Pt. 1	5.12E-3	8.43E-2	2.47E-1	gamma(1.072, 12.71 unit down yrs.)
Nine Mile Pt. 2	8.20E-2	3.20E-1	6.84E-1	gamma(2.808, 8.79 unit down yrs.)
North Anna 1	6.19E-3	9.92E-2	2.89E-1	gamma(1.086, 10.94 unit down yrs.)
North Anna 2	7.19E-3	1.13E-1	3.28E-1	gamma(1.095, 9.68 unit down yrs.)
Oconee 1	6.83E-3	1.08E-1	3.14E-1	gamma(1.092, 10.11 unit down yrs.)
Oconee 2	6.96E-3	1.10E-1	3.19E-1	gamma(1.093, 9.94 unit down yrs.)
Oconee 3	7.67E-2	2.91E-1	6.18E-1	gamma(2.887, 9.91 unit down yrs.)
Oyster Creek	6.45E-2	2.36E-1	4.94E-1	gamma(3.012, 12.78 unit down yrs.)
Palisades	6.19E-2	2.25E-1	4.71E-1	gamma(3.030, 13.45 unit down yrs.)
Palo Verde 1	6.46E-3	1.03E-1	2.99E-1	gamma(1.088, 10.57 unit down yrs.)
Palo Verde 2	7.04E-3	1.11E-1	3.22E-1	gamma(1.093, 9.85 unit down yrs.)
Palo Verde 3	7.86E-3	1.23E-1	3.55E-1	gamma(1.099, 8.96 unit down yrs.)
Peach Bottom 2	2.98E-2	1.58E-1	3.70E-1	gamma(2.098, 13.26 unit down yrs.)
Peach Bottom 3	2.97E-2	1.58E-1	3.69E-1	gamma(2.098, 13.30 unit down yrs.)
Perry	6.93E-3	1.09E-1	3.18E-1	gamma(1.092, 9.99 unit down yrs.)
Pilgrim	6.19E-2	2.25E-1	4.71E-1	gamma(3.030, 13.45 unit down yrs.)
Point Beach 1	3.95E-2	2.16E-1	5.09E-1	gamma(2.045, 9.47 unit down yrs.)
Point Beach 2	3.94E-2	2.16E-1	5.08E-1	gamma(2.046, 9.49 unit down yrs.)
Prairie Island 1	4.18E-2	2.33E-1	5.50E-1	gamma(2.019, 8.68 unit down yrs.)
Prairie Island 2	7.86E-3	1.23E-1	3.55E-1	gamma(1.099, 8.97 unit down yrs.)
Quad Cities 1	3.41E-2	1.83E-1	4.28E-1	gamma(2.083, 11.40 unit down yrs.)
Quad Cities 2	7.05E-2	2.62E-1	5.51E-1	gamma(2.959, 11.31 unit down yrs.)
Rancho Seco	5.46E-3	8.91E-2	2.60E-1	gamma(1.077, 12.08 unit down yrs.)
River Bend	7.14E-3	1.12E-1	3.26E-1	gamma(1.094, 9.74 unit down yrs.)
Robinson 2	5.55E-3	9.04E-2	2.64E-1	gamma(1.078, 11.93 unit down yrs.)
Salem 1	2.98E-2	1.58E-1	3.69E-1	gamma(2.098, 13.28 unit down yrs.)
Salem 2	2.98E-2	1.58E-1	3.69E-1	gamma(2.098, 13.27 unit down yrs.)
San Onofre 1	2.87E-2	1.52E-1	3.55E-1	gamma(2.100, 13.82 unit down yrs.)
San Onofre 2	7.18E-3	1.13E-1	3.28E-1	gamma(1.094, 9.69 unit down yrs.)
San Onofre 3	7.36E-3	1.15E-1	3.35E-1	gamma(1.096, 9.49 unit down yrs.)
Seabrook	8.77E-3	1.36E-1	3.94E-1	gamma(1.101, 8.10 unit down yrs.)
Sequoyah 1	4.87E-3	8.09E-2	2.37E-1	gamma(1.069, 13.21 unit down yrs.)
Sequoyah 2	5.46E-3	8.90E-2	2.60E-1	gamma(1.077, 12.09 unit down yrs.)
South Texas 1	7.21E-3	1.13E-1	3.29E-1	gamma(1.095, 9.65 unit down yrs.)
South Texas 2	7.63E-3	1.19E-1	3.46E-1	gamma(1.097, 9.20 unit down yrs.)
St. Lucie 1	6.42E-3	1.02E-1	2.98E-1	gamma(1.088, 10.62 unit down yrs.)

Table B-4. Event occurrence rates: means, percentiles, and distributions. (continued)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
St. Lucie 2	7.86E-3	1.23E-1	3.55E-1	gamma(1.099, 8.97 unit down yrs.)
Summer	7.57E-3	1.18E-1	3.43E-1	gamma(1.097, 9.27 unit down yrs.)
Surry 1	6.06E-3	9.74E-2	2.84E-1	gamma(1.084, 11.13 unit down yrs.)
Surry 2	6.12E-3	9.82E-2	2.86E-1	gamma(1.085, 11.04 unit down yrs.)
Susquehanna 1	7.17E-3	1.13E-1	3.27E-1	gamma(1.094, 9.70 unit down yrs.)
Susquehanna 2	7.80E-3	1.22E-1	3.53E-1	gamma(1.098, 9.03 unit down yrs.)
Three Mile Isl 1	5.01E-3	8.29E-2	2.43E-1	gamma(1.071, 12.91 unit down yrs.)
Trojan	5.63E-3	9.15E-2	2.67E-1	gamma(1.079, 11.80 unit down yrs.)
Turkey Point 3	6.61E-2	2.42E-1	5.09E-1	gamma(2.999, 12.37 unit down yrs.)
Turkey Point 4	3.14E-2	1.67E-1	3.91E-1	gamma(2.094, 12.52 unit down yrs.)
Vermont Yankee	3.87E-2	2.11E-1	4.96E-1	gamma(2.052, 9.73 unit down yrs.)
Vogtle 1	4.46E-2	2.54E-1	6.05E-1	gamma(1.979, 7.79 unit down yrs.)
Vogtle 2	9.16E-3	1.42E-1	4.11E-1	gamma(1.102, 7.76 unit down yrs.)
Wash. Nuclear 2	3.67E-2	1.98E-1	4.64E-1	gamma(2.068, 10.45 unit down yrs.)
Waterford 3	7.93E-3	1.24E-1	3.58E-1	gamma(1.099, 8.89 unit down yrs.)
Watts Bar 1	9.96E-3	1.55E-1	4.49E-1	gamma(1.099, 7.09 unit down yrs.)
Wolf Creek	4.16E-2	2.31E-1	5.46E-1	gamma(2.022, 8.76 unit down yrs.)
Yankee-Rowe	3.99E-2	2.19E-1	5.16E-1	gamma(2.041, 9.32 unit down yrs.)
Zion 1	5.34E-3	8.75E-2	2.56E-1	gamma(1.075, 12.29 unit down yrs.)
Zion 2	3.26E-2	1.74E-1	4.06E-1	gamma(2.090, 12.05 unit down yrs.)

Momentary events (8 unit events, excluding Pilgrim)

Industry	9.66E-3	1.89E-2	3.07E-2	gamma[a](8.500, 448.8 unit down yrs.)

Grid-related events

Sustained events. The 3 unit shutdown events and one initiating event consisted of only three site events at two sites. All the grid-related events are listed in Table C-2. Because of the strong dependencies, the possibility of unit-specific differences, and the possibility of a trend in time, no statistical analysis was performed.

Momentary events. One momentary event occurred in 1627 unit calendar years (excluding Pilgrim).

Industry	1.68E-4	1.43E-3	3.73E-3	gamma[a](1.500, 1048.2 site cal. yrs.)

Severe-weather events

Sustained events (10 site events)

Industry	1.34E-8	9.12E-3	4.67E-2	gamma[a](0.205, 22.51 site cal. yrs.)
Arkansas	4.29E-9	5.20E-3	2.69E-2	gamma (0.197, 37.93 site cal. yrs.)
Beaver Valley	4.29E-9	5.20E-3	2.69E-2	gamma (0.197, 37.93 site cal. yrs.)
Big Rock Point	4.29E-9	5.20E-3	2.69E-2	gamma (0.197, 37.93 site cal. yrs.)
Braidwood	6.08E-9	6.41E-3	3.31E-2	gamma (0.199, 31.03 site cal. yrs.)
Browns Ferry	4.29E-9	5.20E-3	2.69E-2	gamma (0.197, 37.93 site cal. yrs.)
Brunswick	1.51E-3	3.05E-2	9.18E-2	gamma (0.986, 32.35 site cal. yrs.)
Byron	5.45E-9	5.97E-3	3.08E-2	gamma (0.198, 33.24 site cal. yrs.)
Callaway	5.36E-9	5.91E-3	3.05E-2	gamma (0.198, 33.54 site cal. yrs.)
Calvert Cliffs	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Catawba	5.43E-9	5.96E-3	3.08E-2	gamma(0.198, 33.31 site cal. yrs.)
Clinton	6.16E-9	6.47E-3	3.34E-2	gamma(0.199, 30.77 site cal. yrs.)
Comanche Peak	6.89E-9	7.03E-3	3.62E-2	gamma(0.199, 28.39 site cal. yrs.)

Table B-4. Event occurrence rates: means, percentiles, and distributions. (continued)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Cook	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Cooper	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Crystal River	1.20E-2	8.11E-2	2.01E-1	gamma(1.743, 21.50 site cal. yrs.)
Davis-Besse	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Diablo Canyon	5.38E-9	5.92E-3	3.06E-2	gamma(0.198, 33.48 site cal. yrs.)
Dresden	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Duane Arnold	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Farley	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Fermi	5.55E-9	6.04E-3	3.12E-2	gamma(0.199, 32.86 site cal. yrs.)
Fitzpatrick	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Fort Calhoun	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Fort St. Vrain	1.36E-3	3.75E-2	1.18E-1	gamma(0.878, 23.43 site cal. yrs.)
Ginna	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Grand Gulf	5.33E-9	5.89E-3	3.04E-2	gamma(0.198, 33.66 site cal. yrs.)
Haddam Neck	4.31E-9	5.21E-3	2.69E-2	gamma(0.197, 37.86 site cal. yrs.)
Harris	5.95E-9	6.32E-3	3.26E-2	gamma(0.199, 31.47 site cal. yrs.)
Hatch	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Hope Creek	5.83E-9	6.23E-3	3.22E-2	gamma(0.199, 31.90 site cal. yrs.)
Indian Point	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Kewaunee	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
La Crosse	6.71E-9	6.88E-3	3.55E-2	gamma(0.199, 28.98 site cal. yrs.)
LaSalle	4.84E-9	5.56E-3	2.88E-2	gamma(0.198, 35.55 site cal. yrs.)
Limerick	5.57E-9	6.05E-3	3.13E-2	gamma(0.199, 32.80 site cal. yrs.)
Maine Yankee	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
McGuire	4.60E-9	5.40E-3	2.79E-2	gamma(0.197, 36.55 site cal. yrs.)
Millstone	1.51E-3	3.05E-2	9.18E-2	gamma(0.986, 32.35 site cal. yrs.)
Monticello	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Nine Mile Pt.	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
North Anna	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Oconee	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Oyster Creek	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Palisades	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Palo Verde	5.52E-9	6.02E-3	3.11E-2	gamma(0.199, 32.97 site cal. yrs.)
Peach Bottom	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Perry	5.91E-9	6.29E-3	3.25E-2	gamma(0.199, 31.62 site cal. yrs.)
Pilgrim	6.14E-3	5.58E-2	1.47E-1	gamma(1.445, 25.90 site cal. yrs.)
Point Beach	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Prairie Island	1.51E-3	3.05E-2	9.18E-2	gamma(0.986, 32.35 site cal. yrs.)
Quad Cities	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Rancho Seco	6.10E-9	6.43E-3	3.32E-2	gamma(0.199, 30.96 site cal. yrs.)
River Bend	5.65E-9	6.11E-3	3.15E-2	gamma(0.199, 32.53 site cal. yrs.)
Robinson	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Salem	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
San Onofre	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Seabrook	6.86E-9	7.00E-3	3.61E-2	gamma(0.199, 28.47 site cal. yrs.)
Sequoyah	4.43E-9	5.29E-3	2.74E-2	gamma(0.197, 37.28 site cal. yrs.)
South Texas	6.29E-9	6.56E-3	3.38E-2	gamma(0.199, 30.35 site cal. yrs.)
St. Lucie	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Summer	4.90E-9	5.60E-3	2.89E-2	gamma(0.198, 35.32 site cal. yrs.)
Surry	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Susquehanna	4.90E-9	5.60E-3	2.89E-2	gamma(0.198, 35.32 site cal. yrs.)
Three Mile Isl	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Trojan	5.17E-9	5.78E-3	2.99E-2	gamma(0.198, 34.28 site cal. yrs.)
Turkey Point	1.51E-3	3.05E-2	9.18E-2	gamma(0.986, 32.35 site cal. yrs.)
Vermont Yankee	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Vogtle	6.00E-9	6.35E-3	3.28E-2	gamma(0.199, 31.31 site cal. yrs.)
Wash. Nuclear	5.24E-9	5.83E-3	3.01E-2	gamma(0.198, 34.02 site cal. yrs.)

Table B-4. Event occurrence rates: means, percentiles, and distributions. (continued)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Waterford	5.47E-9	5.98E-3	3.09E-2	gamma(0.198, 33.17 site cal. yrs.)
Watts Bar	8.23E-9	8.77E-3	4.53E-2	gamma(0.199, 22.67 site cal. yrs.)
Wolf Creek	5.52E-9	6.02E-3	3.11E-2	gamma(0.199, 32.96 site cal. yrs.)
Yankee-Rowe	5.38E-9	5.92E-3	3.06E-2	gamma(0.198, 33.50 site cal. yrs.)
Zion	4.29E-9	5.20E-3	2.69E-2	gamma(0.197, 37.93 site cal. yrs.)
Momentary events (2site events, excluding Pilgrim)				
Industry	5.46E-4	2.39E-3	5.28E-3	gamma[a](2.500, 1048.2 site cal. yrs.)

a. As explained in the text, the parameters shown for the gamma distribution are the shape parameter and the scale parameter.

For two data sets, between-unit or between-site variation was modeled. The unit-specific or between-site frequencies are shown in Figures B-3 and B-4, arranged from the highest frequency to the lowest.

Figures B-8 through B-9 show the frequencies of the sustained events, by year. The dots and vertical lines are maximum likelihood estimates and 90% confidence intervals, based on assumed Poisson data for a single year. The fitted trend line is shown for the plant-centered initiating event data, even though the trend is not statistically significant. No trend lines are shown in the other plots, for reasons explained with each figure.

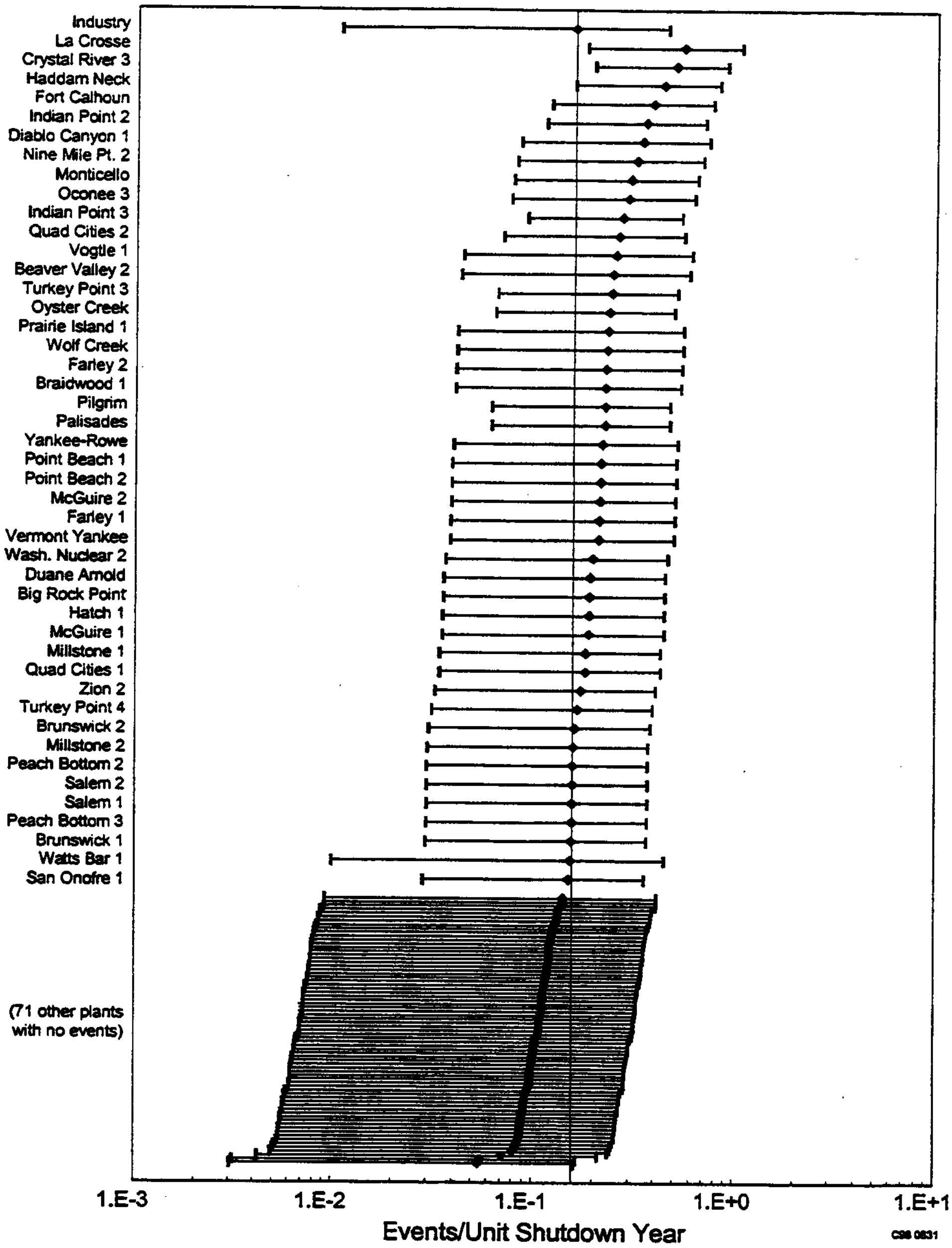

Figure B-3. Frequency of plant-centered LOSP sustained events during shutdown. The empirical Bayes estimate and 90% uncertainty interval are shown for each unit.

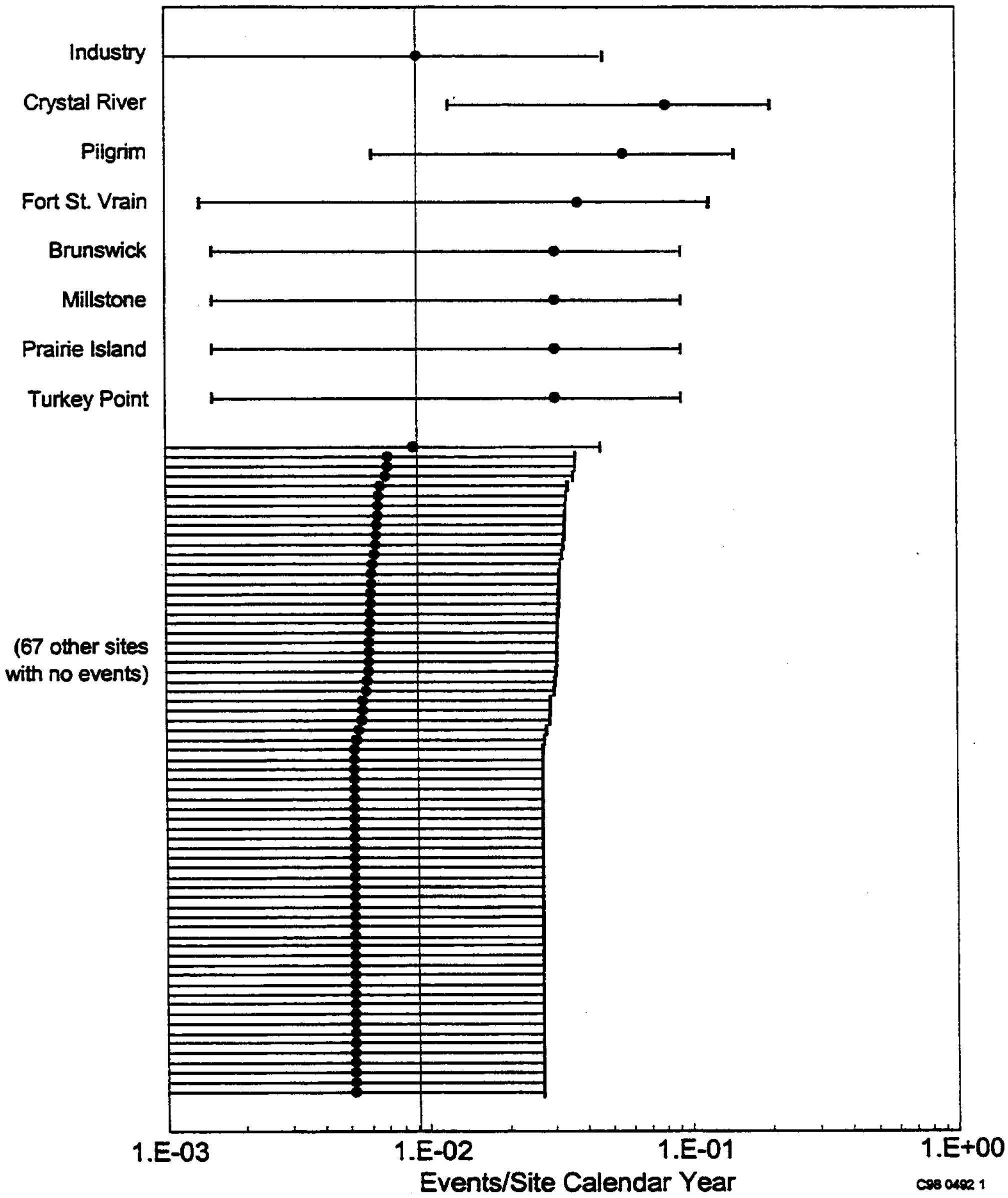

Figure B-4. Frequency of severe-weather LOSP sustained events. The empirical Bayes estimate and 90% uncertainty interval are shown for each power plant unit. The left ends of many intervals extend far to the left of the visible portion of the figure, and are not meaningful.

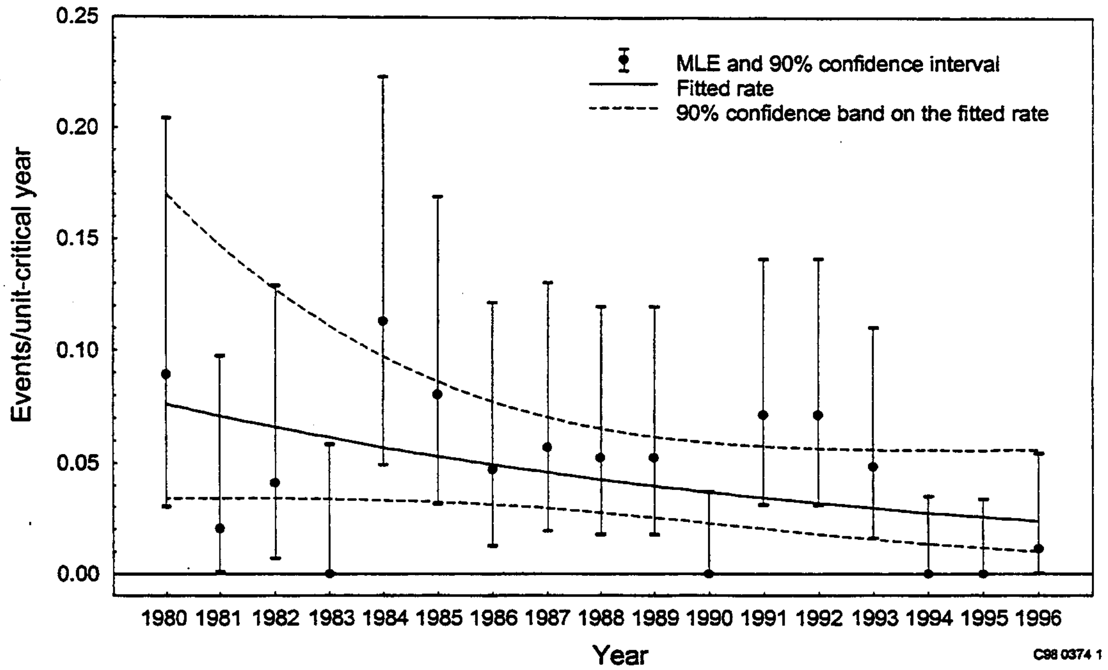

Figure B-5. Frequency of plant-centered LOSP sustained initiating events during operation. When the extra-Poisson scatter is accounted for, the trend is not statistically significant (p-value = 0.11).

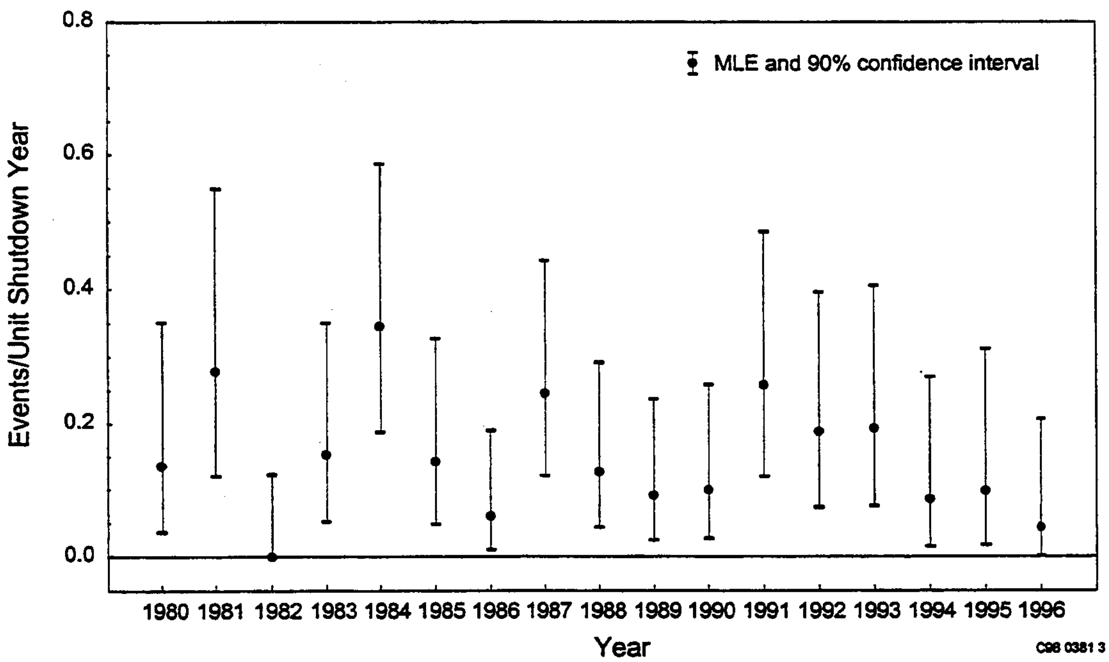

Figure B-6. Frequency of plant-centered LOSP sustained events during shutdown. No trend is fitted, because it is not close to statistically significant. Between-unit variation is present, but the confidence intervals for each year ignore this.

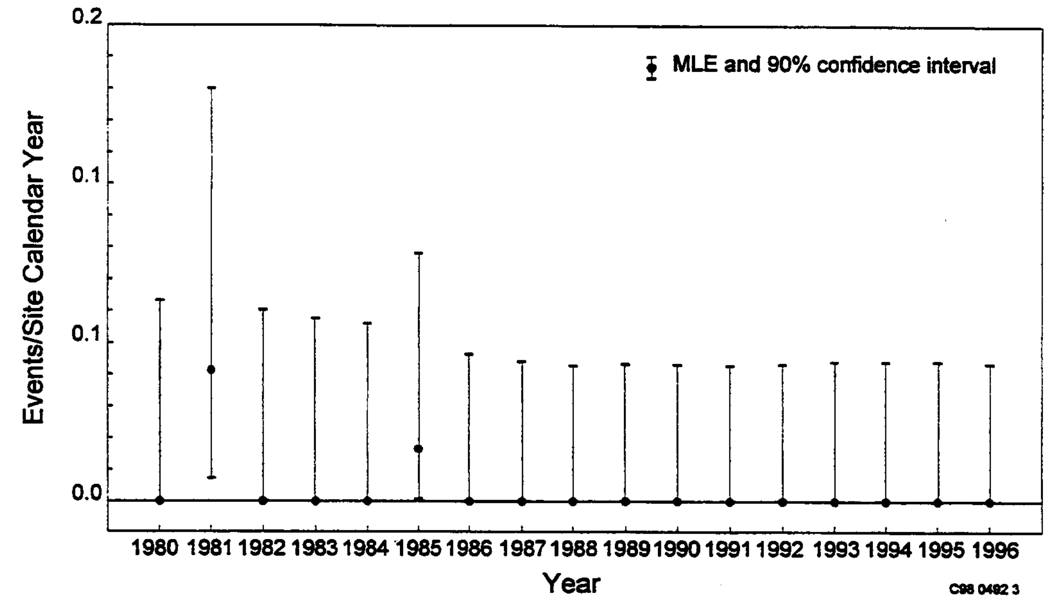

Figure B-7. Frequency of grid-related LOSP sustained events, both initiating events and shutdown events. No trend is fitted, because it is apparently not significant. However, the sparsity of data and possible dependence of events complicate significance calculations.

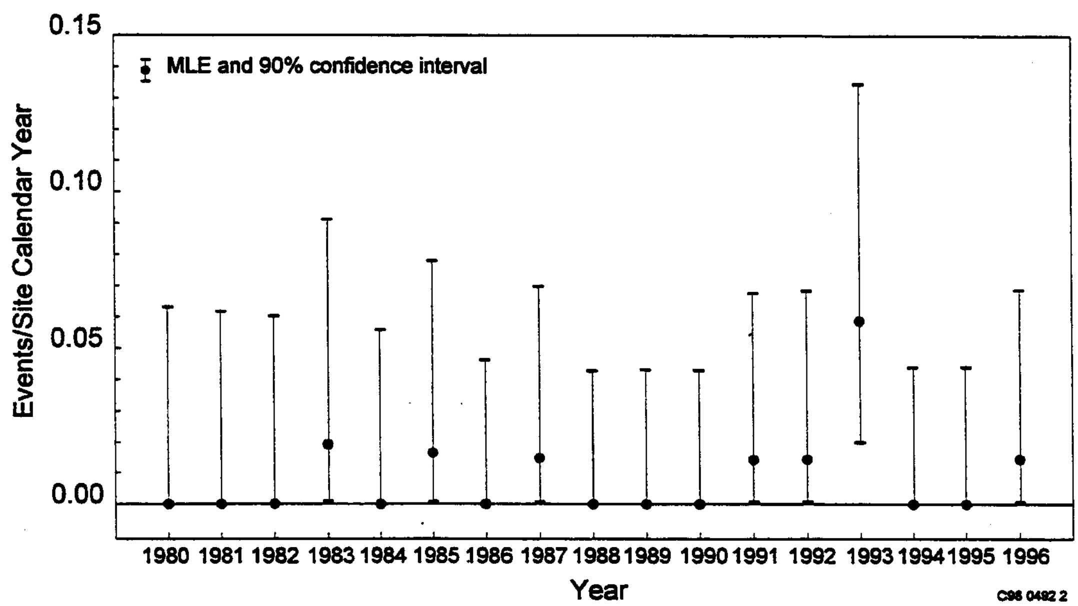

Figure B-8. Frequency of severe-weather LOSP sustained events. No trend is fitted, because it is not statistically significant. The large frequency in 1993 is the result of a single storm affecting several power plant sites. The confidence intervals for each year ignore between-site variation.

B-3. PRELIMINARY ANALYSIS OF RECOVERY TIMES

This section considers only the sustained recovery times. The momentary recovery times are all approximately one minute, and do not need analysis.

To decide on the data subsets that should be analyzed separately, the sustained recovery times were compared. Initially, all the recovery times were counted separately. Later, it was observed that when an event causes LOSP at multiple units, the recovery times tend to be similar. In fact, the variation between units from a single event is extremely small compared to the variation between events or the variation between sites. It was decided to eliminate the statistical dependence between recovery times by averaging the recovery times whenever a single event caused LOSP at more than one power plant unit.

Therefore, the initial examination was redone, using only the average recovery time if the event caused LOSP at more than one unit. Those results are presented here. Recall that the data have three 1032-categories, four causes, and three unit conditions, shown here with self-explanatory abbreviations.

1032 Category	
P	plant-centered
G	grid-related
W	severe weather
Causes	
ExtEnv	external environment (typically lightning)
Equip	equipment problem
Human	human error
Other	Other
Unit Conditions	
Power	power-operation (reactor was at power and did not trip)
ShutD	shutdown (reactor was shut down during when LOSP occurred)
Trip	trip (reactor tripped, typically as a result of the LOSP)

B-3.1 Plant-Centered Events

Consider first only the plant-centered events. Figure B-9 shows box plots of the recovery times for three classes of events: trip events, shutdown events, and power-operation events. Shutdown events tend to have somewhat shorter recovery times than trip events. The difference is not statistically significant, however. (The p-value is 0.3 by the Wilcoxon or Kruskal-Wallis test, and 0.4 by the less powerful Kolmogorov-Smirnov test.). For this analysis, the trip events included the four non-initiators, in which the trip preceded the LOSP. These recovery times did not appear different from those of other trip events, and engineering considerations suggested that the recovery time would not depend on which came first, the LOSP or the trip.

The power-operation events, in which the unit did not trip after LOSP, tended to have longer recovery times, and the difference is statistically significant. An engineering explanation is that personnel will act very deliberately, to prevent a trip, if the unit is operating without offsite power. Therefore, recovery times are not characterized for power-operation events. They would require separate analysis, and were deemed not of great interest. They were used for the following investigation of causes, because the cause was considered to be independent of the unit response.

Recall that Table B-1 displayed the different causes of plant-centered sustained events. The recovery times were investigated to determine whether the different causes correspond to different recovery times. The equipment problems have a slightly longer median recovery time, but a box plot shows that the three primary causes have almost identical distributions of recovery time; the differences are not close to statistically significant. Because this investigation did not reveal any interesting patterns, the box plot is not shown.

More differences are seen when the event cause is considered separately for each unit condition. This comparison is given in Figure B-10. Even here, however, the differences are not statistically significant.

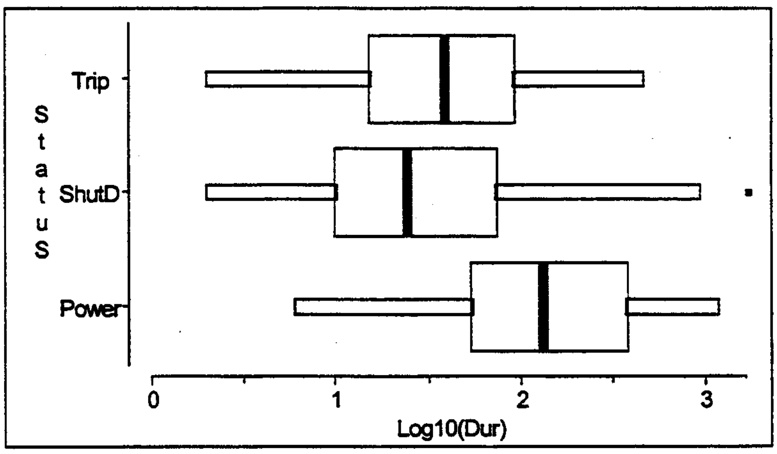

Figure B-9. Logarithms of sustained recovery times, for three classes of plant-centered events. The power-operation recovery times are longer than each of the other groups of recovery times, to a statistically significant degree. The difference between trip and shutdown times is not statistically significant (p-val. = 0.3).

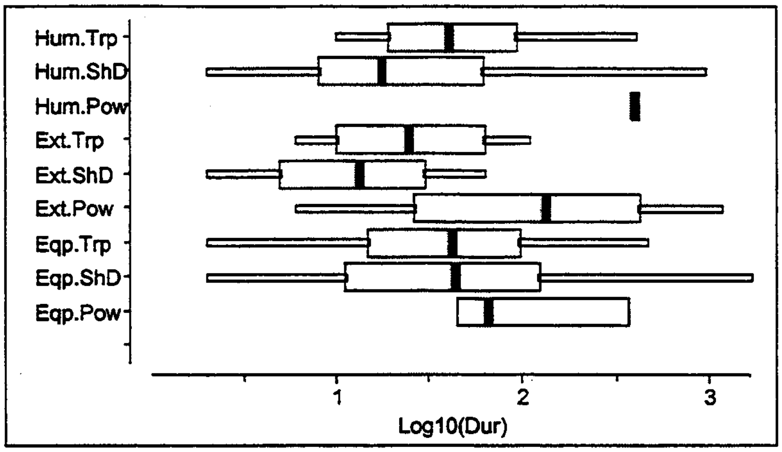

Figure B-10. Logarithms of sustained recovery times of plant-centered events, for combinations of event cause and unit condition. The differences are not statistically significant, although when combined as in Figure B-9 some differences are statistically significant.

In summary, plant-centered sustained events do not show any strong correspondence with particular causes. Therefore, plant-centered shutdown and initiating events are pooled for analysis of recovery times. The four events for which the trip preceded the LOSP are included in the data. Power-operation events are not used.

B-3.2 Grid-Related and Severe-Weather Events

Figure B-11 shows $\log_{10}$(recovery time) for grid-related events (labeled G) and severe-weather events (labeled W), with shutdown and trip events distinguished. There were no power-operation events in the data. The grid related events have only two trip times and three shutdown times. The data set is too small for the significance calculations to be accurate. For weather events, the difference between trip events and shutdown events is not statistically significant (the p-value is 0.3 for the Wilcoxon and Kruskal-Wallis tests, and 0.6 for the Kolmogorov-Smirnov test.) If a difference exists, there is not enough evidence to reveal the difference clearly. Therefore, for analysis of recovery times for severe-weather events and for grid-related events, no distinction was made between shutdown and trip conditions.

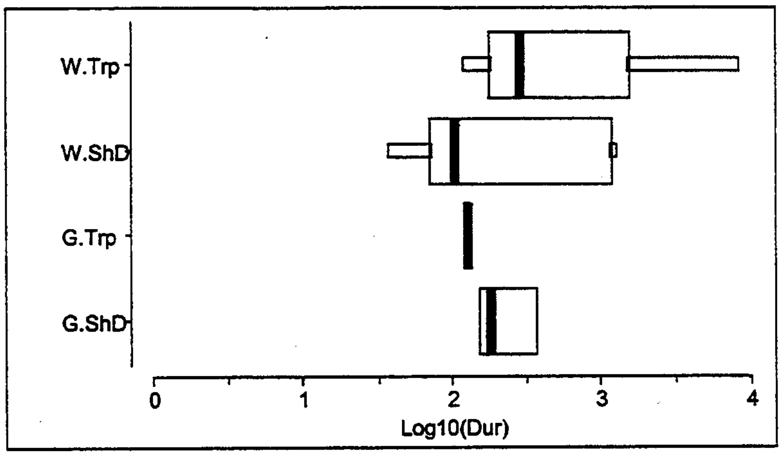

Figure B-11. Logarithms of sustained recovery times, for severe-weather events and grid-related events. Among the severe-weather events the difference between trip events and shutdown events is not statistically significant (p-val. > 0.3). The grid-related data set is too small to allow determination of statistical significance.

B-3.3 Summary: The Three Groups Identified Above

Sections B-3.1 and B-3.2 conclude that each 1032-category of events can be analyzed without splitting it further. Therefore, the three groups for analysis are:

- Plant-centered events, excluding power-operation events,
- Grid-related events, and
- Severe-weather events.

The logs of the sustained recovery times are shown in Figure B-12. The trip events and shutdown events are combined in this plot, and the power-operation events are excluded, based on the above findings that the trip and shutdown sustained events have similar recovery times.

The difference between severe-weather and plant-centered recovery times is statistically very significant, by either the Wilcoxon test or the Kruskal-Wallis test, with p-value of 0.0003. There are too few grid-related events to allow accurate calculation of a p-value.

As mentioned above, the recovery times are analyzed by site, because when a single event caused LOSP at two units, the two recovery times were usually similar. The counts of events used for analyzing recovery times are given in Table B-5. These counts exclude power-operation events, events when the unit experienced LOSP but the reactor did not trip.

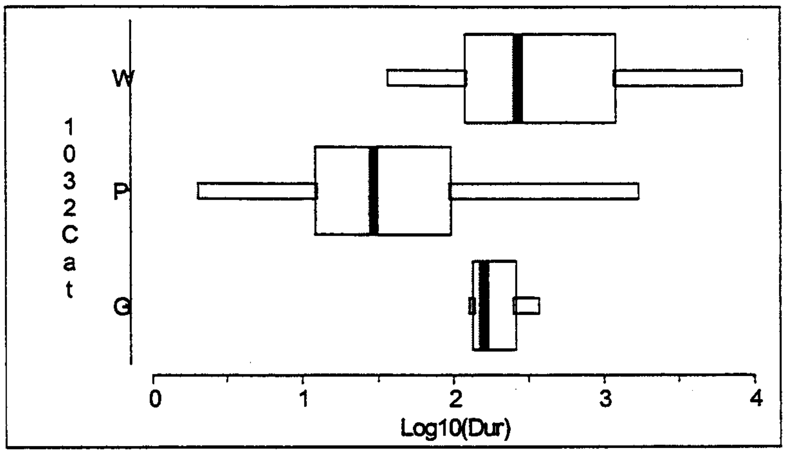

Figure B-12. Logarithms of sustained recovery times for the three 1032-categories of events whose recoveries are analyzed separately. The difference between severe-weather and plant-centered times is statistically extremely significant.

Table B-5. Number of site events used for analyzing sustained recovery times.

	Site Events	Reported Recovery Times
Plant-centered	111	102
Grid-related	4	4
Severe weather	10	9

B-4. ESTIMATION OF DISTRIBUTIONS OF RECOVERY TIMES

B-4.1 Possibility of Time Trends

For plant-centered, grid-related, and severe-weather events, the log(recovery time) was plotted against the event date. Logarithms were used because the distribution of log(recovery time) is roughly symmetrical, whereas the distribution of recovery time is highly skewed. As discussed in Section B-4.2 below, it was eventually decided to average the recovery times for a single event affecting two units. The plots considered here, log(recovery time) versus event date, are based on these averaged times for each site event. Figures B-13 through B-15 show the three cases.

A statistically significant (p-value = 0.03) trend can be fitted to the data. It is slight: over 17 years, the fitted slope corresponds to an increase in the median recovery time by a factor of 3.6. The plot shows that the trend appears to be a result of an absence of events in the upper left and lower right, and the presence of two large values in the upper right. Indeed, if either of the two highest points in the upper right were dropped, the p-value would rise to 0.08, not quite statistically significant. If both were dropped, the p-value would rise to 0.19, indicating virtually no evidence of a trend.

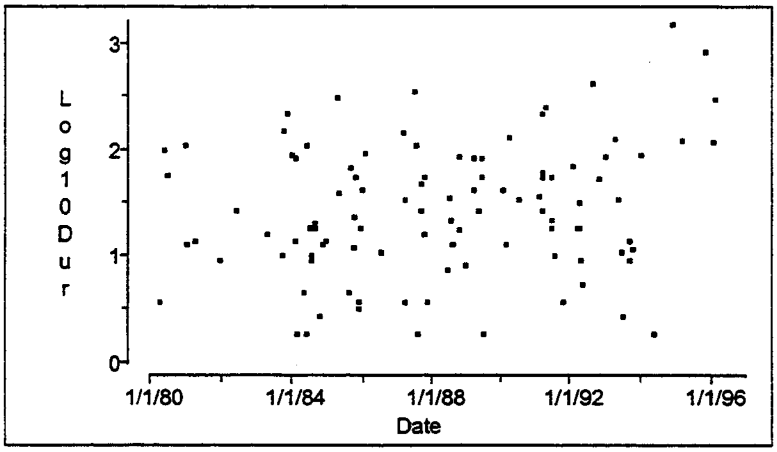

Figure B-13. For sustained plant-centered events, plot of $\log_{10}$(recovery time) against event date. A slight upward trend is statistically significant (p-value = 0.03), but is not modeled for reasons discussed in the text.

To see if the trend had an engineering basis, we reexamined the events corresponding to the two largest times in the upper right of Fig. B-13. One event had duration 917 minutes (LER 27595014). Based on engineering considerations, that event could have happened at any time. Nothing makes such an event more likely in recent years than in the early years. The other event lasted for 1675 minutes (LER 31194014). However, the LER states "vital buses were maintained powered from [their diesels]..., to permit adequate assessment of the event prior to restoring offsite power." The actual time to recovery was coded in the data, because the narrative does not state when offsite power could have been restored. However, the narrative suggests that recovery could have been accomplished sooner if the diesel generators had failed.

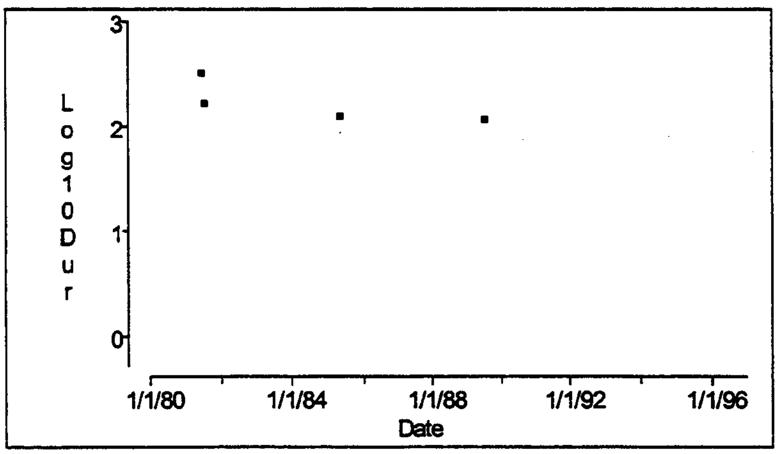

Figure B-14. For sustained grid-related events, plot of $\log_{10}$(recovery time) against event date. There is no visible trend.

The evidence for a trend displayed in Figure B-13 is very sensitive to one or two values, it is not strongly supported by engineering considerations, and the magnitude of the trend is small. Therefore, this report does not model a time trend for plant-centered recovery times.

The grid-related events are rare, and the two events in 1981 may be dependent. This complicates the calculation of a p-value. However, it is evident from the plot that no trend is present.

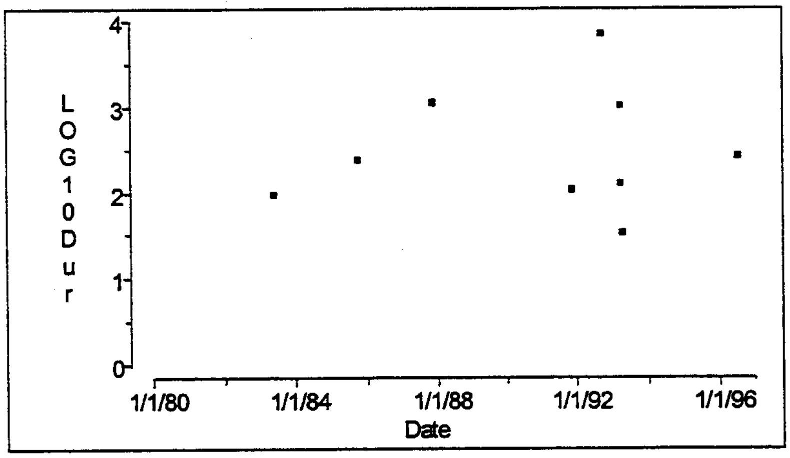

Figure B-15. For sustained severe-weather events, plot of $\log_{10}$(recovery time) against event date. There is no statistically significant trend.

B-4.2 Components of Variance

The work presented above in Sections B-3 and B-4.1 always used the average recovery time, if a single event affected multiple units at one site. The results presented in this section justify the above use of average times. It begins by using the individual recovery times at the units, and concludes that those times should be averaged when a single event causes LOSP at multiple units of a site.

Components of variance were estimated, following Model (A-1) of Appendix A. This model equation is repeated here, for convenience of discussion:

$$\log(\text{duration}) = \mu + X_{\text{site}} + X_{\text{event}} + X_{\text{resid}} \quad . \tag{B-1}$$

The residual variance corresponds to variation between units during a single event. The estimated components of variance are given in Table B-6, in the column labeled Estimated Var. Comp. These are the estimated variances of the X terms in Equation (B-1). In each category, such as plant-centered events, the residual variation contributes very little to the total variance. Therefore, for events that caused loss of offsite power at two units, Table B-6 strongly suggests that the recovery times at the two units should be averaged, and only a single time should be used in the analysis.

Therefore, the model was simplified by averaging times that occurred for a single site event:

$$\log(\text{duration}) = \mu + X_{\text{site}} + X_{\text{event}} \quad . \tag{B-2}$$

The resulting values of the two components of variance are shown in Table B-7.

Table B-6. Estimated components of variance of $\log_{10}$(recovery time), for times ≥ 2 minutes.

Source of variation	Estimated Var. Comp.
Plant-centered (107 reported recovery times by unit)	
site	0.0
event	0.38
resid.	0.003
Grid-related (5 reported by recovery times by unit)	
site	0.006
event	0.030
resid.	0.005
Severe-weather (13 reported recovery times by unit)	
site	0.16
event	0.35
resid.	0.014

In each case, the variance between sites is smaller than the variance of the individual events within a site. Therefore, we performed parametric and nonparametric analyses of variance, to see if the between-site differences were statistically significant. The conclusions were as follows.

For plant-centered recovery times, the analysis of variance test for between-site differences gave a p-value of 0.09 (exact if the log-durations are normally distributed), and the Kruskal-Wallis test gave a p-value of 0.17 (based on an asymptotic approximation). Because the between-event variance was over 80% of the total variance, because the difference between sites did not appear to be statistically significant, and because a simple presentation is generally preferable, we ignored between-site differences and modeled all the variance of the recovery times as if it were between-event variance.

For grid events, we used only one component of variance. It is questionable whether the data should even be analyzed at all.

For severe-weather events, the same tests were performed as for the plant-centered data. The analysis of variance p-value and the Kruskal-Wallis p-value were similar, about 0.44, indicating no statistical evidence of between-site differences. (Recall that a small data set almost never shows strong statistical evidence of anything.) However, the components of variance did not appear so clear-cut. Therefore we tried modeling the two components of variance to obtain site-specific distributions for the recovery times. The site-specific 90% intervals overlapped greatly, and the ratio of the highest to the lowest site-specific median time was only 5.4. By contrast, the typical ratio of the site-specific 95th percentile to the 5th percentile was about 200. Finally, engineering considerations did not give a reason why geography should affect the recovery times. In conclusion, modeling the between-site differences did not seem worth the trouble, so this report presents only a generic distribution of severe-weather recovery times.

Table B-7. Estimated components of variance of $\log_{10}$(recovery time), when times at multiple units are averaged for each event. Only times ≥ 2 minutes are considered here.

Source of variation	Estimated Var. Comp.
Plant-centered (102 reported recovery times by site)	
site	0.07
event	0.32
Grid-related (4 reported by recovery times by site)	
site	0.006
event	0.035
Severe-weather (9 reported recovery times by site)	
site	0.16
event	0.36

In summary, a generic distribution of the sustained recovery times is presented for each of the three categories. For grid-related recovery times, a distribution is modeled in spite of reservations about the small size of the data set.

B-4.3 Forms of the Distributions

The Shapiro-Wilk test was applied to the plant-centered, grid-related, and severe-weather data, to determine whether ln(recovery time) was normally distributed. The p-values were 0.25, 0.23, and 0.59, respectively. This indicates no evidence of non-normality in any case. Therefore, other distributions, such as the Weibull or gamma, were not considered.

Figure B-16 plots the logarithm of the plant-centered sustained recovery times against the corresponding expected quantiles of a normal distribution. The smallest reported values, all 2 minutes, depart somewhat from the line, but the nearly straight line gives visual evidence that the fit is acceptable.

Similarly, Figure B-17 plots the logarithm of the severe-weather sustained recovery times against the corresponding expected quantiles of a normal distribution. There are too few data points to show any lack of fit to the assumed normal distribution.

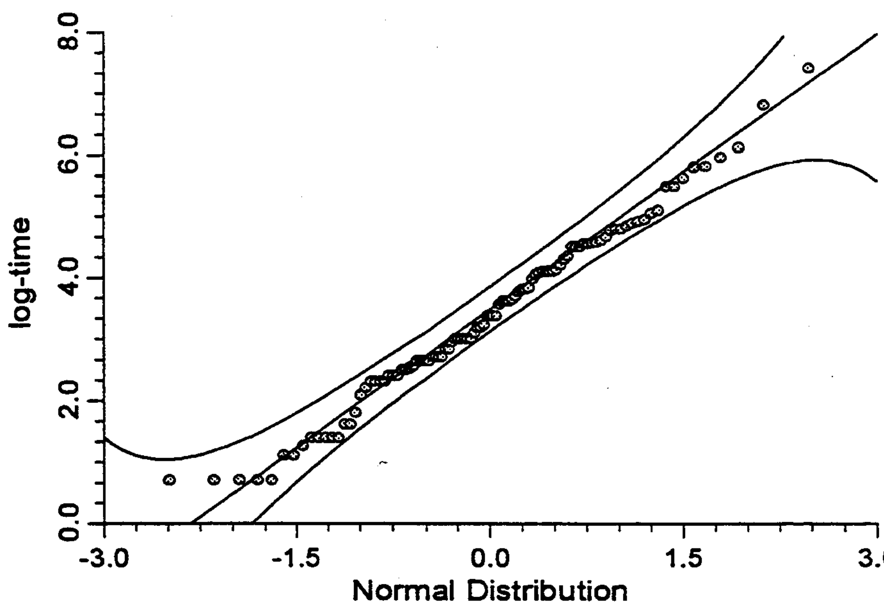

Figure B-16. Reported values of ln(recovery time) vs. normal quantiles, for plant-centered sustained trip and shutdown events. The band represents 95% confidence intervals (in the vertical direction) for the expected values of the ordered observations.

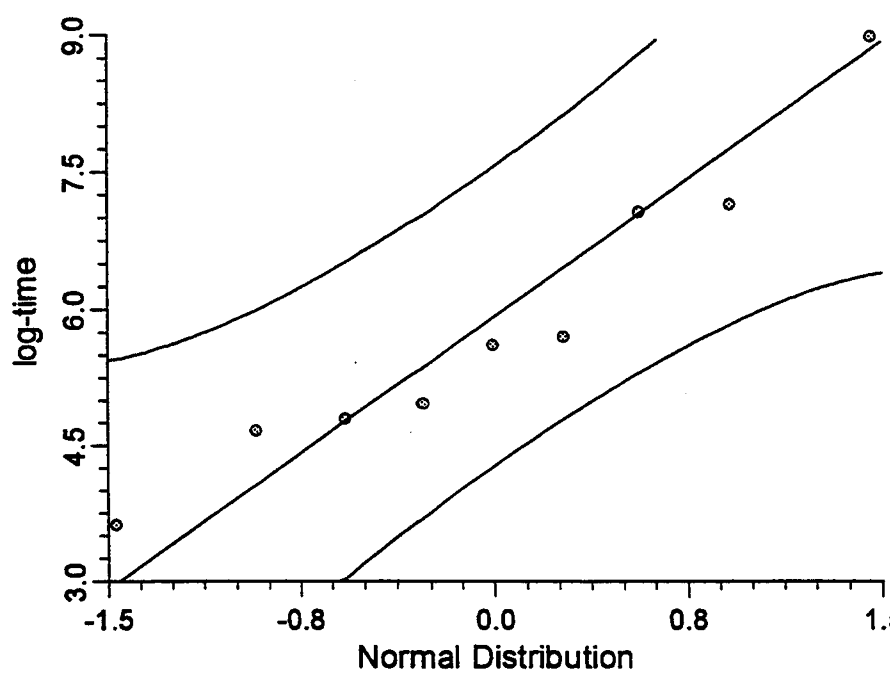

Figure B-17. Reported values of ln(recovery time) vs. normal quantiles, for severe-weather sustained events. The band represents 95% confidence intervals (in the vertical direction) for the expected values of the ordered observations.

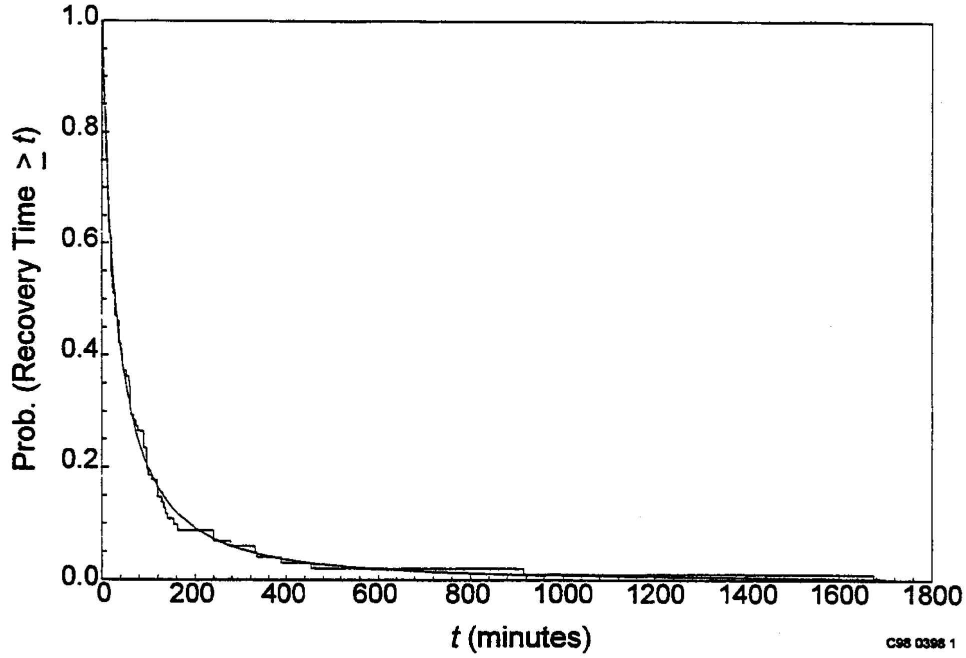

Figure B-18. Recovery curve for plant-centered recovery times, empirical and fitted lognormal. This is based on sustained trip and shutdown events.

Figures B-18 and B-19 show the recovery curves, for sustained events. The recovery curve at time t is defined as the probability that the recovery time exceeds t; it is the same as the complementary cumulative distribution.

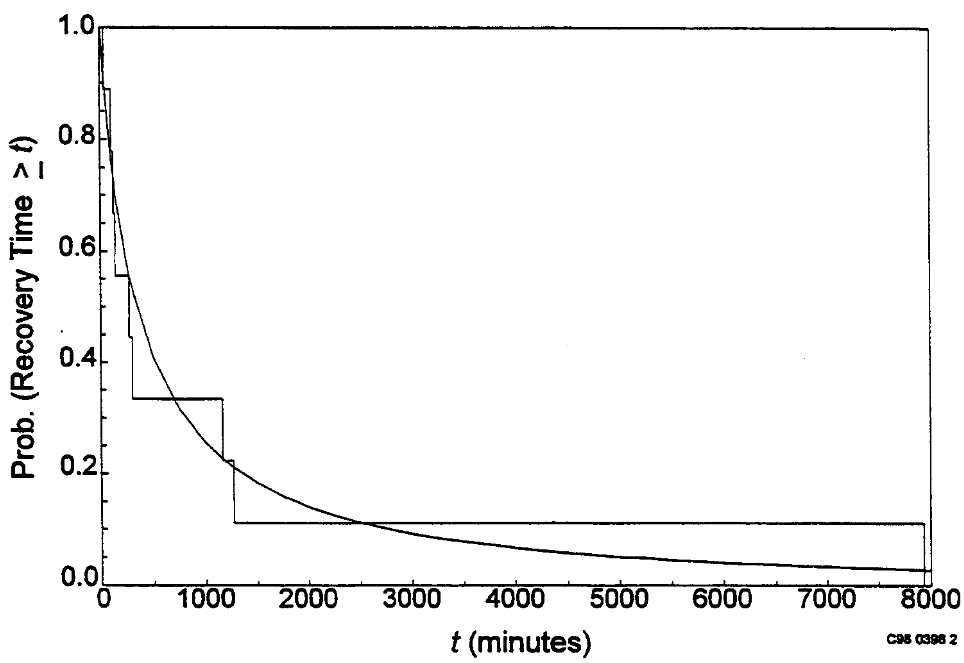

Figure B-19. Recovery curve for severe-weather recovery times, empirical and fitted lognormal. This is based on sustained trip and shutdown events.

Table B-8 summarizes the distributions that were finally estimated. The percentiles and means are expressed in minutes. The format is like that of Table B-3. For the lognormal distribution, the two parameters given are the *median*, and the error factor. The mean for each distribution is given in column 3, and the 5th and 95th percentiles in columns 2 and 4, all expressed in minutes.

Table B-8. Fitted distributions of recovery times of sustained LOSP events: means, percentiles, and distributions. (See text for explanation.)

Category	5^{th} %ile	mean	95^{th} %ile	distribution and parameters[a]
Plant-centered events (102 site events with reported recovery times, single distribution modeled)				
Industry	2.80	82.9	313.7	lognormal[a](29.6 min., 10.6)
Grid-related events (only 4 site events with reported recovery times, two of which may be dependent. Uncertainty from lack of data is not accounted for. Interpret the results with care.)				
Industry	86.5	206.5	397.5	lognormal(185 min., 2.14)
Severe-weather events (9 site events with reported recovery times)				
Industry	23.15	1295	5009	lognormal(341 min., 14.7)

a. As explained in the text, the parameters shown for the lognormal distribution are the *median* and the error factor.

B-5 COMPARISONS WITH NUREG-1032

B-5.1 Frequencies of Plant-Centered Initiating Events

Frequencies of plant-centered initiating events were examined back to 1969. A set of unit calendar years from 1969 through 1979 is given by Modarres et al. (1996). The unit calendar years were also calculated from the INEEL unit information database, although some old units are not contained in this database. For each year, the larger of the numbers from the two sources was used. Table B-9 lists the data used.

Table B-9. Plant-centered LOSP initiating events and unit calendar years, by year.

Year	Events	Cal. Years	Year	Events	Cal. Years
1969	1	9.1	1984	6	81.9
1970	0	12.6	1985	5	90.1
1971	3	17.7	1986	3	96.8
1972	3	22.5	1987	4	102.7
1973	3	30.4	1988	4	107.7
1974	3	42.3	1989	4	109.0
1975	1	50.8	1990	0	110.5
1976	3	55.3	1991	6	111.0
1977	7	61.2	1992	6	110.4
1978	3	64.6	1993	4	108.7
1979	1	66.0	1994	0	109.0
1980	4	66.8	1995	0	109.0
1981	1	70.2	1996	1	110.1
1982	2	73.0			
1983	0	77.5	Total	78	2076.9

The trend in frequencies is shown in Figure B-20. The trend is statistically very significant (p-value = 0.0001). The fit is acceptable (p-value for testing adequacy of fit = 0.08).

The normalization is by unit calendar years. It would have been better to normalize by reactor critical years, but those values were not readily available before 1981. The fraction of time when reactors are critical has increased since the late 1980s. Thus, the decreasing trend would appear slightly more pronounced if critical time had been used instead of calendar time.

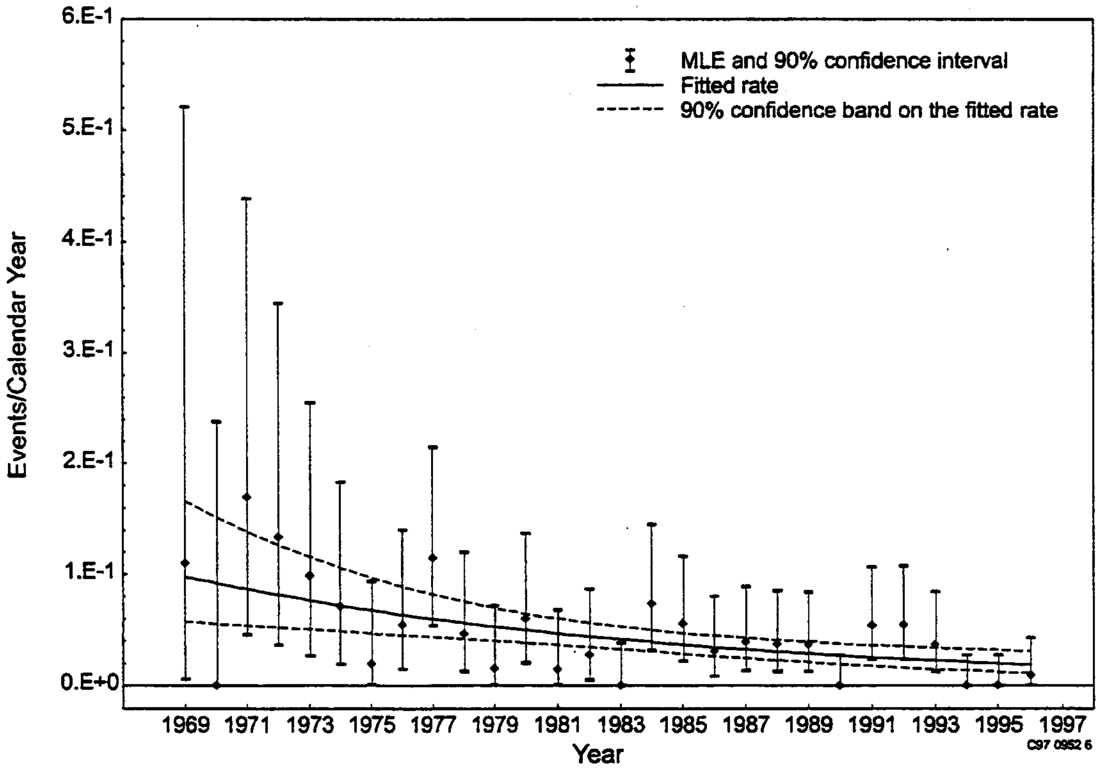

Figure B-20. Frequencies of plant-centered LOSP initiating events during power operation (events per unit calendar year). The trend is statistically very significant (p-value = 0.0001).

B-5.2 Data Used for Analysis of Recovery Times.

The recovery times from NUREG-1032 and from Table C-1 of this report, for events occurring in 1980-1985 were compared. Small discrepancies in times can arise from rounding off a conversion from minutes to hours in NUREG-1032 and then converting back to minutes for this table. Most of the differences between the two studies concern events that are included in the present report but not in NUREG-1032, or shutdown events that were presumably regarded as initiating events in NUREG-1032. Remaining differences in recovery times are matters of judgment concerning when power could have been restored, as determined by engineers with operational experience.

B-5.3 Frequencies of Durations of Initiating Events

The complementary cumulative frequency curves were plotted. A portion of the plot is shown in Section 3 as Figure 3-9. That plot is truncated to have size and shape agreeing with the corresponding plot from NUREG-1032. The full plot is displayed here in Figure B-21.

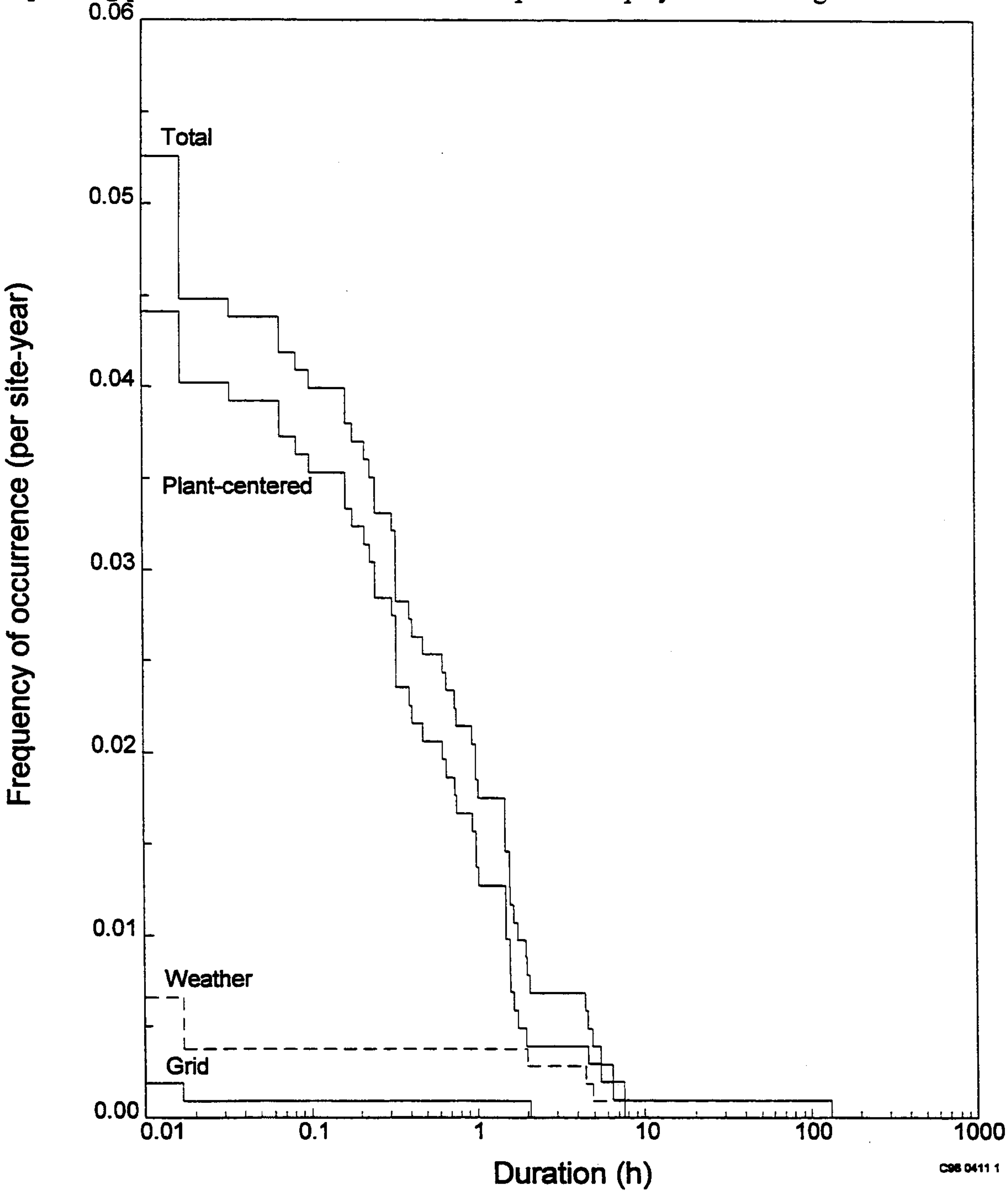

Figure B-21. Complementary cumulative frequency curves of site events, using 1980-1996 initiating event data.

B-5.4 Effect of Design Group on Recovery Times

NUREG-1032 defined three groups of units, based on various design factors concerning offsite power sources and the existence of automatic transfer mechanisms. The categorization used for this report is given in Table C-7 of Appendix C.

Figures B-22 and B-23 show the logarithms of the recovery times for plant-centered sustained events, for each design group. Any differences seen are not statistically significant, by the Kruskal-Wallis test.

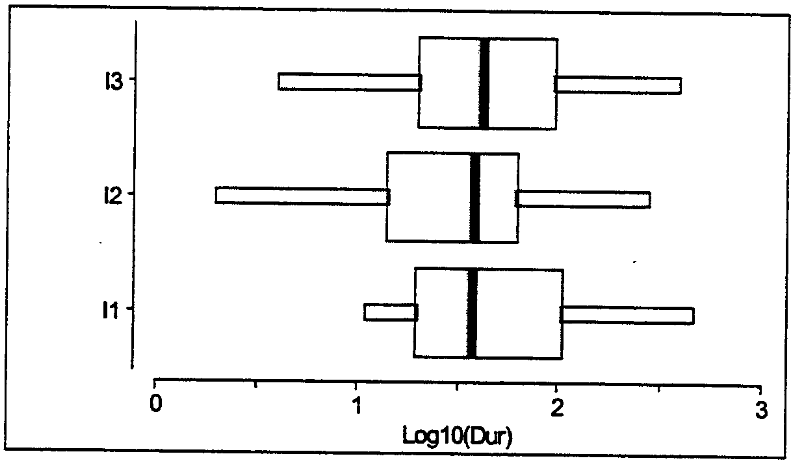

Figure B-22. $\log_{10}$(recovery time), for plant-centered trip events with recovery time ≥ 2 minutes, plotted by design group. The differences are not statistically significant (p-value = 0.39).

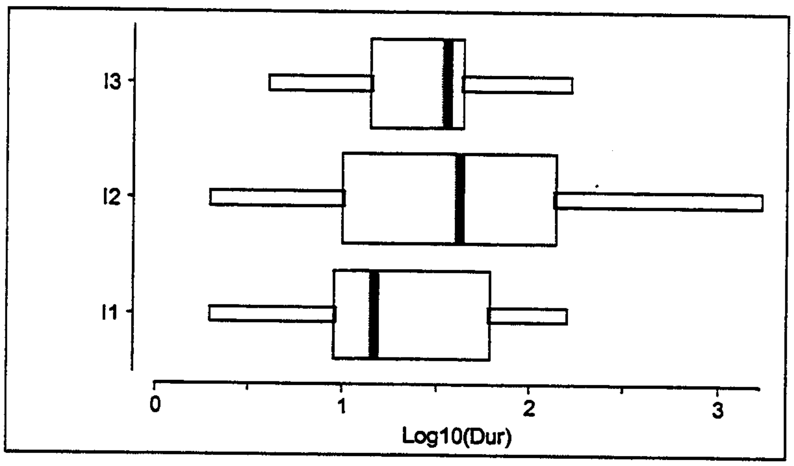

Figure B-23. $\log_{10}$(recovery time), for plant-centered shutdown events with recovery time ≥ 2 minutes, plotted by design group. The differences are not statistically significant (p-value = 0.37). The difference between groups I1 and I3 is also not statistically significant (p-value = 0.35).

Big Rock Point and La Crosse were especially difficult to fit into the classification scheme. When those two power plants were dropped from consideration, the above conclusions concerning statistical significance changed very little, and not in any systematic way. Therefore, the results without Big Rock Point and La Crosse are not shown here.

One might theorize that the design groups could make a difference in the fraction of LOSP events that are momentary. Table B-10 shows that this is not the case. The difference between design groups is not close to statistically significant, and no ordering of the design groups is apparent. Indeed, group I1 has the smallest fraction of momentary events instead of the expected largest, although any pattern seen could result from randomness alone. Pilgrim was excluded from this analysis, because it had so many momentary events that it would dominate the analysis.

Table B-10. Estimated probability that a random LOSP event is momentary.

Design Group	Momentary Events	All Events	Observed Fraction of Momentary Events	90%Conf. Int. on Prob(event is momentary)
Trip Events (p-value for difference between design groups = 0.46)				
I1	0	9	0.0	(0.00, 0.28)
I2	5	33	0.15	(0.06, 0.29)
I3	2	11	0.12	(0.02, 0.33)
Shutdown Events (p-value for difference between design groups = 0.40)				
I1	1	20	0.05	(0.003, 0.22)
I4	4	42	0.10	(0.03, 0.21)
I3	4	23	0.17	(0.06, 0.36)

B-6 REFERENCE

Modarres, M., H. Martz, and M. Kaminsky, 1996, "The Accident Sequence Precursor Analysis: Review of the Methods and New Insights," *Nuclear Science and Engineering*, Vol. 123, pp. 238-258, (Table III).

APPENDIX C

SUMMARY OF DATA

Relay - All relay failures except relays for transformer or individual circuit breaker controls

Circuits - Failure of general protective/sensing circuits such as blackout detection or generator voltage regulator failures etc.

Other - All other equipment failures, including discovery of design failures.

HE = Human error during any operating mode, identified by type.

Testing - Errors by test personnel including errors while establishing or restoring from testing lineups including electrical distribution changes.

Maintenance - Errors by maintenance personnel that directly or indirectly caused an event.

Switching - Errors during electrical switching operations, not directly required by testing, generally involving incorrect breaker manipulation.

Other - All other human errors.

HES = Human error during any shutdown mode, identified by type.

Testing - Errors by test personnel including errors while establishing or restoring from testing lineups including electrical distribution changes.

Maintenance - Errors by maintenance personnel that directly or indirectly caused an event.

Switching - Errors during electrical switching operations, not directly required by testing, generally involving incorrect breaker manipulation.

Other - All other human errors.

EEE = Extreme External Events (For analysis, these were classified as weather-related events.)

Hurricane, Winds > 125 mph
Tornado
Earthquake > R7
Flooding > 500 year flood for the site
Sabotage.

SEE = Severe External Events (For analysis, these were classified as both plant-centered and weather-related events. Individual event classification is displayed in Tables C-1 through C-3.)

Lightening
High Winds
Snow and Ice
Salt Spray
Dust Contamination
Tree Interference
Fires and Smoke Contamination
Earthquake < R7
Flooding < 500 year flood for the site.

OTHER = Self Evident. The only case was a unique event caused by mayflies at La Crosse.

- Docket - Three digit docket number of the affected unit. This number does not always match the LER docket number.

Of the 176 events in the data base, three events occurred before the full power license date (LERs 35486011, 41682045, and 44388004) and are not used in the data analysis; neither are they shown in the tables below. Of the remaining 173 events, 16 are excluded from the frequency analysis. The 11 "POWER OP" events occurred during power operation and challenged the emergency generators to power the safety buses, but they did not cause a reactor trip, thus were not considered initiating events. These 11 events are the first 11 events listed in Table C-1, coded with a P in the "Status" column. In five other events (LERs 39589012, 31186007, 27283033, 24785016, and 23790002), a reactor trip from a non-electrical cause preceded the electrical event and actually triggered the transient resulting in the loss of offsite power. These 16 events are indicated by 0 in the "Initiator" column of Tables C-1 through C-3. They are not used to estimate the frequency of initiating events. In the analysis discussed in Section B-3.1, they were considered for possible use in characterizing the recovery times, with the following conclusions: The 11 POWER-OP events have longer recovery times and were not used in the recovery time analysis. The trip events that were not initiators have recovery times similar to the initiating events, and were combined with the initiating events to characterize recovery times.

C-2 EVENT TABLES

Tables C-1 through C-3 summarize the events contained in the LOSP database used for the analysis. In each of these three tables, the events are listed in order of unit status (power operation, shutdown, or trip), then by LER number. Note that sometimes an LER number corresponds to more than one event, or to an event at more than one power plant unit. There were five events identified for which the licensee did not submit an LER; these are designated by '000' as the last three digits in the "LER Number" field.

The field explanations are as follows: The column field labeled "1032 Category" has value P, G, or W, for plant-centered, grid-related, or severe weather. In the column "Status," the entries P, S, S*, T, and T* are abbreviations for POWER OP, SHUTDOWN, SHUTDOWN*, TRIP, and TRIP*. The "Cause" field is self-explanatory, although the text in the field is too brief to provide a complete description of the event's cause. The column labeled "Initiator" has value 1 if the event is an initiating event, and 0 otherwise. This applies to status P, T, and T* only; it is irrelevant for shutdown events, so a hyphen is displayed for these events. The recovery time is given in minutes. For the analysis of recovery times, estimated times (indicated by 'est' in the Recovery Time column) were treated as if they were actual times, and unknown times were ignored. A 'C' in the Recovery Time column indicates the time at which a licensee could have restored power to a safety bus from a non-standard transformer source, even though they chose to continue operating on the emergency power source. The event date is written as month/day/year.

Table C-1. Plant-centered LOSP events. (continued)

LER Number	Unit Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
36991001	McGuire 1	P	T	HE - testing	1	40	02/11/91
37093008	McGuire 2	P	T	Equip - transformer	1	96	12/27/93
37393015	LaSalle 1	P	T	Equip - transformer	1	15 C	09/14/93
38884013	Susquehanna 2	P	T	HE - testing	1	11.0	07/26/84
40984011	La Crosse	P	T*	Other - mayflies	1	20	07/16/84
40985017	La Crosse	P	T	HE - maintenance	1	60	10/22/85
41287036	Beaver Valley 2	P	T	Equip - breaker	1	4.0 C	11/17/87
41496001	Catawba 2	P	T	Equip - transformer	1	330	02/06/96
44391008	Seabrook	P	T	Equip - relay	1	20	06/27/91
45688022	Braidwood 1	P	T	Equip - breaker	1	95	10/16/88
45886002	River Bend	P	T*	Equip - circuits	1	46	01/01/86
52885058	Palo Verde 1	P	T	Equip - circuits	1	25	10/03/85
52885076	Palo Verde 1	P	T*	Equip - circuits	1	13	10/07/85

Table C-2. Grid-related LOSP events.

LER number	Unit Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
25185011	Turkey Point 3	G	S	G-Other - fire	-	156	05/17/85
31281034	Rancho Seco	G	S*	G-Other - load	-	360	06/19/81
31281039	Rancho Seco	G	S*	G-Other - load	-	180	08/07/81
25185011	Turkey Point 4	G	T	G-Other - fire	1	125	05/17/85
33184028	Duane Arnold	G	T*	G-Equip - other	1	1.0 C	07/14/84
39589012	Summer	G	T*	G-Equip - other	0	130	07/11/89

Table C-3. Weather-related LOSP events.

LER number	Unit Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
26783018	Fort St. Vrain	W	S	SEE - Snow and wind	-	105	05/17/83
29382051	Pilgrim	W	S	SEE - wind, salt	-	1.0 C	10/12/82
29386027	Pilgrim	W	S	SEE - ice	-	1.0 C	11/19/86
29387005	Pilgrim	W	S	SEE - wind	-	1.0 C	03/31/87
29387014	Pilgrim	W	S	SEE - wind, salt	-	1263	11/12/87
30293000	Crystal River 3	W	S	SEE - wind, salt	-	unknown	03/13/93
30293000	Crystal River 3	W	S	SEE - rain, salt	-	142	03/17/93
30293002	Crystal River 3	W	S	SEE - storm flooding	-	37	03/29/93
32593008	Brunswick 2	W	S	SEE - wind, salt	-	814	03/16/93
32593008	Brunswick 1	W	S	SEE - wind, salt	-	1508	03/16/93
33388011	Fitzpatrick	W	S	SEE - wind	-	1.5 C	10/31/88
24585018	Millstone 1	W	T*	EEE - hurricane	1	211 C	09/27/85
24585018	Millstone 2	W	T*	EEE - hurricane	1	330 C	09/27/85
25092000	Turkey Point 3	W	T*	EEE - hurricane	1	7950	08/24/92
25092000	Turkey Point 4	W	T*	EEE - hurricane	1	7908	08/24/92
28296012	Prairie Island 1	W	T	SEE - wind	1	296	06/29/96
28296012	Prairie Island 2	W	T	SEE - wind	1	296	06/29/96
29383007	Pilgrim	W	T	SEE - wind, salt	1	1.0 C	02/13/83
29391024	Pilgrim	W	T*	SEE - wind, salt	1	120	10/30/91
29393004	Pilgrim	W	T	SEE - snow	1	1.0 C	03/13/93
31380013	Arkansas 1	W	T	EEE - tornado	1	1.0 C	04/07/80
31380013	Arkansas 2	W	T	EEE - tornado	1	1.0 C	04/07/80

Descriptions of the events for which there was no LER submitted are listed below in Table C-4. Descriptions of the events for which the licensee submitted LERs may be found in the LERs.

Table C-4. Event descriptions of non-LER events.

Plant Name Docket Event Date	Event Description
Big Rock Point 155 1/29/92	This abstract is taken from NSAC 203. While shutdown for refueling, offsite power was supplied from Charlevoix 46 kV line. The 138 kV Emmet County line was OOS for relay repairs. The repairs were completed but before the 138 kV line was restored, a lightning arrestor failed on the 46 kV line and the plant lost all offsite power. The 138 kV line was energized 1:17 after power was lost. The EDG successfully started and carried essential loads.
Oyster Creek 219 11/14/83	This abstract taken from NSAC 203. The plant was shutdown with the generator links lifted. A fire broke out in a potential transformer in the 34.5 kV yard that supplies two startup transformers causing loss of one startup transformer. Carbon deposits caused arcing in other parts of the 34.5 kV switchyard. A decision was made to deenergize the 34.5 kV yard at about 2:00 p.m. to clean the insulators. The 34.5 kV yard was reenergized at 6:00 p.m. Because the generator links were lifted, power could have been supplied by the unit transformer within several hours. A mobile substation could have been on line in about 4 hours.
Turkey Point, Units 1 and 2 250 and 251 8/24/92	This abstract taken from NSAC 203. The eye of Hurricane Andrew passed directly over Turkey Point early on August 24, 1992. Both Units 3 & 4 had been placed in hot shutdown in preparation for the storm arrival. Due to extensive transmission line damage, Unit 3 lost all offsite power at 4:40 a.m. Offsite power first became available on August 28 but there were two subsequent tripouts because of residual problems. Reliable offsite power became available on August 29 at 5:10 p.m. Because the EDGs were operating without problems, it was decided to continue to power the plant from the EDGs and keep offsite power energized but unloaded for an additional day to confirm reliability.
Crystal River 3 302 3/13/93	This abstract taken from NSAC 203. While in cold shutdown for maintenance, offsite power was being supplied via backfeed through the main unit output transformer and the unit auxiliary transformer. Both the startup and the offsite power transformers were available. Due to storm related winds, rain, and salt spray, one of the two parallel switchyard breakers feeding the main transformer (and hence the unit aux. transformer) tripped. Subsequently the startup transformer also tripped.
Crystal River 3 302 3/17/93	This abstract taken from NSAC 203. While in cold shutdown for maintenance, offsite power was being supplied via backfeed through the main unit output transformer and the unit auxiliary transformer. In addition the offsite power transformer was available. The startup transformer was out of service for extended maintenance. During early morning it began raining. There was flashing and arcing (from salt deposits) in both the 230 kV and the 500 kV switchyards. By 7:25 a.m., 1/2 of the 230 kV switchyard became deenergized. At 10:50 a.m. the remaining power to the 230 kV switchyard tripped off and deenergized the offsite power transformer. One half of the 230 kV switchyard was reenergized at 1 hour 12 min.

The critical hours, shutdown hours, and calendar hours used are summarized in Table C-5. Because no information was found for critical hours and shutdown hours in 1980, the critical hours and shutdown hours for 1980 are estimated. A year was defined as 365 days, or 8760 hours; that is, a critical year was 8760 critical hours for a reactor, a shutdown year was 8760 shutdown hours for a reactor, and a calendar year was 8760 calendar hours at a reactor. A consequence of this is that the period from 1980 through 1996 contains 17.014 calendar years, because of the leap years.

Table C-5. Reactor-years for the study, by calendar year.

Year	Calendar Years	Critical Years	Shutdown Years
1980	66.833	44.778[a]	22.055[a]
1981	70.151	48.599	21.552
1982	72.973	48.754	24.219
1983	77.451	51.343	26.108
1984	81.904	53.058	28.846
1985	90.114	62.234	27.882
1986	96.807	63.826	32.981
1987	102.722	70.250	32.472
1988	107.688	76.428	31.260
1989	108.963	76.358	32.605
1990	110.510	80.624	29.886
1991	111.000	83.944	27.056
1992	110.370	83.836	26.534
1993	108.738	82.868	25.871
1994	109.000	85.801	23.199
1995	109.000	88.841	20.159
1996	110.123	87.299	22.824
Total	1644.345	1188.836[a]	455.509[a]

a. In 1981 – 1987, the average percentage of time shutdown was 33%, with no evident trend. Therefore, the shutdown time for 1980 was estimated as 33% of the calendar time.

The events and exposure times are summarized for each unit in Table C-6. This table includes all the events used in the study, from 1980 through 1986. Therefore, the critical times and shutdown times are estimated for each unit, using the actual times for 1981 through 1996, and estimating the critical time for 1980 for each unit as 67% of the calendar time. To highlight the events that actually occurred, all zero counts are shown as hyphens.

Table C-6. Summary of LOSP events, by unit.

	Power Operation Experience				Shutdown Experience			
Unit	Plant-Centered[a]	Grid-Related[a]	Severe Weather[a]	Critical Years[b]	Plant-Centered[c]	Grid-Related[c]	Severe Weather[c]	Shutdown Years[b]
Arkansas 1	1, -	-, -	1, -	13.054	-	-	-	3.960
Arkansas 2	1, -	-, -	1, -	13.252	-	-	-	3.762
Beaver Valley 1	1, -	-, -	-, -	12.770	-	-	-	4.244

Table C-6. Summary of LOSP events, by unit (continued).

Unit	Power Operation Experience: Plant-Centered[a]	Grid-Related[a]	Severe Weather[a]	Critical Years[b]	Shutdown Experience: Plant-Centered[c]	Grid-Related[c]	Severe Weather[c]	Shutdown Years[b]
Beaver Valley 2	1, -	-, -	-, -	7.884	1	-	-	1.506
Big Rock Point	-, -	-, -	-, -	13.041	1	-	-	3.973
Braidwood 1	1, -	-, -	-, -	7.228	1	-	-	2.280
Braidwood 2	-, 1	-, -	-, -	7.290	-	-	-	1.333
Browns Ferry 1	-, -	-, -	-, -	3.493	-	-	-	13.521
Browns Ferry 2	-, -	-, -	-, -	8.415	-	-	-	8.599
Browns Ferry 3	-, 1	-, -	-, -	3.944	-	-	-	13.070
Brunswick 1	1, -	-, -	-, -	10.548	1	-	1	6.466
Brunswick 2	1, -	-, -	-, -	11.054	1	-	1	5.960
Byron 1	-, -	-, -	-, -	9.770	1	-	-	2.116
Byron 2	-, -	-, -	-, -	8.630	1	-	-	1.297
Callaway	-, -	-, -	-, -	10.704	-	-	-	1.509
Calvert Cliffs 1	1, -	-, -	-, -	11.877	-	-	-	5.136
Calvert Cliffs 2	1, -	-, -	-, -	12.224	-	-	-	4.790
Catawba 1	-, -	-, -	-, -	9.163	-	-	-	2.800
Catawba 2	1, -	-, -	-, -	8.408	-	-	-	2.232
Clinton 1	-, -	-, -	-, -	6.753	-	-	-	2.484
Comanche Peak 1	-, -	-, -	-, -	5.500	-	-	-	1.216
Comanche Peak 2	-, -	-, -	-, -	2.980	-	-	-	0.761
Cook 1	1, -	-, -	-, -	12.867	-	-	-	4.146
Cook 2	-, -	-, -	-, -	11.875	-	-	-	5.139
Cooper	-, -	-, -	-, -	12.077	-	-	-	4.937
Crystal River 3	3, -	-, -	-, -	11.790	5	-	3	5.224
Davis-Besse	-, -	-, -	-, -	11.605	-	-	-	5.409
Diablo Canyon 1	-, -	-, -	-, -	10.180	2	-	-	1.966
Diablo Canyon 2	1, -	-, -	-, -	9.601	-	-	-	1.757
Dresden 2	1, 1	-, -	-, -	11.392	-	-	-	5.622
Dresden 3	1, -	-, -	-, -	11.339	-	-	-	5.675
Duane Arnold	-, -	1, -	-, -	13.103	1	-	-	3.910
Farley 1	-, -	-, -	-, -	14.129	1	-	-	2.885
Farley 2	-, -	-, -	-, -	13.573	1	-	-	2.193
Fermi 2	-, -	-, -	-, -	7.161	-	-	-	4.309
Fitzpatrick	-, -	-, -	-, -	12.073	-	-	1	4.940
Fort Calhoun	-, -	-, -	-, -	13.393	3	-	-	3.620
Fort St. Vrain	-, -	-, -	-, -	3.753	-	-	1	5.914
Ginna	-, 2	-, -	-, -	13.828	-	-	-	3.185
Grand Gulf	-, -	-, -	-, -	10.075	-	-	-	2.269
Haddam Neck	-, -	-, -	-, -	12.290	4	-	-	4.648
Harris	-, -	-, -	-, -	8.337	-	-	-	1.640
Hatch 1	-, -	-, -	-, -	12.992	1	-	-	4.022
Hatch 2	-, -	-, -	-, -	13.289	-	-	-	3.724
Hope Creek	-, -	-, -	-, -	8.633	-	-	-	1.812
Indian Point 2	1, 1	-, -	-, -	12.525	3	-	-	4.489
Indian Point 3	-, 1	-, -	-, -	9.059	3	-	-	7.954
Kewaunee	-, -	-, -	-, -	14.402	-	-	-	2.611
La Crosse	2, -	-, -	-, -	5.053	4	-	-	2.280
LaSalle 1	1, -	-, -	-, -	10.366	-	-	-	4.030
LaSalle 2	-, -	-, -	-, -	9.234	-	-	-	3.551
Limerick 1	-, -	-, -	-, -	9.543	-	-	-	1.864
Limerick 2	-, -	-, -	-, -	6.620	-	-	-	0.738
Maine Yankee	1, -	-, -	-, -	12.730	-	-	-	4.284
McGuire 1	2, -	-, -	-, -	11.433	1	-	-	4.062
McGuire 2	1, -	-, -	-, -	10.780	1	-	-	2.829
Millstone 1	-, -	-, -	1, -	12.512	2	-	-	4.502
Millstone 2	1, -	-, -	1, -	10.818	1	-	-	6.195
Millstone 3	-, -	-, -	-, -	7.748	-	-	-	3.177
Monticello	-, -	-, -	-, -	13.745	2	-	-	3.269
Nine Mile Pt. 1	-, 3	-, -	-, -	10.786	-	-	-	6.228
Nine Mile Pt. 2	-, -	-, -	-, -	6.855	2	-	-	2.653
North Anna 1	-, -	-, -	-, -	12.787	-	-	-	4.227
North Anna 2	-, -	-, -	-, -	13.540	-	-	-	2.834
Oconee 1	-, -	-, -	-, -	13.710	-	-	-	3.304

Table C-6. Summary of LOSP events, by unit (continued).

	Power Operation Experience				Shutdown Experience			
Unit	Plant-Centered[a]	Grid-Related[a]	Severe Weather[a]	Critical Years[b]	Plant-Centered[c]	Grid-Related[c]	Severe Weather[c]	Shutdown Years[b]
Oconee 2	1, -	-, -	-, -	13.892	-	-	-	3.122
Oconee 3	-, -	-, -	-, -	13.414	2	-	-	3.599
Oyster Creek	2, -	-, -	-, -	10.879	2	-	-	6.135
Palisades	1, -	-, -	-, -	10.260	2	-	-	6.753
Palo Verde 1	2, -	-, -	-, -	7.780	-	-	-	3.813
Palo Verde 2	-, 1	-, -	-, -	7.675	-	-	-	3.023
Palo Verde 3	-, -	-, -	-, -	7.127	-	-	-	1.981
Peach Bottom 2	-, -	-, -	-, -	10.704	1	-	-	6.309
Peach Bottom 3	-, -	-, -	-, -	10.663	1	-	-	6.350
Perry	-, -	-, -	-, -	6.981	-	-	-	3.160
Pilgrim	1, -	-, -	3, -	10.264	5	-	4	6.749
Point Beach 1	-, 1	-, -	-, -	14.299	1	-	-	2.715
Point Beach 2	1, -	-, -	-, -	14.283	2	-	-	2.731
Prairie Island 1	-, -	-, -	1, -	15.004	1	-	-	2.009
Prairie Island 2	1, -	-, -	1, -	14.948	-	-	-	2.065
Quad Cities 1	-, -	-, -	-, -	12.502	1	-	-	4.512
Quad Cities 2	1, -	-, -	-, -	12.200	2	-	-	4.814
Rancho Seco	-, -	-, -	-, -	3.932	-	2	-	5.508
River Bend	1, -	-, -	-, -	8.278	-	-	-	2.844
Robinson 2	2, -	-, -	-, -	11.682	-	-	-	5.332
Salem 1	-, 1	-, -	-, -	10.682	2	-	-	6.332
Salem 2	-, 2	-, -	-, -	9.306	.2	-	-	6.323
San Onofre 1	1, -	-, -	-, -	6.061	2	-	-	6.864
San Onofre 2	-, -	-, -	-, -	11.480	-	-	-	2.847
San Onofre 3	-, -	-, -	-, -	10.676	-	-	-	2.627
Seabrook	1, -	-, -	-, -	5.648	-	-	-	1.156
Sequoyah 1	1, -	-, -	-, -	9.499	-	-	-	6.801
Sequoyah 2	1, -	-, -	-, -	9.783	-	-	-	5.523
South Texas 1	-, -	-, -	-, -	5.980	-	-	-	2.805
South Texas 2	-, -	-, -	-, -	5.453	-	-	-	2.316
St. Lucie 1	1, -	-, -	-, -	13.143	-	-	-	3.871
St. Lucie 2	-, -	-, -	-, -	11.508	-	-	-	2.064
Summer	-, -	-, 1	-, -	11.760	-	-	-	2.386
Surry 1	-, -	-, -	-, -	12.576	-	-	-	4.438
Surry 2	-, -	-, -	-, -	12.676	-	-	-	4.338
Susquehanna 1	-, -	-, -	-, -	11.289	-	-	-	2.857
Susquehanna 2	1, -	-, -	-, -	10.390	-	-	-	2.132
Three Mile Isl 1	-, -	-, -	-, -	10.557	-	-	-	6.457
Trojan	-, -	-, -	-, -	7.824	-	-	-	5.187
Turkey Point 3	2, -	-, -	1, -	11.251	2	1	-	5.763
Turkey Point 4	-, -	1, -	1, -	11.427	1	-	-	5.586
Vermont Yankee	1, -	-, -	-, -	14.060	1	-	-	2.954
Vogtle 1	-, -	-, -	-, -	8.566	1	-	-	1.238
Vogtle 2	-, -	-, -	-, -	6.957	-	-	-	0.806
Wash. Nuclear 2	-, -	-, -	-, -	9.111	1	-	-	3.617
Waterford 3	-, -	-, -	-, -	9.818	1	-	-	1.986
Watts Bar 1	-, -	-, -	-, -	0.762	-	-	-	0.138
Wolf Creek	-, -	-, -	-, -	9.506	1	-	-	2.079
Yankee-Rowe	1, -	-, -	-, -	9.581	1	-	-	2.582
Zion 1	-, -	-, -	-, -	11.268	-	-	-	5.746
Zion 2	1, -	-, -	-, -	11.888	1	-	-	5.126
Total	50,15	2, 1	11, -	1188.836	80	3	11	455.509

a. For power operation experience, each pair of counts is the number of LOSP initiating events and the number of LOSP non-initiators. A hyphen indicates a count of zero.

b. Tabulated times assume that each reactor was critical for 67% of its calendar time in 1980.

c. For shutdown experience, each count is the number of LOSP events, regardless of whether or not those events would have caused a reactor trip at power. A hyphen indicates a count of zero.

Sites were categorized by electrical design group, I1, I2, I3, for an investigation of whether the design features of a unit affected the duration of plant-centered LOSP events. The categorized sites are listed in Table C-7. To the extent possible, the classification of NUREG-1032, found in Tables A-2, A-3, and A-4 of that report, was used. Sites that were not classifiedin NUREG-1032 are marked by an asterisk (*). Sites for which no LOSP events were identified for this study and that were not categorized by NUREG-1032 are not included in Table C-7.

Table C-7. Sites listed by design group. Site names preceded by * were categorized for this report. Those without the * were categorized in NUREG-1032 and the same categorization was used in this study.

I1	I2	I3
Haddam Neck	Arkansas	* Braidwood
Indian Point	Beaver Valley	* Byron
Millstone	* Big Rock Point	* Calvert Cliffs
Monticello	* Browns Ferry	* Catawba
Nine Mile Pt.	Brunswick	* Duane Arnold
Oconee	* Cook	Farley
* Robinson	* Crystal River	Fort Calhoun
Susquehanna	* Diablo Canyon	* La Crosse
* Yankee-Rowe	Dresden	Palisades
	* Fitzpatrick	Palo Verde
	* Fort St. Vrain	* Pilgrim
	Ginna	Quad Cities
	* Grand Gulf	San Onofre
	* Hatch	* Seabrook
	* LaSalle	* Sequoyah
	* Maine Yankee	* St. Lucie
	McGuire	* Waterford
	Oyster Creek	* Wolf Creek
	* Peach Bottom	* Zion
	Point Beach	
	Prairie Island	
	* Rancho Seco	
	* River Bend	
	* Salem	
	* Summer	
	Turkey Point	
	* Vermont Yankee	
	* Vogtle	
	* Wash. Nuclear	

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

It is recognized that the availability of AC power to commercial nuclear power plants is essential for safe operations and accident recovery. A loss of offsite power (LOSP) event, therefore is considered an important contributor to total risk at nuclear power plants. In 1988, the NRC published NUREG-1032 to report on an evaluation of the risk from actual LOSP events that had occurred at nuclear power plants within the United States up through 1985. This report documents a similar study whose primary objective was to update the LOSP model parameters, frequency and recovery time, using power plant event data from 1980-1996. An additional objective is to re-examine the engineering insights concerning LOSP events.

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