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Collection and Evaluation of Complete and Partial Losses of Off-Site Power at Nuclear Power Plants

Prepared by R. E. Battle

Oak Ridge National Laboratory

Prepared for
U.S. Nuclear Regulatory
Commission

NOTICE

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COLLECTION AND EVALUATION OF COMPLETE AND PARTIAL LOSSES OF OFF-SITE POWER AT NUCLEAR POWER PLANTS

EXECUTIVE SUMMARY

The purpose of this report is to provide an accurate data base for use by the U.S. Nuclear Regulatory Commission (NRC) in the resolution of Unresolved Safety Issue (USI) A-44--"Station Blackout." Events involving loss of off-site power that have occurred at nuclear power plants through 1983 are described and categorized as complete or partial losses. The events were studied in detail to understand their significance for further statistical analyses by the Nuclear Regulatory Commission staff.

Design features were evaluated to determine those that may be important factors affecting off-site power system reliability. The off-site power failures were identified as plant-centered or grid-related failures. Design features that would affect the frequency and duration of grid-related losses of off-site power (including severe weather) are the number of transmission lines and rights-of-way to the plant switchyard and the availability of generators such as hydro, gas turbines, or fossil units near the nuclear plant. Design features that may be important for plant-centered losses of off-site power are the independence of the sources of off-site power (electrically separate sources), the number of off-site sources, and the relay scheme for transferring between off-site sources. These design features were tabulated for most of the operating nuclear power plants. The tabulated information was provided to NRC for a statistical analysis to determine the importance of these design features for plant-centered losses of off-site power.

In addition, the causes of the failures were classified as weather, human error, design error, or hardware failure. The plant-centered failures were usually of shorter duration than the weather-related grid failures. For this reason, the weather-related events were reviewed in detail.

Tornados have caused the most extensive damage to off-site power systems, but they have caused only one complete loss of off-site power. Hurricanes have not caused extensive damage near a nuclear power plant that resulted in a complete loss of off-site power. Winter storms have caused losses of off-site power, but these storms have not caused extensive damage that resulted in extended duration of loss of off-site power. Windblown salt spray has contaminated switchyard insulators with salt and caused arcing across the insulators. The arcing caused some switchyard equipment to fail and made the off-site power intermittent. However, for these events the off-site power did not fail completely, and it may have been usable in an emergency.

The frequency of losses of off-site power versus duration were estimated for three time periods. The frequency of loss of off-site power was estimated to be 0.09/reactor-year based on industry-wide data for the years 1959 through 1983.

1. INTRODUCTION

This report describes a collection of complete and partial losses of off-site power that have occurred at nuclear power plants. The purposes of this report are to describe accurately the loss of off-site power events and to describe off-site power system design features that may affect the frequency and duration of loss of off-site power.

The event descriptions were derived from Licensee Event Reports (LERs), questionnaire responses from nuclear plant licensees, NRC and utility reports, and discussions with utility engineers familiar with the events. Most of the data sources described what happened in general during loss of off-site power events at the nuclear plants but did not include many details of equipment failures and repairs of the transmission system. Off-site power system design information was collected to use in determining the effect of design features on off-site power system reliability. Design information was collected to determine the redundancy, diversity, and independence of sources of off-site power.

The loss of off-site power data reported here is in support of the NRC Unresolved Safety Issue (USI) A-44, "Station Blackout." The frequency and duration of loss of off-site power combined with an estimate of probability of failure of the on-site power source[1] can be used to calculate a frequency and duration estimate of loss of all ac power--station blackout. The frequency of core melt can be estimated by using the data on failure of systems[2] independent of ac power.

2. OFF-SITE POWER SYSTEM DESIGNS

The design information collected here was provided to NRC for a statistical analysis to determine if design features significantly affect the frequency of loss of off-site power. Losses of off-site power have occurred because of failures in the plant switchyard during which transmission lines to the switchyard remained energized, but, because of the switchyard failures, power could not be connected to the plant ac distribution system. These are plant-centered failures for which switchyard and plant electrical system distribution design features are relevant. Severe weather and grid instabilities cause failures of power delivered to the plant switchyard. These are grid-related failures for which design and operation of the transmission system are relevant.

Design features that may be important for plant-centered losses of off-site power are the following: the number of off-site power sources available to the Class 1E buses; whether alternate off-site power sources are electrically connected or electrically independent; and the number of automatically and manually transferrable power sources. Design features that may be important for severe weather are the following: the number of transmission lines connected to the plant; the number of rights-of-way for the transmission lines and; the availability of independent ac power sources that in an emergency could be dedicated to serve the nuclear plant.

Class 1E is defined in IEEE Standard 308-1980 as the safety classification of the electrical equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, or are otherwise essential in preventing significant release of radioactive material to the environment.

Transmission system design information, such as transmission lines rights-of-way, was not available for most plants. The design information concerning the switchyard was obtained almost completely from Final Safety Analysis Reports (FSARs). The FSARs contain single-line diagrams of the electrical systems and describe how the system operates. Typical drawings of nuclear power plants showing the switchyards and the connections to the switchyards from the plant ac distribution system and from the transmission system are shown in Figs. 2.1, 2.2, and 2.3.

Several design features are classified in Table 2.1a, and these design features are tabulated for most of the operating plants in Table 2.1b for further statistical analysis by the NRC. The ac power sources to a nuclear power plant that are included in the classifications in Table 2.1a are the following: a unit power source is a power source tapped off the main generator; a preferred power source is an off-site power source that is preferred to furnish emergency power under accident or post accident conditions; an alternate off-site power source is an off-site power source in addition to the unit and preferred off-site power sources. The normal power source to the Class 1E buses may be a

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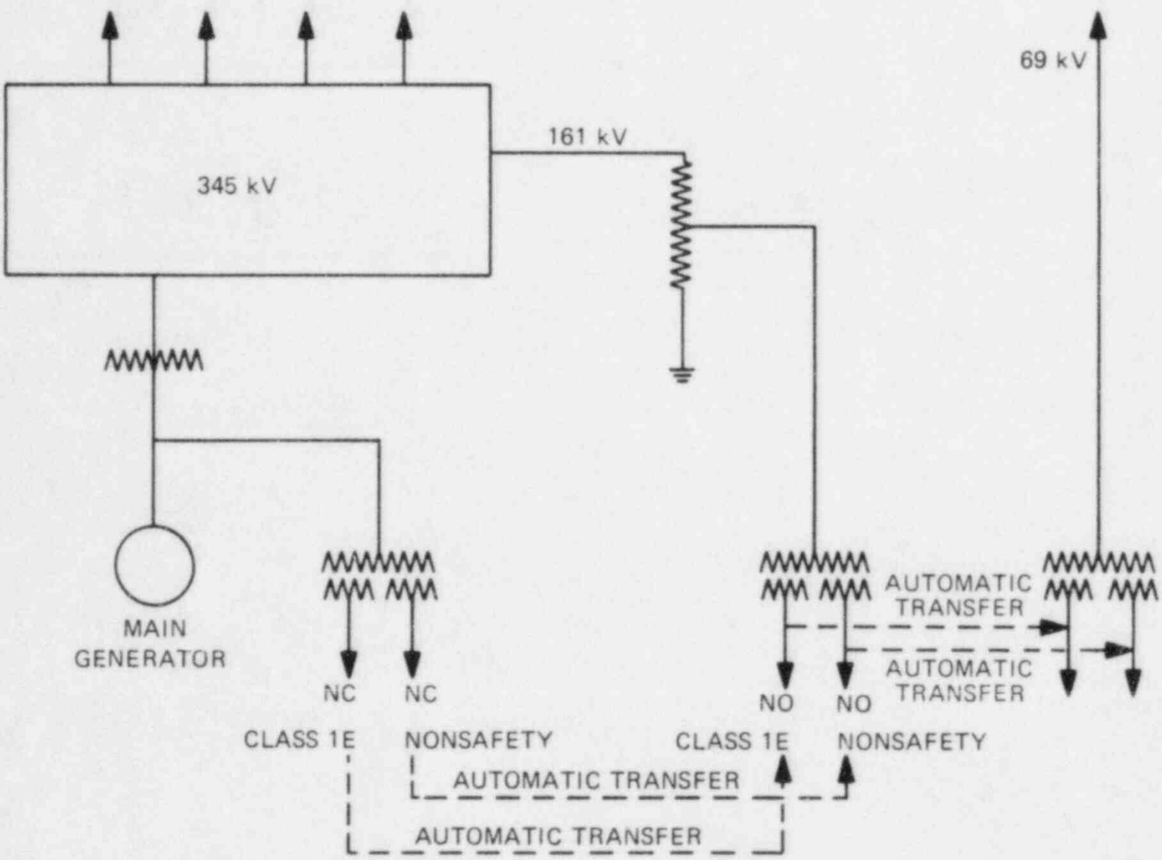

Fig. 2.1. Cooper 1 off-site power system.

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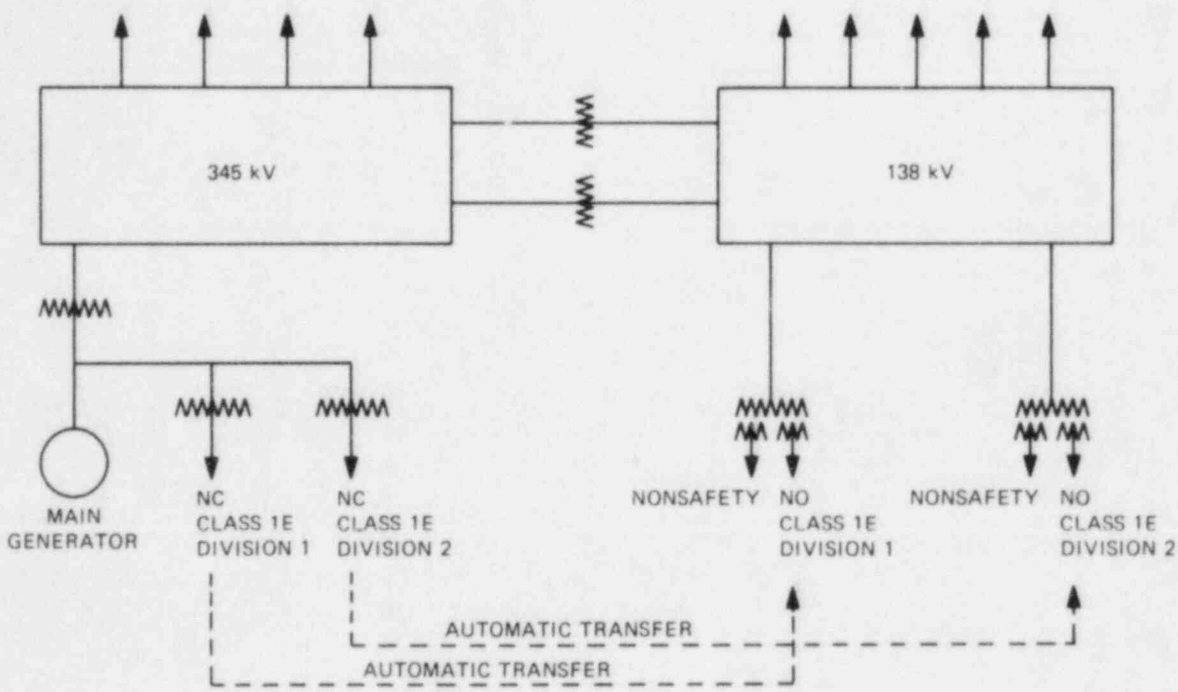

Fig. 2.2. Beaver Valley 1 off-site power system.

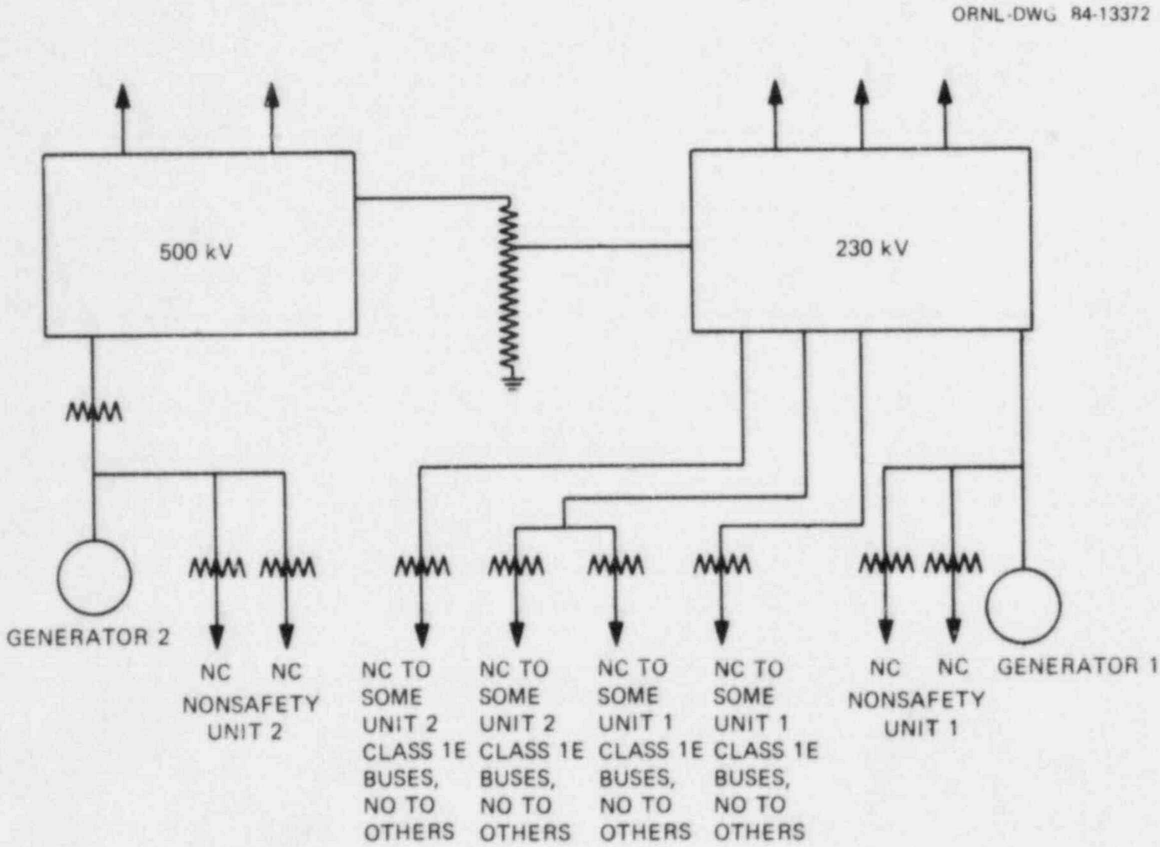

Fig. 2.3. Joseph M. Farley 1 and 2 off-site power system.

Table 2.1a. Classification of off-site power system design categories

CATEGORY I - Independence of off-site power sources to the nuclear power plant

1. All off-site power sources are connected to the plant through one switchyard.

2. All off-site power sources are connected to the plant through two or more switchyards, and the switchyards are electrically connected. The 345- and 138-kV switchyards in Fig. 2.2 represent this design feature.

3. All off-site power sources are connected to the plant through two or more switchyards or separate incoming transmission lines, but at least one of the ac sources is electrically independent of the others. The independent 69-kV line in Fig. 2.1 is representative of this design feature.

CATEGORY II - Power sources for the Class 1E buses during normal plant operation

1. During normal operation, the Class 1E buses are supplied by the main generator through a unit transformer. The normally closed (NC) circuit from the main generator to the Class 1E system in Fig. 2.1 is representative of this design feature.

2. During normal operation the Class 1E power is supplied by a preferred off-site power source. The normally closed (NC) circuits from the 230-kV switchyard to the Class 1E buses in Fig. 2.3 are representative of this design feature.

CATEGORY III - Automatic and manual transfer schemes for the Class 1E buses when the normal source of ac power fails and when the backup sources of off-site power fail

1. If the normal source of ac power fails, there are no automatic transfers and one or more manual transfers to preferred or alternate off-site power sources. Normally open (NO), manually operated circuits to the Class 1E buses as shown in Fig. 2.3 are representative of this design feature.

2. If the normal source of ac power fails, there is one automatic transfer but no manual transfers to preferred or alternate off-site power sources.

   a. All of the Class 1E buses in a unit are connected to the same preferred power source after the automatic transfer of power sources. The transfer of the Class 1E buses from one preferred source to another preferred source in Fig. 2.3 is representative of this design if the transfer were automatic instead of manual.

b. The Class 1E buses in a unit are connected to separate off-site power sources after the automatic transfer of power sources. The transfer to the two 138-kV switchyard sources in Fig. 2.2 is representative of this design feature.

3. After loss of the normal ac power source, there is one automatic transfer. If this source fails, there may be one or more manual transfers of power sources to preferred or alternate off-site power sources. The manual transfer from the autotransformer to the 69-kV source in Fig. 2.1 is representative of this design feature except the transfer from the autotransformer to the 69-kV source would be manual.

   a. All of the Class 1E buses in a unit are connected to one preferred power source after the first automatic transfer.

   b. The Class 1E buses in a unit are connected to separate off-site power sources after the first automatic transfer.

4. If the normal source of ac power fails, there is an automatic transfer to a preferred source of power. If this preferred source of power fails, there is an automatic transfer to another source of off-site power. The transfer from the 161-kV autotransformer to the 69-kV source in Fig. 2.1 is representative of this design feature.

   a. All of the Class 1E buses in a unit are connected to the same preferred power source after the first automatic transfer.

   b. The Class 1E buses in a unit are connected to separate off-site power sources after the first automatic transfer of power sources.

Table 2.1b. Nuclear power plant off-site power system design categories

Plant Name	Category I	Category II	Category III
Arkansas Nuclear One	2	1	3a
Arnold	2	2	2a
Beaver Valley 1	2	1	2b
Browns Ferry	3	1	4b
Brunswick 1	1	1	3a
Brunswick 2	1	1	3a
Calvert Cliffs	1	2	1
Connecticut Yankee	3	2	2c
D. C. Cook	3	1	3a
Cooper	3	1	4a
Crystal River 3	3	2	1
Davis-Besse	1	1	4a
Dresden 2	2	1	3a
Dresden 3	2	1	3a
J. F. Farley	2	2	1
J. A. FitzPatrick	3	1	2b
Ft. Calhoun	2	2	1
Ft. St. Vrain	1	1	2
Ginna	2	Unknown	Unknown

Table 2.1b (continued)

Plant Name	Category I	Category II	Category III
E. I. Hatch	2	2	2
Indian Point 2 and 3	2	2	1 & 2a
Kewaunee	2	2	1
Maine Yankee	3	1	3b
Millstone	3	1	3
Monticello	2	1	4a
Nine Mile Point	3	2	1
North Anna 1	1	2	Generator breaker
North Anna 2	1	2	Unknown
Oconee	3	1	3a
Oyster Creek	2	1	2b
Palisades	1	1	2a
Peach Bottom	3	2	2a
Pilgrim	3	1	4a
Point Beach	1	2	3a
Prairie Island	2	1	3b
Quad Cities	1	1 & 2	1
Rancho Seco	1	2	2b
H. B. Robinson	2	1 & 2	2a
St. Lucie	1	1	2b

Table 2.1b (continued)

Plant Name	Category I	Category II	Category III
Salem	2	2	2b
San Onofre	2	2	1
Sequoyah	2	1	4b
Surry	2	2	Unknown
Trojan	1	1	2b
Turkey Point	1	1	3a
Vermont Yankee	3	1	3a
Yankee Rowe	1	1 or 2	1
Zion	1	1 or 2	3a

unit or a preferred power source; but the normal source is the source that energizes the Class 1E buses when the plant is generating power and the breakers are aligned as described in the FSAR. Most of the information in Table 2.1b was obtained from FSARs. However, some of the FSARs did not include the information we needed; and some plants did not fit precisely into the categories. If there were significant questions about a category, none was assigned. Where one off-site circuit was in one category and another in a separate category, both categories were included in Table 2.1b.

Design features affect the probability of having a loss of off-site power. Plants that have electrically independent power sources from a separate switchyard or a separate transmission line, as shown in Fig. 2.1, appear less likely to suffer a plant-centered loss of off-site power than a plant where all sources are electrically connected. The 69-kV power source in Fig. 2.1 is connected automatically if the preferred source fails. Power plants that have suffered loss of the unit and preferred power sources but not of an electrically independent power source are the following: D. C. Cook, Cooper, Oconee, Pilgrim, and Vermont Yankee. Plant-centered losses of off-site power are usually not of long duration. Two separate switchyards or a transmission line not connected electrically to the main switchyard may reduce the frequency of the short-duration, plant-centered losses of off-site power, but will probably not reduce the frequency of the long-duration, severe weather events that may affect a large part of the transmission system.

A parameter that has been identified for analysis is the normal source of power for the Class 1E buses. Some plants normally power the Class 1E buses from a unit transformer connected to the output of the main generator as shown in Fig. 2.2. If the unit trips, the Class 1E buses are automatically transferred to a preferred off-site power source. Other plants normally power the Class 1E buses from a preferred source as shown in Fig. 2.3. For the design shown in Fig. 2.3, a unit trip will not cause the Class 1E buses to transfer, and, if a preferred power source trips during reactor operation, a reactor trip may not occur even though a Class 1E bus loses power (although a reactor trip has occurred in some cases). This design feature concerning the normal power source for Class 1E buses is more important for plant-centered losses of off-site power than for grid-related power failures because an equipment failure or human error can prevent transferring to a preferred power source even though the switchyard remained energized.

The number of transmission lines, the number of rights-of-way, and a nearby ac power source such as a gas turbine or hydro unit are important for maintaining off-site power when tornados disrupt transmission lines. Right-of-way information was usually not available and was difficult to document because rights-of-way split, rejoin, and cross; but some information on rights-of-way was obtained for three plants that have had transmission lines damaged by tornados. A tornado or tornados near Browns Ferry on April 3, 1974, caused significant damage to three 500-kV lines east of the plant and to one 500-kV line and one 161-kV line south of the plant. A 161-kV line northeast of the plant and a 500-kV line southwest of the plant were not damaged by the tornados. At Arkansas Nuclear One, two 500-kV lines south of the plant and one 500-kV and one 161-kV line east of the plant failed because of tornado damage. One 161-kV line east of the plant did not fail. In 1965 a tornado damaged the 138-kV system at Dresden. The 138-kV transmission lines were on a single right-of-way, but the transmission lines on the main 138-kV trunk were not damaged by the tornado. Tap lines connected to the 138-kV system were damaged by a tornado or tornados. The events at Browns Ferry and Arkansas Nuclear One were partial losses because of the redundancy of transmission lines and rights-of-way. Dresden has only one right-of-way, but the transmission lines on the right-of-way were not damaged.

Other factors that affect the probability of loss of off-site power are wind, snow, and ice loadings that transmission lines are designed to withstand. Wind-blown salt from an ocean has contaminated insulators and caused losses of off-site power. Insulator type and availability of insulator cleaning equipment are factors that would affect the frequency and duration of off-site power losses caused by salt contamination.

Many design features affect the reliability of off-site power to nuclear power plants, but the ones discussed here are based on design features that have been identified to be important in the recorded losses of off-site power to nuclear power plants.

3. LOSS OF OFF-SITE POWER DATA

3.1 DATA QUALITY

Most of the event descriptions contained in the LERs and other documentation within the U.S. Nuclear Regulatory Commission (NRC) files did not contain sufficiently detailed information for our purposes. For example, a licensee reported off-site power restoration time to be 6 h, but we have determined that one off-site power source was restored in 8 mi and all off-site power was restored in 6 h. Since restoration of one source of off-site power terminates a loss of off-site power event, the documented description was not accurate enough for our purposes. Off-site power was available to be reconnected in several events, but the plant operators did not reconnect it for some time after it was available. The time that power was reconnected was usually reported in the LERs, however, the time that power was available for reconnection was the information we needed. The events in Table A.1 include information on reconnection times and availability times when both were known.

The documented data were collected from LERs, responses to an NRC questionnaire, and sundry reports prepared by the utilities. The documents are referenced in the list of events in Appendix Table A.1. Additional information was obtained by contacting utility engineers for more complete explanations of events. Conflicting information was reported for some events, but the events were described as accurately as possible based on our understanding of the events and discussion with others familiar with the events.

Because many of the event descriptions were not complete or adequate, we requested that IEEE Working Group 4.3, Loss of All AC Working Group, help improve the quality of the data. The Working Group investigated events to obtain better descriptions of the causes, sequences of events, and the times and methods of restoring off-site power. This group obtained additional information for several events.

3.2 EVENT DESCRIPTIONS

All complete and some selected partial losses of off-site power at nuclear power plants through 1983 are described in Table A.1. The entries in Table A.1 that are not self-explanatory are explained in this section. The entry "Equipment failure and cause of failure" describes as best we understand what equipment failed. It also attributes the cause of failure to the transmission grid, weather, or a plant-centered event. The failure is further attributed to design error, human error, or hardware malfunction. The column "Category" contains an evaluation of the significance of each event. A description of each category follows:

- Category I. Failure of the preferred, alternate and unit power sources either when the reactor was at power or when shutdown, but if the plant was shut down the loss would have occurred had the plant been operating.

   a. Power was not restored within 30 min
   b. Power was restored within 30 min
- Category II. Failure of the preferred and alternate power sources. The unit did not trip or, if not operating, would not have tripped had it been operating.
- Category III. Failure of the preferred and unit off-site power sources. An alternate off-site power source was available by manual switching.
- Category IV. Failure of all off-site power during a cold shutdown. These special maintenance conditions do not occur during or immediately following operation.
- Category V. Low voltage conditions on the transmission system. Voltage was near or below 90% of normal.

The restoration time is the time needed to make one power source available for reconnection. When special circumstances were involved and known to us, the circumstances for restoration were summarized in the "Description of event." If a utility reported equipment unavailable when the event occurred, that information was included in the table. Reactor power refers to the percentage of full power immediately prior to the loss of off-site power. Events were categorized and evaluated.

The data entries in Table A.1 are based on written reports and telephone conversations with utility engineers familiar with the events. The event descriptions in Table A.1 included information that is pertinent to this study of off-site power system reliability. Additional information may be in the references. Interpretations of the significance of the events is implicitly part of the event categories. Category I events have the most significance for safety. The other categories have less safety significance either because all off-site power did not fail or because the reactor was in cold shutdown and could probably maintain safe shutdown for an extended time without ac power.

3.3 SITE YEARS

A list of the plants included in this analysis and the site years are in Table 3.1. The site years were calculated using the Operating License Date[3] for all of the plants except Big Rock Point, Dresden, Indian Point, and Nine Mile Point. Humboldt Bay and LaCrosse were not included in this study because there was only one off-site source to each plant. LaCrosse has a switchyard with more than one off-site power line, but only a single line connects the plant to the switchyard. Big Rock Point and Indian Point were not included until more than one transmission line served these plants; Big Rock Point added transmission capacity in March 1968, and Indian Point added transmission capacity in October 1971.[4] The Nine Mile Point and Dresden criticality dates were reported in reference 5 to be prior to the licensing date in reference 3, but this report uses the criticality dates for Nine Mile Point and Dresden.[5] Plants with only one connection to an off-site system were not included because they are not typical and may bias the statistics. Most nuclear plants have two or more connections to the off-site system.

Table 3.1. Nuclear power plant site years

Name	Operating license date	Site years through		
		1975	1980	1983
Arkansas Nuclear One	5/74	1.6	6.6	9.6
Arnold	2/74	1.8	6.8	9.8
Beaver Valley	1/76	0	4.9	7.9
Big Rock Point	3/68*	7.8	12.8	15.8
Browns Ferry	6/73	2.5	7.5	10.5
Brunswick	12/74	1	6	9
Calvert Cliffs	7/74	1.4	6.4	9.4
Connecticut Yankee	1/68	7.9	12.9	15.9
Cook	10/74	1.2	6.2	9.2
Cooper	1/74	1.9	6.9	9.9
Crystal River 3	12/76	0	4	7
Davis-Besse	4/77	0	3.7	6.7
Dresden	10/59*	16.2	21.2	24.2
Farley	6/77	0	3.5	6.5
FitzPatrick	10/74	1.2	6.2	9.2
Fort Calhoun	5/73	2.6	7.6	10.6
Fort St. Vrain	12/73	2	7	10
Ginna	9/69	6.3	11.3	14.3
Grand Gulf	6/82	0	0	1.5
Hatch	8/74	1.3	6.3	9.3
Indian Point	10/71*	4.2	9.2	12.2
Kewaunee	12/73	2	7	10
La Salle	4/82	0	0	1.7
Maine Yankee	9/72	3.3	8.3	11.3
McGuire	1/81	0	0	2.9
Millstone	10/70	5.2	10.2	13.2
Monticello	1/71	4.9	9.9	12.9
Nine Mile Point	9/69*	6.3	11.3	14.3
North Anna	11/77	0	3.1	6.1
Oconee	2/73	2.8	7.8	10.8
Oyster Creek	4/69	6.7	11.7	14.7
Palisades	3/71	4.8	9.8	12.8
Peach Bottom	8/73	2.3	7.3	10.3
Pilgrim	6/72	3.5	8.5	11.5
Point Beach	10/70	5.2	10.2	13.2
Prairie Island	8/73	2.3	7.3	10.3
Quad Cities	10/71	4.2	9.2	12.2
Rancho Seco	8/74	1.3	6.3	9.3
Robinson	7/70	5.4	10.4	13.4
St. Lucie	3/76	0	4.8	7.8
Salem	8/76	0	4.3	7.3
San Onofre	3/67	8.8	13.8	16.8
Sequoyah	10/80	0	0.2	3.2
Summer	8/82	0	0	1.3

Table 3.1 (continued)

Name	Operating license date	Site years through		
		1975	1980	1983
Surry	5/72	3.6	8.6	11.6
Susquehanna	7/82	0	0	1.4
Three Mile Island	6/74	1.5	6.5	9.5
Trojan	11/75	0.1	5.1	8.1
Turkey Point	7/72	3.4	8.4	11.4
Vermont Yankee	3/72	3.8	8.8	11.8
Yankee Rowe	6/61	14.5	19.5	22.5
Zion	4/73	2.7	7.7	10.7
Total		159.5	383.0	532.8

*See Sect. 3.4.

The site years were calculated for three time periods that were analyzed to determine the change in frequency of loss of off-site power over time. The period ending in December 1975 was selected because the events prior to 1976 were not usually documented as well as they were later. The period beginning in January 1981 was selected to evaluate recent performances of off-site power systems.

4. WEATHER-RELATED LOSSES OF OFF-SITE POWER

Failure of the unit and off-site ac power sources at nuclear power plants makes the plants dependent on emergency generators for ac power. Subsequent failure to restore either emergency or off-site power soon enough could result in reactor core damage. Based on events in which complete or partial losses of off-site power occurred, weather-related failures usually take longer to restore power than other events. The weather-related events were selected from Table A.1 for a more detailed analysis.

The weather-related events were examined in detail to determine the significant occurrences that caused the event or affected restoration of off-site power. Design and operational features were examined to determine how they may have affected the outage. The events selected for review were complete and partial losses of off-site power caused by severe weather; the events are listed in Table 4.1. Most of the losses were caused by strong winds or ice, but three events were included in which multiple lightning strikes could have contributed to an extensive outage.

4.1 EVENT SUMMARIES

A review of each of the 16 events listed in Table 4.1 follows.

Arkansas Nuclear One on 2/22/75[6]

A partial loss of off-site power and reactor trip occurred because of tornado damage to transmission lines. At 1:45 p.m. one 161-kV line became deenergized, and an attempt to reenergize this line failed when the breaker at the far end of the line from the nuclear plant switchyard would not close. At 4:08 p.m. a tornado extensively damaged three towers for one of the 500-kV transmission lines. A breaker in the 500-kV switchyard opened and then reclosed onto the faulted line causing a unit trip. This caused all 500-kV breakers to open, leaving only one 161-kV line to the plant still energized.

Two transmission lines became deenergized, but only one was severely damaged by the tornado; one 500-kV line remained energized, but the breakers in the 500-kV switchyard had locked out; and one 161-kV line was deenergized because a breaker at the distant end had opened. The transmission line damaged by the tornado was repaired after several days.

Arkansas Nuclear One on 4/7/80[6-8]

A tornado caused a partial loss of off-site power to Arkansas Nuclear One Units 1 and 2 on April 4, 1980. At 5:28 p.m. a tornado caused the loss of the 500-kV line to Ft. Smith, and at 6:25 p.m. a tornado caused the loss of the 500-kV line to Mabelvale. At 6:48 Units 1 and 2 tripped from 100% power because of the loss of the remaining 500-kV line and one of

Table 4.1. Selected complete and partial weather-related failures of off-site power systems

Plant	Date	Cause
Arkansas Nuclear One	02/22/75	Tornado
Arkansas Nuclear One	04/07/80	Tornado
Browns Ferry	04/03/74	Tornado
Browns Ferry	03/01/80	Ice Storm
Dresden 1	11/12/65	Tornado
Fort Calhoun	02/21/76	Storm
Fort St. Vrain	05/17/83	Snow and wind
Indian Point	07/13/77	Lightning and grid failure
Indian Point	06/03/80	Lightning
Millstone	08/10/76	Hurricane
Pilgrim	05/10/77	Snow storm
Pilgrim	02/06/78	Wind and snow
Pilgrim	10/12/82	Storm and salt spray
Pilgrim	02/13/83	Ice and salt
Point Beach	02/05/71	Ice, snow
Prairie Island	07/15/80	Electrical storm

the two 161-kV lines. One line from Morrilton remained connected to the 161-kV switchyard, but because of overloading or a failed relay, power from the 161-kV switchyard was not immediately available to the plant. Manual action could have been taken to connect the 161-kV source to a shutdown transformer ST-2 within approximately 10 min, but the plant was stable using on-site power, so the 161-kV source was not used. Off-site power was restored to Unit 1 at 7:40 p.m. and to Unit 2 at 7:10 p.m. Arkansas Power and Light estimated shortly after the event that it would take one to two weeks to restore the 500-kV system, but we did not determine the actual restoration time for the 500-kV system.

Several 500-kV transmission towers collapsed because of the tornado. Arkansas Nuclear One has three 500-kV lines and two 161-kV lines. Apparently because of the separation of the lines some were not damaged by the tornados.

Browns Ferry 1 on 4/3/74[9,10]

Browns Ferry experienced a partial loss of off-site power because of tornado damage to the transmission facilities when several tornados occurred in the Tennessee Valley. Units 2 and 3 did not have operating licenses, and Unit 1 was at 92% power at 6:53 p.m. when the unit tripped because of transmission line interruptions caused by tornados. There was extensive damage on four of the five 500-kV lines and to one of the two 161-kV lines.

One 500-kV line and the 161-kV line from Trinity substation tripped followed by a reactor trip. Off-site power was supplied throughout the event by the 161-kV line from Athens. The 500-kV line #1 to Madison failed and was restored on April 27. The 500-kV line #2 to Madison was taken out of service on April 1 and was nearly ready to be returned to service when it was damaged by a tornado. It was returned to service on July 26. The 500-kV line #3 to Trinity was not completed at the time of the event. The 500-kV line #4 to Trinity failed on April 3 because of a tornado and was restored on November 1. The 500-kV line #5 to Westpoint tripped but was not damaged; it was reenergized after approximately 120 h. The 161-kV line to Athens did not fail.

Browns Ferry on 3/1/80[11,12]

An ice storm and winds caused a partial loss of off-site power. At the time of the event, Unit 1 was down for refueling; Unit 2 was shut down for maintenance; and Unit 3 was at normal power. High winds and freezing rain caused both 161-kV transmission lines to trip, but off-site power was backfed from the Unit 1 main transformer. The 161-kV power was restored after 6 min. Improper lineup of the 161-kV Athens line protective zone relays contributed to the loss of the 161-kV system. The 161-kV transmission lines were not damaged, so the power was restored by reclosing the feeder breakers after 6 min.

Dresden 1 on 11/12/65[13-15]

A tornado passed 4.8 km (3 mi.) northwest of the unit and caused a complete loss of off-site power. The unit tripped from 200 MW(e) because of the power failure; the on-site emergency diesel generator was started and loaded with essential loads. Five 138-kV lines on one right-of-way were connected to the plant, and there were two 34-kV lines. The 34-kV lines normally were not used to supply off-site power to Dresden but could be configured to do so.

A 138-kV main trunk line had taps that provide large industrial customers. One or more tornados downed some of the 138-kV transmission line taps to industrial customers, and this caused the 138-kV system to Dresden to be isolated. The 34-kV lines tripped also. Power was restored to the 138-kV main trunk to Dresden by sending a maintenance crew to open disconnects between the 138-kV trunk lines and damaged tap lines. It took 4 h to restore off-site power to Dresden. A 34-kV line was restored after 2 h and 25 min, but the system load dispatcher would not reconnect this line to Dresden because the source was considered too weak.

Since this failure, a 345-kV system has been installed, and now a second right-of-way heads south from the station.

Fort Calhoun on 2/21/76[16]

A storm caused a 161-kV line to trip; subsequent failure of two buses to transfer caused the unit to trip. When the unit tripped, all off-site power was lost to the unit, but two transmission lines to the 345-kV switchyard remained energized. The licensee reported that off-site power was restored after 54 min. However, power probably could have been restored sooner because there is a motor-driven disconnect switch that could be opened to isolate the main generator such that power could be backfed from the 345-kV switchyard through the main transformer.

Details of this event were not reported, but, because the storm caused only one line to fail, it appears that the restoration time could have been shorter had off-site power been required for an emergency.

Fort St. Vrain on 5/17/83[17]

Severe wind and snow caused a loss of all off-site power to the unit. The reactor was shut down at the time of the event. One diesel was out of service for maintenance, and the other diesel, which was operating in parallel with the off-site system, tripped when off-site power failed. The unit was without all ac power for approximately 25 min until the diesel that had failed was returned to service. Off-site power was restored after 1 h and 45 min, but the actions taken to restore off-site power were not reported.

Indian Point on 7/13/77[18]

Two separate lightning strikes caused grid instability and a loss of all off-site power. These strikes caused a trip of Indian Point; 55 min later all off-site power was lost because of grid instability. Off-site power was restored 6 h and 28 min later. Although weather initiated the event bv causing two transmission lines to fail, restoration of ac power was not significantly affected by the weather.

Now three gas turbines can provide alternate ac power sources to Indian Point. These gas turbines can be controlled from the Unit 2 control room.

Indian Point on 6/3/80[19,20]

A lightning strike caused a complete loss of off-site power. A shield wire was struck by lightning and fell onto two 345-kV feeders causing them to trip. The resulting surge caused a second shield wire to fall onto a 138-kV feeder. Both units lost the preferred power sources; Unit 2 tripped, but Unit 3 did not trip and continued to receive ac power from its unit auxiliary transformer. The two gas turbines at Buchanan substation were operating when the lightning struck, and both tripped. The gas turbine at Indian Point was "black-started" and placed on standby. Unit 2 received ac power from its diesel generators.

A design change made by Consolidated Edison to avoid recurrence of this event was to supply the 345/138-kV autotransformer from the Buchanan substation North Bus rather than from the 345-kV feeder W93 (one that failed during the event). This improves the reliability of the 138-kV switchyard because with the new design the autotransformer's source of power to the 138-kV switchyard is supplied from the 345-kV switchyard rather than from the 345-kV transmission line W93.

The actions taken to restore off-site power were not reported.

Millstone on 8/10/76[21,22]

Hurricane-force winds and salt spray without much rain to wash switchyard insulators caused a complete loss of off-site power to Unit 1 and a short loss of off-site power to Unit 2. Both units tripped from power operation. Because of the salt contamination on the insulators, transmission lines were available intermittently for a 5-h period from 4:00 a.m. to 9:00 a.m. The 27-kV transmission line tripped because of salt contamination on a cable termination that had not been made properly; it was unavailable for 16 h. At 9:00 a.m. the off-site power source to Unit 1 was deenerigized to wash salt off the insulators. After the switchyard was deenergized, Unit 1 was without off-site power for 11 h and 29 min. Power was available to Unit 1, but had it been reconnected it was subject to tripping because of salt contamination. Unit 2 lost off-site power briefly when a breaker opened but automatically reclosed successfully.

Because of the salt contamination, a surge arrester failed; three circuit breakers opened but were damaged; a fourth circuit breaker had burn marks but was undamaged; and a transformer had burn marks but was undamaged.

All of the damage occurred in the switchyard, but none occurred because of flashover on the 345-kV transmission line insulators.

Power remained connected to the switchyard, but it was not connected to Unit 1 because of the possibility of flashover at the insulators. Four separate flashovers occurred in 19 min. Off-site power could have been used, but it was not a reliable source of power.

Pilgrim on 5/10/77[23,24]

A snow storm caused a transmission line to trip, and subsequent transmission system instabilities caused Canal 2 fossil plant and Pilgrim Nuclear Power Plant to trip. Ice buildup during a snow storm caused a static wire to fall onto a 345-kV transmission line. This caused a loss of load on the system, and Pilgrim and Canal 2 tripped while adjusting for this loss of load. The 23-kV line also failed, but the cause of its failure was not reported. Whether it failed because of the snow storm, the system instability, or other causes was not reported. The 345-kV system was deenergized for 9 h and 40 min; the 23-kV transmission line was denergized for 2 h and 40 min.

Pilgrim on 2/6/78[24,25]

Severe winds, heavy snow, and ice caused a complete loss of off-site power. Intermittent line faults were caused by ice and salt coated insulators. The 345-kV system was out of service for 18 h and 34 min, and the 23-kV line was out of service for 8 h and 54 min. The 23-kV line failed a second time for 65 min, but the time it was in service prior to the second failure was not reported.

Through personal conversation it was reported that the 345-kV system was deenergized voluntarily for washing of the insulators. However, the 345-kV system was apparently not energized for over 18 h, and its functional capability was not tested. The cause of the 23-kV line failure was not reported. This 23-kV line is underground from a substation to the plant, and the substation is 0.4 km (0.25 mi) inland such that it should not have a salt-spray problem. Boston Edison has since installed equipment for washing insulators while the system is energized.

Pilgrim on 10/12/82[26]

A partial loss of off-site power occurred because an ocean storm deposited salt on insulators causing 345-kV line faults, but the 23-kV system remained energized. The insulators were washed with fresh water and restored after 11 h and 33 min.

In November 1983, Boston Edison acquired high-pressure equipment for washing 345-kV yard insulators while the switchyard remains energized. Use of this equipment may reduce the failures caused by salt-coated insulators. However, the effectiveness of this equipment for icing conditions was not reported.

Pilgrim on 2/13/83[27]

A partial loss of off-site power occurred because of ice and salt contamination on the 345-kV switchyard insulators. The 23-kV line remained energized. Additional details of this event were not reported.

Point Beach on 2/5/71[27,28]

A complete loss of off-site power was caused by an ice storm and failure of a transformer differential relay. An ice storm caused a line fault, which caused differential lockout relay to operate on three transformers at the plant. Through personal conversations, it was determined that off-site power was restored in 8 min. However, all off-site power was not restored for 6 h and 22 min to evaluate transformer gas samples to determine if the transformers were damaged. The means of restoring off-site power was not reported. Both transformers from the preferred power--1X03 and 2X03--locked out, so the question of how power was restored remains unanswered. Unit 1 was at power when the trip occurred, and Unit 2 was not yet licensed for operation.

Prairie Island on 7/15/80[29]

A complete loss of off-site power resulted from an electrical storm and degraded voltage. Unit 1 was in cold shutdown and Unit 2 was at 100% power when an electrical storm caused Unit 2 to trip at 8:30 p.m. Power from the 345-kV system failed at 9:38, but the 161-kV system remained energized at approximately 80% normal voltage, which was considered unusable. The 345-kV system was restored after 1 h and 45 min, and approximately 2 h later the system voltages were normal.

4.2 DISCUSSION OF EVENTS

The events selected to be included in the previous discussion were caused by severe weather that resulted in or had potential to result in extended losses of off-site power. Some of the events were only initiated by weather, and subsequent failures or grid instabilities contributed to the length of the outage. The widespread severe weather may cause a grid failure, and also affect the speed of restoration by causing extensive damage or hampering maintenance crews trying to get to the damaged equipment.

Tornados have caused the most extensive damage to transmission lines and towers, but they have caused only one complete loss of off-site power--Dresden, 1965. A tornado near Browns Ferry damaged five of seven functioning transmission lines, and it took 5 days to restore the first of the five downed lines. At Arkansas Nuclear One, several transmission line towers were damaged, but all of the transmission lines were not damaged simultaneously. At Dresden 1 a tornado caused a complete loss of off-site power, but the main 138-kV trunk to Dresden was not damaged by a tornado. Dresden now has a 345-kV system in addition to the 138- and 34-kV systems, and it has two transmission line rights-of-way to the plant. The separation of transmission lines should be an important design feature to provide protection against a complete loss of off-site power because of a tornado.

Salt spray from the ocean onto switchyard insulators has caused some extended outages of off-site power. Although all or part of the switchyards were deenergized because of salt contamination, off-site power probably could have been restored to the switchyards, at least intermittently. However, switchyard equipment is damaged occasionally when flashovers occur because of salt contamination, and the equipment failures could contribute to an extended loss of off-site power. Better switchyard insulators can be installed to "buy time" before a flashover would occur, and water spray equipment to wash salt contamination off the insulators can be installed permanently or on mobile equipment. Some washing equipment is designed to wash the insulators while the switchyard is energized, but the effectiveness of this equipment below freezing is questionable.

Snow and ice storms accompanied by strong winds have caused several complete and partial losses of off-site power. Restoration of off-site power after failures caused by cold weather storms usually does not take long. For the cold weather storm events that we evaluated, descriptions of the failures and repairs were not detailed, but they did not involve extensively damaged transmission equipment. Ice loading and winds have caused intermittent faults or downing of a single line, but widespread damage has not occurred at nuclear power plants. However, details on transmission systems failures and repairs were not reported for some of these events, but in each case there was at least one off-site power source without serious damage because the restoration time was not long. Although extensive damage has not resulted, snow and ice may delay maintenance crews' attempting to get to remote locations even for minor repairs.

Lightning has been involved in many complete and partial losses of off-site power, but the restoration times for most events were short. Two lightning-initiated events occurred at Indian Point resulting in grid instability from one, and the downing of several lines from the other. An event occurred at Prairie Island in which the 345-kV system failed and the 161-kV system had degraded voltage. The longest restoration times for the lightning-initiated events were those that resulted in grid instability.

5. FREQUENCY OF LOSS OF OFF-SITE POWER

The frequencies and durations of losses of off-site power vary among plants because of the different plant distribution, switchyard, and transmission systems designs and because of the different weather conditions. However, point estimates of frequency versus duration for loss of off-site power were calculated. The loss of off-site power system data was reported to the NRC for detailed statistical analyses to determine frequencies and durations for the different off-site power system designs and weather conditions. The estimates of loss of off-site power were calculated for the following time periods: 1959-1976, 1959-1980, and 1959-1983. No statistical tests were performed to determine the significance of any differences in frequencies or durations.

The losses of off-site power that occurred at Humboldt Bay and at Indian Point on 11/9/65 were included in Table A.1 but were not included in the following statistical analysis because both had only one off-site power connection. Also, the duration of the power failure at Indian Point 1 was not reported to us. There have been several power failures at LaCrosse, but, because it had only one connection from the plant to the switchyard, it was not included in the statistical analysis (nor was LaCrosse included in Table A.1). Two losses of off-site power occurred at St. Lucie, and two failures occurred at Turkey Point on 5/16/77. These events were caused by an area-wide grid failure and restoration followed by a second grid failure. Because the grid probably had not been restored to normal before the second failure occurred, these events were counted as two losses of off-site power rather than four. However, the duration times of the losses were added for the statistical analysis.

For Category I events, the numbers and frequencies of loss of off-site power versus selected time periods are shown in Table 5.1. These calculations were based on industry-wide data and are not intended to apply to any specific plant. The frequencies were calculated using the total site years in Table 3.1.

Table 5.1. Number of events and frequencies of losses of off-site power for selected time periods

Duration (h)	1959-1976 No.	1959-1976 Frequency (yr^{-1})	1959-1980 No.	1959-1980 Frequency (yr^{-1})	1959-1983 No.	1959-1983 Frequency (yr^{-1})
0-0.5	15	0.094	20	0.055	21	0.039
0.5-1.0	6	0.038	10	0.026	11	0.021
1-2	0		5	0.013	6	0.011
2-3	0		1	0.003	2	0.004
3-4	0		1	0.003	1	0.002
4-5	1	0.006	1	0.003	1	0.002
5-6	1	0.006	3	0.008	3	0.006
6-7	0		0		0	
7-8	0		0		0	
8-9	0		1	0.003	1	0.002
>9	0		0		0	
Total	23	0.144	42	0.114	46	0.087

6. SUMMARY

Data on losses of off-site power at nuclear power plants were collected and tabulated as a reference data base. Information on the events was obtained from NRC documents, but where the descriptions were not clear additional information was gathered by talking to utility engineers who were familiar with the events. The events were categorized to indicate the significance of the events. Category I events are the most significant because they challenge the emergency ac power system immediately after a reactor trip. A detailed description of weather-related events was included because of the potential of an extended loss of off-site power caused by severe weather. Design information was also reported because the plant design features are important factors affecting the frequency and duration of loss of off-site power. Category I events were used to estimate the frequencies of loss of off-site power for the three selected time periods.

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This project required an extensive amount of time for collecting documentation describing the complete and partial losses of off-site power and obtaining clarification or additional information from persons who were familiar with the events. Members of the IEEE Working Group on Loss of All ac Power provided manpower to obtain information on some events. A significant amount of the data collection was conducted at Electric Power Research Institute (EPRI) under the direction of H. L. Wyckoff. The IEEE Working Group members are

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APPENDIX

COMPLETE AND SELECTED PARTIAL LOSSES OF OFF-SITE POWER

Losses of off-site power that have occurred at nuclear power plants through 1983 are listed in Table A.1. All complete losses of off-site power reported to the NRC are listed, but not all partial losses are included. Selected partial losses of off-site power that involved the loss of several transmission lines or that involved the loss of power to some buses were included. Many events involving failure of only one transmission line were not included. Descriptions of the entries in Table A.1 are included in Sect. 3.2.

Table A.1. Complete and selected partial losses of off-site power through 1983

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Arkansas Nuclear One	2/22/75	A tornado caused transmission line failures. Weather-related, grid failure	III	Not reported	None reported	#1-at power #2-unlicensed	Letter from AP&L to NRC 6/11/80	A tornado damaged a 500-kV line and caused a 161-kV line to trip. The reactor tripped when the 500-kV line failed
Arkansas Nuclear One	9/16/78	Auto transformer protection was not set for two unit operation. Startup transformer #2 was not designed to carry full auxiliary load for both units. Plant-centered, design, and procedural error	Ia	1:29	None reported	#1-100 #2-hot standby	AP&L response to NRC questions (date not known)	Unit 1 tripped and its loads transferred to startup transformer #1. This caused the auto-transformer to trip on overload because it had not been reset for two unit operation. Both units transferred to startup transformer #2 which does not have the capacity to carry full load for both units for an extended time. The operators did not shed load and Unit 2 buses tripped on undervoltage. Unit 1 continued to receive power from startup transformer #2
Arkansas Nuclear One	4/7/80	A tornado caused the loss of all but one line. Grid failure	III	#1-0:22 #2-0:52	None reported	#1-100 #2-100	Letter from AP&L to NRC 6/11/80	Tornado damage caused the loss of the Ft. Smith 500-kV line. The Mabelvale 500-kV line failed 57-min later because o: the tornado. The startup transformers were unavailable because of relay failures in the switchyard. Power was available from the 161-kV switchyard and could have been connected within 1 min. The diesels supplied power to the emergency buses
Arkansas Nuclear One	6/24/80	A 500-kV line fault and resulting overload caused a grid failure	III	-	None reported	#1-100 #2-92	Letter from AP&L to NRC 7/31/80	The 500-kV Mabelvale line tripped on ground fault and the Ft. Smith line opened at the Ft. Smith end. One 161-kV line tripped on overload, but one remained connected. Subsequently, the autotransformer

								locked out causing a loss of preferred power to both units. Off-site power was available to both units through a manual transfer to startup transformer #2. The diesels supplied emergency power to Unit 1
Duane Arnold								No complete losses or significant partial losses of off-site power
Beaver Valley	7/28/78	Fault in main transformer. Main generator out-of-step relay subsequently tripped all off-site power sources. Plant-centered, hardware failure	Ib	0:17	None reported	100	LER 78-43	A fault in the main transformer caused a generator trip. As the generator was coasting down, a faulty out-of-step relay caused all 345-kV line breakers and three 138-kV line breakers to open. The Shippingport power station was isolated as the only power source, but it was tripped on overload. A diesel generator failed to start
Big Rock Point	1/25/72	Power from 138-kV failed because of high winds and a subsequent relay failure. Transfer relay in plant failed to transfer power. Plant-centered, hardware failure	Ib	0:20	None reported	At power	Letter from Consumers Power Co. to NRC 3/3/72	High winds and ice caused "galloping conductors" in the 138-kV system causing momentary line faults. On the thirteenth operation, a trip coil burned out. The plant did not transfer to the 46-kV system because of a failed relay. It required 2 h to restore the 46-kV line. Power was restored to the 138-kV system in 20 min
Browns Ferry	4/3/74	Tornados caused the loss of several transmission lines. Weather/tornado, grid	III	120 h for 161-kV line	One 500-kV line was out of service	#1-92 #2-unlicensed #3-unlicensed	Letter from TVA to USAEC 4/19/74	Four of five 500-kV lines and one of two 161-kV lines failed because of tornado damage. Several towers were down on each line. Unit 1 tripped, but off-site power was available from the remaining 161-kV line
Browns Ferry	3/1/80	Ice storm caused loss of 161-kV system. Weather/ice, storm	II	0:06	None reported	#1-refueling #2-0 #3-at power	LER 80-19	An ice storm caused the loss of both 161-kV lines. Power was provided by backfeeding through Unit 1 main transformer. Unit 3 did not trip

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Bruns-wick 2	3/26/75	Grounding connections were improperly designed. A line fault initiated protection relay actuation. Plant-centered, design error	Ib	0:04	Two 230-kV buses were down for maintenance	#1-not licensed #2-0	AO-75-5	Five 230-kV lines were supplying 230-kV buses 1A and 2A. A 230-kV line fault caused a differential current relay to operate and open breakers to all 230-kV lines. The relay operated because of improper ground connections for the differential current transformers
Bruns-wick	4/26/83	Maintenance during a plant shutdown caused the one remaining feeder to trip. Plant-centered, human error	IV	0:17	One transformer feeder down for maintenance	#1-0 #2 startup	LER 83-23	Unit 1 was shutdown for refueling with one of its switchyard buses out for maintenance. The remaining bus to Unit 1 tripped and all off-site power was lost to Unit 1. Unit 2 did not lose off-site power. The switchyard bus is not taken out of service during normal operation
Calvert Cliffs	4/11/78	Protective relaying deenergized a vital bus. Plant-centered, hardware failure	III	Not reported	None reported	#1-10 #2-75	LER 78-26	Protective relaying in the 500-kV switchyard deenergized 4-kV Bus 11. Diesel generator 11 automatically started but its output breaker did not automatically close. The diesel generator breaker was manually closed. Off-site power remained available to the switchyard, but a manual transfer was required to reenergize plant loads. Both reactor units tripped. The plant loads were manually reenergized
Calvert Cliffs	4/13/78	A protective relay operated erroneously causing a loss of off-site power. Plant-centered, design error	Ia	5:50	None reported	#1-80 #2-50	LER 78-20	During upgrade of a battery charger, a short occurred and protective relays in the 500-kV switchyard operated because of a sneak circuit. All off-site power was lost. Troubleshooting consumed most of the outage time. Relay modifications have been made to prevent inadvertent operation of the relays. Diesel generator 11 failed to start

Connecticut Yankee	4/27/68	Relay test switch set improperly during switching. Plant-centered, human error	Ib	0:29	One 115-kV line down for maintenance	100	RO 68-4	A human error caused the l ss of a line while the other was down for maintenance. The reactor tripped. All three diesels tripped, but were restored immediately
Connecticut Yankee	7/15/69	Protective relays were not defeated for a line being taken out of service. Plant-centered, human error	Ib	0:09	None reported	100	Letter from CYAPC to NRC 7/24/69	Operator switching error while taking one 115-kV line out of service caused the second 115-kV line to trip. The main generator is connected to a 345-kV switchyard but the loss of the 115-kV switchyard will cause a plant trip because the unit auxiliary transformer does not have the capacity to supply the total plant load. One diesel generator did not pick up load
Connecticut Yankee	7/19/72	Lightning strike caused a loss of both 115-kV lines. Weather-related, plant-centered	Ib	0:01	None reported	100	Letter from Northeast Utilities to NRC 12/27/79	Lightning caused the loss of all off-site power
Connecticut Yankee	1/19/74	A faulted line and incorrect relay operation caused power loss. Plant-centered, weather/ice and hardware failure	Ib	0:20	None reported	Not reported	AO 74-3	A lightning arrestor faulted during an ice storm, and a relay in the plant failed. Diesel generator A service water pump failed to start automatically
Connecticut Yankee	6/26/76	Induced voltage caused inadvertent operation of protective relays. Plant-centered, design error	Ib	0:16	One 115 kV line and one station service transformer	0	LER 76-14	When a line that had been out of service was being restored, protective relays operated and caused a complete loss of off-site power. Restoration time encompasses the time power was restored, failed, and restored three separate times
Cook	2/17/75	A fault in a cable was caused by a poor splice. Plant-centered, human error	III	Unit-3:58; preferred-73:06	None reported	#1-5 #2-unlicensed	Letter from Indiana and Michigan Electric Co. to USNRC 1/3/80, LER 75-5	Unit 1 was in mode 2 and receiving auxiliary power from the preferred power source. A fault caused the preferred power source to trip, but the 69-kV alternate off-site power source was unaffected. Power was backfed after 3 h and 58 min by removing the generator links. The preferred power source was restored after 73 h and 6 min

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Cook	9/1/77	A lightning strike and a breaker failure caused the preferred power source to fail. A second lightning strike caused a unit trip. Plant-centered, lightning	III	Preferred-2:11	None reported	#1-100 #2-unli-censed	LER 77-30	A lightning strike caused a line fault which was followed by a breaker failure. Breaker failure relays isolated the 345- and 765-kV sources from the perferred power source trains. A second lightning strike caused a unit trip. The 69-kV alternate off-site power source remained available
Cooper	2/21/76	A fault and subsequent false relaying caused loss of power. Weather/wind, snow, and lightning	III	0:29	None	85	Nebraska Public Power District letter to NRC, 12/14/79	During blizzard conditions, a line fault occurred. False relaying opened breakers to two lines, and the remaining line was tripped by an out-of-step relay. This caused a unit trip and loss of preferred power, but the 69-kV alternate source was automatically connected to supply power
Crystal River 3	6/16/81	Lightning strike and arrestor failure caused loss of a startup transformer. Weather/lightning, fossil plant-centered	III	Not reported	None reported	100	LER 81-33	A lightning strike and a lightning arrestor failure caused the loss of a startup transformer The B diesel generator failed, but off-site power from the fossil plant startup transformer was manually connected to provide power to the B division
Davis-Besse	11/29/77	An operator switching error caused a momentary loss of off-site power. Plant-centered, human error	III	11 S	None reported	Startup	LER 77-98	After a reactor trip, an operator opened the main generator breakers and attempted a manual transfer of power. The procedure was incorrect and a loss of power occurred until a manual transfer was made 11 s later. A diesel tripped on overspeed.
Davis-Besse	10/15/79	A breaker muffler ruptured and caused a transmission line short. Plant-centered, hardware failure	Ib	0:26	None reported	60	LER 79-96	The Integrated Control System failed and caused a reactor trip. Subsequently, a circuit breaker in the switchyard failed and caused a loss of off-site power. One bus was reenergized after 26 min and the second bus after 43 min. A service water pump did not start automatically

Dresden 1	11/12/65	A tornado caused all off-site power to fail. Weather/tornado, grid failure	Ia	4:00	None reported	100	Letter from Com Ed to NRC 12/29/79, 28th Amer. Power Conf.	Tornados caused loss of all 138- and 34-kV transmission lines. A 138-kV line was restored after 4 h; the unit was in operation after 25 h and 40 min
J. M. Farley	9/16/77	Lightning caused breakers to open. Weather/lightning, plant-centered	Ia	0:54	One 230-kV line. Two breakers were open to isolate the main generator	#1-startup #2-unknown	LER 77-12	Lightning caused switchyard br akers to open. Startup transformer 1A was reenergized after 54 min and startup transformer 1B was reenergized after 4 h and 59 min
J. M. Farley	10/8/83	A breaker failure caused two startup transformers to lose power while unit was shutdown. Plant-centered, hardware failure	Ia	2:45	None reported	#1-unknown #2-0	Telephone conversation (EPRI)	A switchyard breaker failed and a breaker failure relay opened adjacent breakers, which deenergized both startup transformers for Unit 2. Because Unit 2 was shutdown, a complete loss of off-site power resulted. One startup transformer was reenergized after 2 h and 45 min, but the operators decided not to reconnect off-site power until the second startup transformer was reenergized, which was 3 h and 17 min after the failure occurred
J. A. Fitz-Patrick	10/4/78	A maintenance error caused a loss of off-site power. Plant-centered human error	IV	14s	None reported	0	Letter from PASNY to NRC 4/18/80	A grounding br aker was installed improperly for testing and caused off-site power to trip. Power was restored automatically in 14 s
J. A. Fitz-Patrick	3/27/79	During maintenance, protective relays actuated and caused a loss of power. Plant-centered, human error	IV	0:03	Maintenance was being performed on transformer relays	0	LER 79-21	A maintenance error caused a loss of off-site power during a cold shutdown. One diesel was down for maintenance
Ft. Calhoun	3/13/75	Transformer protective relays failed because of moisture in a junction box. Plant-centered, hardware failure	IV	11:05	The 161-kV line to Ft. Calhoun was down for maintenance	0	AO 75-7 and EPRI	A transformer tripped because of faulty protective relays and caused a loss of off-site power. One diesel generator failed to automatically close onto the emergency bus, but it was manually connected. Off-site power could have been restored sooner if required. The unit was being refueled.

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Ft. Calhoun	2/21/76	A storm caused a 161-kV line fault and power did not transfer. Plant-centered, hardware failure	Ia	0:54	None reported	At power	Letter from Omaha Public Power District to NRC 3/20/80	A 161-kV line tripped during a storm, but the emergency buses did not transfer to the alternate power source. The unit tripped on low reactor coolant flow
Ft. Calhoun	8/22/77	A 161-kV line tripped, buses failed to transfer and the unit tripped. Plant-centered, hardware failure	Ib	<0:01	None reported	At power	Letter from OPPD to NRC 3/20/80	A faulty relay in the 161-kV switchyard caused a loss of power from this switchyard. Two buses failed to transfer and the unit tripped causing a loss of off-site power
Fort St. Vrain	5/17/83	Snow and wind caused a loss of off-site power. Weather/snow and wind, grid failure	Ia	1:45	None reported	0	LER 83-18	Snow and wind caused problems with the off-site power system. Diesel 1B was started and connected in parallel with the off-site power system. Diesel 1A was out of service for maintenance. A loss of off-site power occurred, and diesel 1B overloaded and tripped. The plant was without all ac power for 25 min until diesel 1B load shedding relays were reset and on-site power was restored. Diesel 1A was returned to service 45 min after the power failure. The unit was in cold shutdown prior to the power failure
Grand Gulf								No complete losses or significant partial losses of off-site power
Ginna	3/4/71	A 34.5-kV bus section shorted. Plant-centered, human error	Ia	0:30	None reported	0	Letter from Rochester Gas and Electric Corp. to NRC 11/15/79	A section of the plant siding (facade) fell onto a 34.5-kV bus section causing a short circuit. The siding had been attached with the wrong clips. The unit was in cold shutdown when the failure occurred

Ginna	10/21/73	After one 115-kV line was removed from service the remaining lines overloaded. Grid-related, design error	Ia	0:40	One 115-kV line was out of service	93	Letter from RGE Corp. to NRC 11/15/79.	When one of four 115-kV transmission lines was removed from service the remaining three picked up additional load. As the lines heated they sagged, and one shorted to a 34.5-kV line below it on the same tower. The resulting transient caused the remaining lines to trip
Ginna	4/18/81	A breaker faulted and caused the 34.5-kV source to fail. Plant-centered, hardware failure	II	Not reported	None reported	95	LER 81-7	A fault in a breaker caused a loss of the 34.5-kV off-site source. The diesel generators energized the emergency buses. The unit did not trip, but it had a 10% runback
E. I. Hatch								No complete losses or significant partial losses of off-site power
Humboldt Bay*	7/17/70	Switching error. Plant-centered, human error	Ib	0:18	None reported	Unknown	Abnormal occurrence report. Report date 10/2/70	Switching error at Humboldt Bay substation and subsequent relay failures at two locations caused a loss of off-site power. (Information for this event was sparse)
Humboldt Bay*	11/27/70	Storm	Ib	0:14	None reported	Unknown	Unit Operations rpt. 7/1-12/31, 1970, PG&E, 3/4/71	A storm caused a loss of off-site power, one line was out of service for 14 min, but the other line was out for 28 h. (Information for this event was sparse)
Indian Point 1*	11/9/65	Grid failure	Ia	Unknown	Unknown	0	Telecon with utility	The "Great Northeast Blackout" caused a loss of off-site power
Indian Point	7/20/72	Grid failed but the cause was not reported	Ia	0:55	Nearby transmission line was out of service.	#1-95 #2-0 #3-unlicensed	Letter from Con Ed to NRC 8/18/72	A grid failure caused a loss of off-site power. The cause of the failure was not reported. Fuel had been unloaded from Unit 2

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Indian Point	7/13/77	Lightning strikes caused line failures and grid failure. Weather/lightning, grid failure	Ia	6:28	None reported	#2-0 #3-91	Letter from Con Ed to NRC 8/18/72	Two separate lightning strikes led to grid failure. Since 1975 there have been two gas turbines at nearby Buchanan substation (21 MW and 26 MW) and one gas turbine at Indian Point (16 MW) all of which are controllable from the Unit 2 control room. At the time of this event, two of the gas turbines were down for maintenance and the third failed because of a malfunctioning voltage regulator. Since 1980, Tech Specs require that one gas turbine be available at all times. Unit 2 was in cold shutdown
Indian Point	6/3/80	Lightning strike caused a ground wire to fall onto feeder. Plant-centered, weather/lightning	Ia	1:45	None reported	#2-100 #3-60	LER 80-6 & 80-8	A ground wire fell and faulted four 138-kV feeders. Unit 2 tripped, but Unit 3 continued to operate with diesel generators 32 and 33 supplying power to 480-V buses. Two gas turbines at Buchanan, a nearby substation, were operating when the fault occurred, but they tripped. One of the gas turbines was restarted but not loaded prior to restoration of the off-site power lines
Indian Point	10/4/83	Faulty relay caused a loss of preferred power. Plant-centered, hardware failure	III	Not reported	None reported	#2-0 #3-unknown	Telecon with EPRI	The 138-kV feeder to the station auxiliaries was deenergized because of a faulty relay. The generators powered the buses for 15 min. The 13-kV alternate off-site power source was available throughout
Maine Yankee	8/31/78	Transformer failure caused a unit trip and depression of voltage. Plant-centered, hardware failure	III	0:01	Not reported	47	Nuclear power experience 6/30/83	Failure of one of two main power transformers caused a unit trip and depressed the voltage from the preferred power source. Undervoltage relays blocked an automatic transfer, so the diesel generators started and loaded. Operators manually closed the preferred power source breakers within approximately 1 min

Maine Yankee	4/25/83	Lightning strike caused a line trip. Plant-centered, weather/lightning	II	115 kV-3:45	One 115-kV line	100	LER 83-14	One preferred source 115-kV line was out of service for improvements when lightning caused a trip of the remaining 115-kV line. The unit continued to operate at 100%
Maine Yankee	7/2/83	Lightning strike caused a line trip. Plant-centered, weather/lightning	II	115 kV-0:04	One 115-kV line	100	LER 83-25	One preferred source 115-kV line was out of service for improvements when a lightning strike caused a trip of the remaining 115-kV line. The unit continued to operate at 100%
Kewaunee								No complete losses or significant partial losses of off-site power
LaSalle								No complete losses or significant partial losses of off-site power
McGuire								No complete losses or significant partial losses of off-site power
Mill-stone 2	7/21/76	Undervoltage relays tripped off-site and on-site power. Plant-centered, design error	Ib	0:05	None reported	#2-at power	NNECO letter to NRC, 7/22/76, and R.O 76-42	Undervoltage relays had been reset at Millstone because of previous problems. On 7/21/76 a 1500-hp motor was being started, and the resulting voltage drop caused the off-site power to trip. The diesels started, but when a large pump was being started, the safety loads tripped on undervoltage. The undervoltage relays were reset to a higher value and the safety loads were reconnected
Mill-stone	8/10/76	A hurricane caused salt spray to coat insulators with salt which caused a flash-over. Plant-centered, design and weather/hurricane	Ia	5:00	None reported	#1-45 #2-100	LER 76-49, EPRI, and NE Utilities telecon	Hurricane Belle caused salt spray to be blown into the Millstone switchyard and coat transmission line insulators with salt. There was not enough rain to wash the insulators, so fault currents flowed through the salty insulators. Both off-site sources to Unit 1 were unavailable for 5 h. After the 5-h interval, the 345-kV switchyard was being cleared of salt but could have been restored if necessary. The switchyard has been reinsulated to protect against this problem

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Mill-stone 2	1/2/81	An operator deenergized one dc bus. Plant-centered, operator error, and design error	III	0	None reported	100	NRC/AEOD report, 11/81	A switching error in the dc system led to a reactor trip, loss of breaker control, and loss of a diesel. The second diesel tripped from another cause. The main generator breakers did not trip because of loss of dc power
Monti-cello	4/27/81	An operator racked out a breaker under load. Plant-centered, human error and design error	Ib	0:15	None reported	Not reported	LER 81-9	An operator caused a bus fault when he racked out a breaker under load and caused a short circuit on the bus. Power to the 4-kV essential buses failed although it was still available in the switchyard. The relaying has been redesigned so that both buses will not trip when only one is faulted
Nine Mile Point	11/17/73	An electrician bumped a relay cabinet and caused protective relays to operate. Plant-centered, human error	Ib	10 s	One 115-kV line from NMP to Fitz-Patrick	Startup	Letter from Niagara Mohawk Power Corp. 11/21/73	An electrician working on a line out of service caused the remaining line to trip. The diesels supplied power to the emergency buses although the 115-kV breaker reclosed in 10 s
Nine Mile Point	2/7/82	Faulty relay operation. Plant-centered hardware failure	II	10 s	One 115-kV line	99	LER 82-4	One 115-kV line was removed from service and the second 115-kV line failed during breaker testing. The diesel generators started when the preferred power failed, but the unit did not trip
North Anna	7/3/81	Transformer fault and fire. Plant-centered, hardware failure	III	Not reported	None reported	#1-100 #2-8	NRC internal memo from B. Engle to T. M. Novak 7/6/81	A main transformer faulted, started a fire, and caused Unit 2 to trip. Transformer oil burned and caused nitrogen bottles to explode. After 18 min, the fire melted open bus bars which supply emergency power to both units. Diesels 1H and 2J started and restored power to the two emergency buses; one emergency bus in each unit did not lose off-site power

Oconee	1/4/74	Induced voltage in a protective relay cable caused relays to operate. Plant-centered, design error	III	1:00 for 230 kV	None reported	#1-0 #2-75 #3-unlicensed	Letter from Duke Power Company to USAEC 1/14/74	An induced voltage in a breaker failure relay cable caused the 230-kV switchyard to be isolated. At the time of the event, Keowee #1 was generating 80 MW; it was isolated from the grid to provide power to Oconee. The 100-kV line was available. An attempt to connect the 100-kV line 30 s after the failure was not successful because the Emergency Power Switching Logic was automatically connecting the Keowee units to supply power. The 100-kV line was subsequently used to supply offsite power. The status of the three gas turbines at Lee Steam Station, which can be dedicated to Oconee, was not reported
Oyster Creek	9/8/73	Differential relays for two breakers were miswired. Plant-centered, human error	Ib	Not reported	None reported	14	Letter from Jersey Central Power Light Co. to USAEC 9/18/73	When power sources were being transferred from a unit auxiliary transformer to startup transformers, two breakers tripped because of a control wiring error. Differential relays tripped feeder breakers each time a condensate pump was started. Power was available in the switchyard, but 4160-V breaker operation inhibited using it. Restoration was accomplished by resetting lockout relay and reclosing breakers. Both diesels failed to start once because the start circuits had not been reset
Oyster Creek	11/14/83	Switchyard fire caused line failure. Plant-centered, hardware failure	III	34.5 kV-4 h	None reported	0	Telecon with EPRI	The unit was shut down and the generator links had been removed. A fire in the 34.5-kV switchyard caused one of two startup transformers to fail. Carbon deposits caused arcing so the 34.5-kV switchyard was deenergized to clean the insulators. The 345-kV yard probably could have been reenergized at any time. A mobile substation was dispatched to Oyster Creek and could have been on-line in approximately 4 h

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Pali-sades	9/2/71	A breaker failed to open following a line fault. Plant-centered, hardware failure	Ia	0:56	None reported	0	Letter from Consumers Power Co. to USAEC 9/9/71	A line fault occurred and a breaker failed to open. A breaker-failure relay operated and isolated the 345-kV "R" bus, which resulted in a loss of off-site power. The unit was in cold shutdown
Pali-sades	9/24/77	The "R" bus failed but the reason was not ascertained. Plant-centered, design error	Ia	4:45	None reported	At power	LER 77-47	The 345-kV "R" bus failed, which resulted in a reactor trip and a loss of off-site power. The reason for the failure was not determined, but an electrical storm was in the area when the failure occurred. Within 30 min the cause of the problem was determined by observing relay targets, and the equipment was visually inspected. The decision was made, however, to remain connected to on-site power until electrical checks were completed
Pali-sades	11/25/77	The "R" bus failed, but the reason was unknown. Plant-centered, design error	Ia	2:20	None reported	At power	LER 77-55, Letter from Consumers Power to NRC, 1/31/80	The "R" bus became deenergized and the reactor was manually tripped. The reason for the bus failure was not known. Off-site power was not restored immediately so that the cause of the relay failure could be investigated. It was reported that power could have been restored in 30 min
Pali-sades	12/11/77	The "R" bus failed, but the reason was unknown. Plant-centered, design error	Ia	1:30	None reported	100	LER 77-54	The "R" bus became deenergized and caused a loss of off-site power. The "R" bus tripping scheme has been modified to avoid a loss of off-site power because of spurious operation of the "R" bus relays. Off-site power was not restored immediately so that the relay failure could be investigated. It was reported that power could have been restored in 30 min

Pilgrim	4/15/74	Plant-centered, weather/lightning	III	345 kV-0:22	None reported	0	Boston Edison response to NRC questionnaire undated	Both 345-kV lines tripped because of lightning, but the 23-kV line did not fail. One line was restored in 22 min and the other in 1 h and 8 min
Pilgrim	5/26/74	Unknown	III	345 kV-1:19	None reported	0	Boston Edison response to NRC questionnaire undated	Both 345-kV lines were deenergized, but the 23-kV line did not fail. The cause of the failure was not reported. One line was restored in 1 h and 19 min and the other was restored in 1 h and 21 min
Pilgrim	9/13/75	Faulty-breaker. Plant-centered, hardware failure	III	345 kV-0:26	None reported	Unknown	Boston Edison response to NRC questionnaire undated	A faulty breaker caused both 345-kV lines to trip. The 23-kV line did not trip. One 345-kV line was restored in 26 min, and the other was restored in 1 h
Pilgrim	5/1/77	Faulted line, forest fire. Grid-related	III	345 kV-0:31	One 345-kV line out for maintenance	32	Boston Edison response to NRC questionnaire undated	While one 345-kV line was out of service for maintenance, the second one was faulted by a forest fire. The 23-kV line was available throughout. The faulted line was restored in 31 min
Pilgrim	5/10/77	Severe snow storm caused a static wire to fall onto 345-kV feeder. Grid failure, design error, and weather	Ia	2:40-23 kV 9:40-345 kV	None reported	65	LER 71-21	A 345-kV line was faulted when a snowstorm caused a static wire to fall onto the feeder. The disturbance caused Canal #2 fossil unit and Pilgrim Nuclear Power Plant to trip. All off-site power was lost to Pilgrim because of the system disturbance
Pilgrim	2/6/78	Wind and snow coated insulators and caused a flashover. Weather/snow, storm	Ia	23 kV-8:54 345 kV-18:54	None reported	24	LER 78-3	Severe winds and heavy snow caused 345-kV insulators to be coated with ice which then caused line faults. Insulator flashover caused a unit trip and loss of off-site power. Power was restored after the insulators were washed with fresh water
Pilgrim	8/6/78	Lines tripped because of lightning. Plant-centered, weather/lightning	III	345 kV-0:22	None reported	100	Boston Edison response to NRC questionnaire undated	A lightning strike caused both 345-kV lines to trip, but the 23-kV line did not fail. Both lines were restored in 22 min

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Pilgrim	7/27/79	Lines tripped because of lightning. Plant-centered, weather/ lightning	III	345 kV-0:14	None reported	100	Boston Edison response to NRC questionnaire undated	A lightning strike caused both 345-kV lines to trip, but the 23-kV line did not fail. Both lines were restored in 14 min
Pilgrim	8/28/79	Lines tripped because of lightning. Plant-centered, weather/ lightning	III	345 kV-0:16	None reported	100	Boston Edison response to NRC questionnaire undated	Lightning caused both 345-kV lines to trip, but the 23-kV line did not fail. Both lines were restored in 16 min
Pilgrim	10/12/82	Salt spray during a storm caused insulators to be coated with salt. The 345-kV breakers opened. Plant-centered, weather	III	11:33	None reported	0	LER 82-51	Heavy ocean storms caused 345-kV insulators to be coated with salt. The 345-kV system failed, but the 23-kV line was available. The 345-kV system was restored by washing the salt off the insulators
Pilgrim	2/13/83	Ice and salt caused an electrical fault. Plant-centered, weather/ice	III	Not reported	None reported	55	EPRI telecon	The startup transformer was lost because of melting, salty ice on its insulators. A portion of the 345 kV switchyard became deenergized, the unit tripped, and the diesels started. The 23-kV alternate off-site power source was available throughout
Peach Bottom								No complete losses or significant partial losses of off-site power
Point Beach	2/5/71	All transmission lines were lost and transformer differential relays operated improperly. Weather/ snow and hardware	Ib	0:08	None reported	#1-0 #2-unlicensed	Letter from Wisconsin Electric Power Co. to NRC 11/16/79	A major ice storm caused a loss of all transmission lines; transformer differential relays on three transformers operated and caused the transformers to lockout. One off-site source was restored after 8 min, and all three lines were restored in 6 h and 22 min

Point Beach	10/13/73	A lightning mast fell on one transformer while the other was out of service. Plant-centered, hardware failure	II	0:55	One transformer and gas turbine were unavailable	#1-0 #2-at power	Letter from Wisconsin Electric Power Co. to NRC 11/16/79	A lightning mast fell on Unit 2 startup transformer 2X03 while Unit 1 startup transformer 1X03 was out of service. The diesels supplied the safeguards buses for both units, but Unit 2 continued to operate. The gas turbine was started after 55 min and supplied power for 4 h and 30 min at which time transformer 1X03 was returned to service
Point Beach	4/27/74	A 345-kV bus section was isolated because of a maintenance error. Plant-centered, human error and design error	III	Momentary	None reported	Not reported	Letter from Wisconsin Electric Power Co. to NRC 11/16/79	A maintenance error caused a 345-kV bus section to be isolated. The normal power source to Unit 1 was lost, so a fast transfer to the alternate off-site source was initiated. Before the transfer was completed, undervoltage relays tripped the buses and the diesels started. The buses were immediately reconnected to off-site power
Prairie Island	7/15/80	An electrical storm caused transmission lines to trip. Weather/lightning, plant-centered	Ia	1:02	None reported	#1-0 #2-100	LER 80-20	Unit 2 tripped at 8:30 p.m., but off-site power was not lost immediately. An electrical storm caused a loss of off-site power. The 161-kV line remained energized at 80% voltage which was unusable
Quad Cities	11/6/77	A transformer fault caused loss of power to Unit 2. Plant-centered, hardware failure	Ia	1:09	One 345-kV line	#1-at power #2-at power	LER 77-37; letter from Commonwealth Edison to NRC 12/20/79; letter to W. E. Berger, Sargent and Lundy from Commonwealth Edison, 8/22/84	A transformer feeding the canal spray pumps faulted and caused Unit 1 and Unit 2 to trip. One transmission line remained in service supplying Unit 1, but Unit 2 was without off-site power. A cross tie between Units 1 and 2 could have been closed manually to restore power to Unit 2
Quad Cities	2/13/78	Undervoltage relays tripped buses, but transmission lines remained connected. System design, grid failure	V	0:20	None reported	#1-startup #2-0	Letter from Commonwealth Edison to NRC 12/20/79	Undervoltage relays tripped off-site power sources to safeguards buses, and Unit 1 tripped. The system dispatcher increased the grid voltage. Off-site power was available throughout at a degraded voltage

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Quad Cities	6/22/82	Plant-centered, human error	Ia	0:34	Unit 2 startup transformer was being removed	#1-53 #2-100	LER 82-12	The Unit 2 startup transformer was being removed from service for maintenance when an operator error caused Unit 2 to trip. Because the startup transformer was deenergized when the main generator tripped, Unit 2 lost all off-site power. Diesel generators 2 and 1/2 started and energized the emergency buses. Diesel generator 1/2 tripped while attempting to load a residual heat removal pump. Diesel generator 1 was down for maintenance, but Unit 1 did not lose off-site power. The auxiliary transformer was restored after 34 min. A cross tie between Units 1 and 2 could have been closed to reenergize Unit 2
Rancho Seco	6/19/81	There was low voltage on the grid because of high local electrical demand. Grid operation	V	Not reported	None reported	0	LER 81-34	High local electrical demand caused the switchyard voltage to decrease to 207-kV. The safeguards buses were transferred to diesel generators to maintain 214-kV in the switchyard
Rancho Seco	8/7/81	There was low voltage on the grid because of high local electrical demand. Grid operation	V	Not reported	None reported	0	LER 81-39	High local electrical demand caused the switchyard voltage to decrease to 206-kV. This is below 0.9 per unit for the 230-kV system. The safeguards buses were transferred to diesel generators to maintain 214-kV in the switchyard
Robinson 2								No complete losses or significant partial losses of off-site power
St. Lucie	5/16/77	Grid instability caused two losses of off-site power. Grid-system design	Ia	Event 1 - 0:20 and Event 2 - 1:30	None reported	at power	LER 77-26	A grid disturbance caused a reactor trip, and subsequent low voltage caused a loss of off-site power. Voltage was restored to normal after 20 min, but 1 h later off-site power was lost again

St. Lucie	5/14/78	An electrician's switching error and a design error caused loss. Grid-related design and human error	Ib	0:08	None reported	0	LER 78-17	A design error and a human error caused an area-wide blackout including St. Lucie. An electrician was transferring lines at Pratt and Whitney substation and a loss of off-site power resulted at St. Lucie. One diesel was down for maintenance. The unit was being refueled
Salem								No complete losses or significant partial losses of off-site power
San Onofre	6/7/73	An improper ground in a test circuit caused a loss of power. Plant-centered, human error	IV	4:59	"C" Auxiliary transformer	0	Letter from SCE to USAEC 7/6/73	When off-site power was being transferred, a ground in a test circuit caused all off-site power to be lost. Diesel generator 1 and 2 were operating in parallel DG 1 failed after 50 min of operation and caused both DGs to trip. DG 2 was reconnected in 1 min
San Onofre	4/22/80	An operator opened the wrong breaker. Plant-centered, human error	IV	0:04	"C" auxiliary transformer, No. 1 DG, and load sequencer	0	LER 80-38	A technician failed to block relays during maintenance and caused a loss of off-site power. Diesel generator 2 was started manually but was not connected because the operator anticipated restoring off-site power in a few minutes
San Onofre	11/22/80	Breakers were incorrectly aligned. Plant-centered, human error	Ib	15 s	None reported	0	LER 80-38	Incorrect breaker alignment during a power transfer caused a loss of off-site power. Both diesels started but were not loaded because power was restored to the original source
Sequoyah								No complete losses or significant partial losses of off-site power
Summer								No complete losses or significant partial losses of off-site power
Surry								No complete losses or significant partial losses of off-site power
Susquehanna								No complete losses or significant partial losses of off-site power

Table A.1 (continued)

Plant name	Event date	Equipment failure and cause of failure	Category	Restoration time (h: min)	Equipment unavailable at the time of the event	Reactor power (%)	References	Description of event
Trojan								No complete losses or significant partial losses of off-site power
Turkey Point	4/3/73	Turkey Point 3 tripped and initiated a grid instability. Grid-related design	Ib	0:18	Turkey Point #1 and #2 were down for maintenance (fossil units)	#3-73 #4-unlicensed	Report to Florida Public Service Commission (FPSC) on FPL disturbances. April 3 & 4, 1973	Trip of Turkey Point 3 led to a system instability and a blackout of southern Florida
Turkey Point	4/4/73	Turkey Point 3 tripped and initiated a grid instability. Grid-related design	Ib	0:15	Turkey Point 1 was down. Turkey Point 2 was limited to 220 MW (fossil units)	#3-73 #4-unlicensed	Report to Florida Public Service Commission (FPSC) on FPL disturbances. April 3 & 4, 1973.	A trip of Turkey Point 3 led to a system instability and a blackout of southern Florida. The sequence of events were similar to those of April 3, 1973
Turkey Point	4/25/74	Turkey Point Units 3 & 4 tripped and caused a grid instability. Plant-centered, human error	Ib	0:20	Startup transformer #4	#3-97 #4-98	Letter from FPL to USAEC 5/3/74	Maintenance personnel were working on startup transformer #4 and caused a trip of both reactor units. Unit 4 had no off-site power but it was unclear if Unit 3 was being supplied off-site power. Off-site power was restored to Unit 4 in ~20 min
Turkey Point	6/28/74	Units 3 and 4 tripped because of grid instability. Grid-related, design	Ib	0:11	None reported	#3-100 #4-100	Letter from FPL to Federal Power Commission 7/19/74	A grid instability in southern Florida caused a trip of Units 3 and 4. All off-site power was lost
Turkey Point	5/16/77	Turkey Point 3 tripped. Shortly thereafter a line fault caused a system instability. Grid-related design	Ia	Event 1-1:02 Event 2-<2:00	None reported	#3-99 #4-0	Letter from FPL to NRC 7/20/77	Turkey Point 3 tripped, and a subsequent line fault led to a blackout of southern Florida. Power was lost for 1 h and 2 min, failed again after 37 min, and was restored less than 2 h later. Turkey Point fossil Units 1 and 2 tripped during the transient, but a fossil unit was operating 7 min after power was restored the first time and soon (time not reported) after power was restored the second time

Turkey Point	4/4/79	Lines tripped because of salt and dust. Grid failure, weather/ dry weather and strong winds	III	1:05 0:22 3:59	None reported	#3-0 #4-90	FPL report 4/25/79 rev. 5/8/79	Extended dry weather followed by strong winds and an increase in humidity caused a trip of all off-site transmission lines to Turkey Point. Unit 4 tripped, fossil Unit 2 tripped, but fossil Unit 1 reduced its generation and remained on-line supplying the plant auxiliary loads. The loss of generation caused system isolation and load shed. After 1 h and 5 min, one line was reconnected, but it tripped after 3 min. A line was reconnected 22 min later but tripped after 45 min. Power was restored a third time after 3 h and 59 min
Turkey Point	8/3/79	Unit trip while start-up transformer was unavailable. Plant-centered, design	III	Unknown	Unit 4 startup transformer	#3-100 #4-100	IE Information Notice 79-25	Unit 4 tripped while the Unit 4 startup transformer was out of service which caused a loss of power to Unit 4. Load shedding relays shed loads for Unit 3, which was on a common bus. This caused Unit 3 to trip. The diesels started, but off-site power was available to both units from the Unit 3 startup transformer
Vermont Yankee	12/27/72	The startup transformer was isolated by a differential relay trip. Plant-centered, hardware failure	III	11:22	Unit auxiliary transformer was out of service because of an earlier failure	0	NSIC abstract of VY operations report for Dec. 72	The startup transformer was isolated while it was supplying the plant loads. The unit auxiliary transformer was unavailable because of a failure on 11/11/72. The Vernon hydro unit supplied power to the Class IE buses
Yankee (Rowe, MA)	11/9/65	Northeast blackout caused a loss of power. Grid-related design	Ia	0:33	None reported	0	Letter from Yankee Atomic Electric Co. to NRC 3/11/80	The blackout of the Northeast caused a loss of all off-site power. A nearby hydro unit was used to reenergize the nuclear unit
Zion								No complete losses or significant partial losses of off-site power

*Not included in the statistical analysis. See Sect. 5.

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16. ABSTRACT (200 words or less)

Events involving loss of off-site power that have occurred at nuclear power plants through 1983 are described and categorized as complete or partial losses. The events were identified as plant-centered or grid-related failures. In addition, the causes of the failures were classified as weather, human error, design error, or hardware failure. The plant-centered failures were usually of shorter duration than the weather-related grid failures. For this reason, the weather-related events were reviewed in detail. Design features that may be important factors affecting off-site power system reliability were tabulated for most of the operating nuclear power plants. The tabulated information was provided to NRC for a statistical analysis to determine the importance of these design features for losses of off-site power. The frequency of losses of off-site power versus duration were estimated for three time periods. The frequency of loss of off-site power was estimated to be 0.09/reactor-year based on industry-wide data for the years 1959 through 1983.

17. KEY WORDS AND DOCUMENT ANALYSIS — 17a. DESCRIPTORS

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