APPENDIX G

GENERIC PROBABILITY OF A CONSEQUENTIAL LOOP: AN EVALUATION

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Acronyms and Abbreviations

BNL	Brookhaven National Laboratory
CFR	Code of Federal Regulations
DBA	Design basis accident
ECCS	Emergency core-cooling system
EDG	Emergency diesel generator
EPRI	Electric Power Research Institute
ESF	Engineered safety feature
FSAR	Final safety analysis report
GDC	General Design Criterion
HEP	Human error probability
HPCS	High pressure core spray
HVAC	Heating, ventilation, and air conditioning
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IN	(NRC) Information Notice
INEEL	Idaho National Engineering and Environmental Laboratory
LBLOCA	Large-break LOCA
LER	Licensee event report
LOCA	Loss of coolant accident
LOOP	Loss of offsite power
LPCI	Low pressure coolant injection
LPCS	Low pressure core spray
MCS	Minimal cut set
NEI	Nuclear Energy Institute
NPP	Nuclear power plant
NPRDS	Nuclear Power Reliability Data System
NUCLARR	Nuclear Computerized Library for Assessing Reactor Reliability
PRA	Probabilistic risk assessment
SCSS	Sequence Coding Search System
SIS	Safety injection signal
USNRC	U.S. Nuclear Regulatory Commission
VAR	Volt amperes reactive

G.1 INTRODUCTION

In SECY-01-0133 [Ref. G.1], one of the recommendations that the staff made to the Commission was that rulemaking should be undertaken to develop a risk-informed alternative to the emergency core cooling system (ECCS) reliability requirements. This alternative would be voluntary on the part of licensees and would include technical requirements to ensure an ECCS reliability that is commensurate with the frequency of challenges to systems. Attachment 2 of SECY-01-0133 describes the proposed voluntary alternative to the ECCS reliability requirements. For this alternative, it is envisioned that both a generic and a plant-specific option for ensuring ECCS safety function reliability would be offered in a regulatory guide, in place of the current requirements in General Design Criterion (GDC) 35 for postulating a loss of offsite power (LOOP) and additional single failure.

The needed technical work to support rulemaking for the proposed changes associated with ECCS functional reliability involves the following three principal areas:

- loss of coolant accident (LOCA) frequencies
- conditional probability of LOOP given a LOCA
- ECCS risk/reliability analyses

The objective of this work is to address the second main area, namely, the conditional probability of LOOP given a LOCA. In particular, this report focuses on the first option proposed by Attachment 2 of SECY-01-0133, which involves assessing the generic probability of a LOOP given a LOCA. Generic means an assessment that would apply to the entire population of nuclear plants in the United States, or to a large group of them.

Section G.2 discusses the causes of a LOOP after a LOCA. Section G.3 uses a data-driven approach to attempt to evaluate its probability. As discussed in Section G.3, the data-driven approach yields an estimate of this probability that may be inaccurate due to the scarcity of data. Section G.4 proposes a hybrid approach that uses a model, insights gained during the data-driven evaluation, and engineering judgment to estimate the generic probabilities of a LOOP given a LOCA due to plant-centered factors and due to transient factors. Finally, Section G.5 uses the results from Section G.4 to obtain an estimate of the total generic probability of a LOOP given a LOCA.

G.2 CAUSES OF LOOP AFTER A LOCA

GDC 17 (Appendix A of 10 CFR 50) states, in part, “Provisions shall be included to minimize the probability of losing electric power from any of the remaining supplies as a result of, or coincident with, the loss of power generated by the nuclear power unit...” Accordingly, licensees are required to demonstrate that their offsite power supplies are available after a unit trips or after a design basis accident (DBA).

However, operational data shows that a LOOP has occurred after a reactor trip or after an event similar to a LOCA. For example, Salem Generating Station Unit 2 had a LOOP after actuation of the ECCS (and a reactor trip) in 1986. One contributor to this LOOP was the fact that additional electrical loads were added to the Salem Station electrical distribution system since the completion of a transient study in 1981. When these loads were added, a static analysis of their effect on the system was performed which showed the system to be more than adequate to handle the additional load. However, the 1981 transient analysis for higher startup currents was never updated to account for the additional loads.

A LOCA causes the following electrical-related events in a nuclear power plant (NPP):

1. A reactor trip (loss of generation). The loss of a large amount of electric-power generation can cause voltage instability in the offsite transmission-system grid.

2. The transfer of the power source of the plant loads from the main generator to offsite power. In many plants, the main generator normally feeds the plant loads through a unit’s auxiliary transformer. When the reactor trips, the main generator often remains connected to the plant’s electrical systems and high-voltage switchyard until protective relaying transfers the power source from the main generator to the offsite transmission-system grid.

3. Loading of safety loads to Class 1E buses[(1)]. The pumps of the ECCS are started and aligned. The AC-powered ECCS loads are powered from the Class 1E buses which, in turn, are fed from the offsite transmission-system grid.

The first event results in a sudden loss of a large amount of electric-power generation to the offsite transmission-system grid, and the last two events demand electric power from this grid to feed safety and non-safety loads. Starting these loads requires a motor-starting (inrush) current which, in turn, can cause undervoltage at the Class 1E buses. Thus, a LOCA can cause voltage instability in the offsite transmission-system grid due to the combined effect of losing electric-power generation and demanding electric power for safety and non-safety loads. This instability can degrade voltage at the unit’s switchyard, thereby actuating degraded voltage protection (relays) which then disconnect the Class 1E buses from the offsite grid. These buses subsequently are powered by the onsite emergency AC power sources, usually the EDGs.

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[1]The term “Class 1E buses” is used to represent the safety buses that provide AC power to ECCS loads. These buses can be fed by offsite power and the emergency diesel generators (EDGs).

A LOOP occurs when the Class 1E buses are disconnected from the offsite transmission-system grid, so that the buses cannot meet the required success criteria to respond to a DBA without the support of the onsite emergency-power system. The success criteria may be stated in the final safety analysis report (FSAR). In many instances, this definition means that all Class 1E buses are disconnected from the offsite transmission-system grid. However, sometimes a disconnection from the offsite grid of several Class 1E buses, but not all of them, also is considered a LOOP because those buses that remain powered from the offsite transmission-system grid cannot meet the success criteria required to respond to a DBA.

The electrical transient (disturbance) triggered by the LOCA due to a sudden loss of a large amount of electric-power generation and a demand to power safety and non-safety loads can be exacerbated by inadequate or degraded voltage conditions of the offsite transmission-system grid. The NRC Information Notice (IN) 2000-06 [Ref. G.2] documents and discusses several events related to the voltage adequacy of offsite power sources, that is, power from the transmission grid to nuclear power plants. This IN identifies several factors that could result in inadequate offsite voltages, such as line outages, high system demand, and unavailability of other local voltage support.

One recent event at Callaway Unit 1 potentially tied the concern about inadequate voltage in the offsite system to industry deregulation. The licensee stated in licensee event report (LER) 50-483/99-005 that such magnitude of power being transported across the grid during the period of the event had not been observed previously and was far in excess of typical levels. This LER also stated that the deregulated wholesale power market contributes to conditions in which higher grid power flows are likely to occur, and these large flows were observed at that time. These statements imply that in a deregulated environment, there may be a greater potential for experiencing degraded voltage conditions in the offsite transmission-system grid.

To simplify this discussion, the two factors identified above that contribute to the occurrence of a LOOP after a LOCA, namely, the electrical disturbance triggered by the LOCA and the conditions of the offsite transmission-system grid, are called here “transient factors”.

In addition to the transient factors, a LOOP after a LOCA can be caused by failures of plant electrical equipment. For example, if the Class 1E buses are fed during power operation by the main generator, and are required to be transferred to an offsite source, but the transfer fails, then these buses will not be connected to the offsite source, and will effectively experience a LOOP.

Examples of plant electrical equipment that are relevant to a LOOP after a LOCA are the transfer schemes, undervoltage protective schemes (mainly relays), transformers, and circuit breakers. These components may fail to operate due to a hardware-related cause, or human error. Examples of human errors are failures during maintenance, testing, or calibration. To simplify this discussion, the failures of plant electrical equipment that contribute to a LOOP after a LOCA are called here “plant-centered factors.” Strictly speaking, the electrical transient triggered by a LOCA also is “plant-centered,” but for convenience it is classified here as a “transient factor.”

Summarizing, a delayed LOOP can be caused by transient and/or plant-centered factors. Since this LOOP occurs as a consequence of the LOCA, it is called a consequential LOOP. Also, the

LOOP does not occur simultaneously with the LOCA, but some time elapses during the electrical disturbance after the LOCA. For this reason, it also is called a delayed LOOP.

G.3 A DATA-DRIVEN APPROACH TO ESTIMATING THE GENERIC PROBABILITY OF LOOP GIVEN A LOCA

This section presents a data-driven approach to assess the generic probability of a LOOP given a LOCA. Generic means an assessment that would apply to the entire population of nuclear plants in the United States, or to a large group of them.

An approach consisting of examining the operational experience for the entire population of nuclear plants was used to obtain the generic probability of consequential LOOP. Since no operational events of a LOCA with a consequential LOOP have occurred, it is necessary to identify operational events that match, as closely as possible, such occurrence. For this identification, two types of events that cause an impact similar to a LOCA were considered: reactor trip and major actuation of ECCS loads. The first surrogate can cause a consequential LOOP because the loss of the main generator disturbs the offsite power grid, and plant-centered failures of electrical equipment may occur after the trip of the main generator. The second surrogate, major actuation of the ECCS loads, causes a reactor trip and, in addition, the loading of the ECCS loads to the safety buses; the combined effect of these two events could cause an undervoltage at these buses, ultimately causing a LOOP.

The second surrogate, major actuation of the ECCS loads, is expected to more closely resemble a LOCA because it encompasses both the reactor trip and the loading of the ECCS loads to the safety buses. The generic probability of consequential LOOP after this surrogate was assessed. However, the generic probability of consequential LOOP after the first surrogate, reactor trip, was also evaluated because of the following reasons:

1. There are more consequential LOOPs after reactor trips than after major ECCS actuations. Insights were gained by examining consequential LOOPs after reactor trips.

2. It is relevant for probabilistic risk assessments (PRAs) to consider the scenario of a delayed LOOP after a reactor trip. The results of the generic probability of consequential LOOP after a reactor trip obtained here can be used in PRA studies for nuclear power plants.

A consequential LOOP is mainly a function of the response of the electrical systems at a plant and their interactions with the external power grid. Hence, a consequential LOOP is not expected to depend on the type of nuclear power plant. Accordingly, the data for PWRs and BWRs were merged to obtain a single estimate of the probability of a consequential LOOP, applicable to both types of plants. The source of operational data was the LERs contained in the Sequence Coding Search System (SCSS).

A typical nuclear power plant has two safety trains with their respective emergency buses. Some of the events in the operational experience (LERs) involve a loss of offsite power to one of the emergency buses, while the other has offsite power available. This type of event is named here partial LOOP, and it has the potential to become a complete LOOP (i.e., loss of offsite power to both emergency buses). One possibility to account for this potential is to estimate the conditional probability that the second emergency bus loses offsite power given loss of offsite power to the first emergency bus. On the other hand, since the quantitative guidelines from the Option 3 framework

[Ref. G.3] only involve an order-of-magnitude evaluation, the contribution of partial LOOPs is not expected to be significant.

The consequential LOOPs identified in the operational experience are due to “internal” causes, such as the electrical disturbance triggered by the generator trip. Therefore, in the following evaluation of the generic probability of consequential LOOP given a LOCA (or reactor trip), the estimate of this probability represents the probability due to “internal” events. An analysis of the impact of “external” events on the probability of consequential LOOP was not within the scope of this work. The term “external” events is used here to have the meaning in the typical PRA jargon, that is, those events such as seismic and fire events.

The following subsections (G.3.1 and G.3.2) describe the derivation of generic probabilities of consequential LOOP after a reactor trip and after a major ECCS actuation, respectively.

G.3.1 Generic Probability of Consequential LOOP After a Reactor Trip

Using the SCSS, the LERs from January 1, 1984 to October 31, 2001 were searched to count the number of reactor trips. The consequential LOOPs after a reactor trip that happened in this period were identified using the following steps:

1. The consequential LOOPs in the period January 1, 1984 to December 31, 1992 had already been identified in NUREG/CR-6538 [Ref. G.4].
2. For the period January 1, 1993 to October 31, 2001, a search of LERs using the SCSS was conducted. An LER had to fulfill two search criteria to be selected: (1) the event was related to components in high voltage AC power (greater than 35kV) or in medium voltage AC power (35kV to 600V), and (2) it happened during one of the following modes of power operation: steady state operation, load change, power reduction, or during hot shutdown.
3. The LERs in the list resulting from the previous step were individually reviewed to identify consequential LOOPs after a reactor trip.

The review yielded the following results:

Number of consequential LOOPs after a reactor trip = 8 events. They are listed in Table G.1.

Number of reactor trips = 3415 events.

The point estimate and uncertainty due to variability in the data were assessed using a binomial distribution. This distribution is used because the data, the number of failures in a given number of demands, and the consideration that the probability is constant across these demands, correspond to this distribution.

Table G.1 Consequential LOOPs After a Reactor Trip from 1984 to 2001

Plant	Manufacturer	Date of Event	Docket#/LER#
Robinson 2	Westinghouse	01/28/86	261/86-005
Byron	Westinghouse	10/02/87	455/87-019
Point Beach 2	Westinghouse	03/29/89	301/89-002
Virgil C. Summer	Westinghouse	07/11/89	395/89-012
Dresden 2	General Electric	01/16/90	237/90-002
Oyster Creek 1	General Electric	08/01/97	219/97010
Nine Mile Point 2	General Electric	06/24/99	410/99010
Indian Point 2	Westinghouse	08/31/99	247/99015

In estimating the confidence limits, the following expressions are used: “p” is the probability being evaluated, “f” is the number of observations of the event, and “n” is the number of demands. The point estimate of “p” is

$$p = f/n \tag{1}$$

The upper 100 (1 - α)% confidence limit on “p” is obtained by solving:

$$\alpha = \sum_{x=0}^{f} \binom{n}{x} p^x (1-p)^{n-x} \tag{2}$$

for “p.” The lower 100 (1 - α)% confidence limit on “p” is obtained by solving:

$$\alpha = \sum_{x=f}^{n} \binom{n}{x} p^x (1-p)^{n-x} \tag{3}$$

for p.

The following results were obtained using equations (1) through (3):

Point estimate of generic probability of LOOP given a reactor trip = 2.3×10^{-3}

95% confidence limit = 4.2×10^{-3}

5% confidence limit = 1.2×10^{-3}

A continuous probability distribution can also be obtained by applying Bayes theorem. Applying a binomial model with a non-informative prior (i.e., a uniform prior), the posterior distribution obtained is a beta distribution:

$$f(x) = \frac{x^{a-1}(1-x)^{b-1}}{B(a,b)} \quad (4)$$

for 0 < x < 1, where B(a,b) is the beta function. The parameters obtained are the following:

mean = 2.3×10^{-3}

a = 8

b = 3407

G.3.2 Generic Probability of Consequential LOOP after a Major ECCS Actuation

Since the DBA of concern is a large LOCA, the appropriate surrogate is a "major ECCS actuation" that is similar to that expected in such a LOCA. This event involves the loading of several or all of the ECCS loads to the safety buses, and it may happen within a short time (typically, within 1 or 2 minutes) before or after a reactor trip, or this event may even cause a reactor trip. In fact, when a large LOCA occurs, the initiation of ECCS loading and the reactor trip are expected to happen very close in time. The combined effect of the loading of ECCS loads and the reactor trip could cause a LOOP.

A search was conducted in the SCSS of LERs related to engineered safety feature (ESF) actuations to identify major ECCS actuations and LOOPs after such actuations. However, the SCSS only classifies the ESF response type (such as safety injection) from 1987. On the other hand, it was known from NUREG/CR-6538 that a consequential LOOP after an ECCS actuation had occurred in 1986. Accordingly, major ECCS actuations and LOOPs after such actuations were identified using the following steps:

1. For the period January 1, 1987 to November 30, 2001, a search of LERs using the SCSS was conducted. An LER had to fulfill three search criteria to be selected: (1) the event was related to components in high voltage AC power (greater than 35kV) or in medium voltage AC power (35kV to 600V), and (2) it happened during one of the following modes of power operation: steady state operation, load change, or power reduction, and (3) it resulted in one of the following types of response of ESF: safety injection (water), safety injection (no water), other, or unknown.

2. For the period January 1, 1986 to December 31, 1986, a search of LERs using the SCSS was conducted. An LER had to fulfill two search criteria to be selected: (1) the event was related

to components in high voltage AC power (greater than 35kV) or in medium voltage AC power (35kV to 600V), and (2) it happened during one of the following modes of power operation: steady state operation, load change, or power reduction.

3. The LERs in the lists resulting from the previous steps were individually reviewed to identify major ECCS actuations and LOOPs after such actuations.

The full text of most LERs that are before 1986 are not currently available in the SCSS. For this reason, a search for these LERs was not carried out.

For an ECCS actuation to be considered major, it had to fulfill the following requirements:

1. For a PWR, a full safety injection signal (SIS) occurred. The term “full” means that a SIS is present in both ECCS trains. Partial SISs, such as an SIS of a single train, are not counted because the electrical load is less than that resulting from a full SIS, which would occur after a LOCA.

2. For a BWR, the automatic start of high-pressure and low-pressure ECCS systems occurred. For example, almost immediately after a DBA large LOCA in a BWR6, the following systems should start: the high-pressure core spray (HPCS) system, the low-pressure core spray (LPCS) system, and the low-pressure coolant injection (LPCI) mode of the residual heat removal system. If the description of an event in an LER does not contain the start of these systems within a few seconds of each other, then the LER is not counted as a major ECCS actuation.

3. For both PWRs and BWRs, no LOOP occurred before the ECCS actuation. If a LOOP occurred before the ECCS actuation, then this actuation is not counted because it could not have caused the LOOP.

The review of LERs yielded the following results:

Number of consequential LOOPs after a major ECCS actuation = 1 event

This event is listed in Table G.2.

Number of major ECCS actuations = 14 events

Table G.2 Consequential LOOP after a Major ECCS Actuation from 1986 to 2001

Plant	Manufacturer	Date of Event	Docket#/LER#
ECCS Actuation - LOOP Events			
Salem 2	Westinghouse	08/26/86	311/86-007

Using equations (1) through (3), the following results were obtained:

Point estimate of generic probability of LOOP given a major ECCS actuation = 7.1×10^{-2}

95% confidence limit = 3.0×10^{-1}

5% confidence limit = 3.7×10^{-3}

As done previously in this section, these results can also be used to obtain a continuous probability distribution by applying Bayes theorem. The posterior distribution obtained is a beta distribution (Equation 4) with the following parameters:

mean = 7.1×10^{-2}

a = 1

b = 13

The number of demands (n) used to assess the point estimate of the generic probability of LOOP given a major ECCS actuation (7.1×10^{-2}) is 14. This is a relatively small number of demands and, hence, the resulting point estimate may be inaccurate. In fact, the interval between the 95% and 5% confidence limits (3.0×10^{-1} and 3.7×10^{-3}) spans almost two orders of magnitude. To attempt to obtain an estimate of this probability that is more accurate, an approach that uses a model, insights gained during the data-driven evaluation, and engineering judgment is described and used in the next two sections.

G.4 A HYBRID APPROACH TO ESTIMATE THE GENERIC PROBABILITY OF LOOP GIVEN A LOCA

This section proposes an approach that uses a model, insights gained during the data-driven evaluation, and engineering judgment to estimate the generic probability of a LOOP given a LOCA.

As discussed in Section G.2, a delayed LOOP can be caused by transient and plant-centered factors. In summary, the electrical disturbance triggered by the LOCA is called here a "transient factor." In addition to the transient factors, a LOOP after a LOCA can be caused by failures of plant electrical equipment. For example, if the Class 1E buses are fed during power operation by the main generator, and are required to be transferred to an offsite source, but the transfer fails, then these buses will not be connected to the offsite source and will effectively experience a LOOP.

Examples of plant electrical equipment that are relevant to a LOOP after a LOCA are the transfer schemes, undervoltage protective schemes (mainly relays), transformers, and circuit breakers. These components may fail to operate due to a hardware-related cause or human error. Examples of human errors are failures during maintenance, testing, or calibration. To simplify this discussion, the failures of plant electrical equipment that contribute to a LOOP after a LOCA are called here "plant-centered factors." Strictly speaking, the electrical transient triggered by a LOCA also is "plant-centered," but for convenience it is classified here as a "transient factor."

Since a LOCA can cause an electrical disturbance in the offsite and onsite electrical systems, the transient factors and the plant-centered factors are not independent of each other. However, since either of the two factors can cause a delayed LOOP, an approximation of the generic probability of a consequential LOOP given a LOCA can be obtained by adding the probability of LOOP due to plant-centered factors and the probability of a LOOP due to transient factors, as follows:

$$P(\text{LOOP given a LOCA}) \sim P(\text{LOOP due to plant-centered factors}) + P(\text{LOOP due to transient factors}) \quad (5)$$

This approximation only should be used when the individual probabilities on the right-hand side of the expression are less than 0.1.

To assess the generic probability of LOOP due to plant-centered factors a model (fault tree) of typical designs of electrical equipment in nuclear power plants can be developed and evaluated. Section G.4.1 presents this approach. On the other hand, to evaluate the generic probability of a LOOP due to transient factors, developing a model that predicts the relationship between a plant and its interconnections with the offsite grid is well beyond the scope of this work. To estimate this probability, insights gained during the evaluation of consequential LOOP using a data-driven approach described in the previous section are combined with engineering judgment. This approach is discussed in Section G.4.2. Section G.5 combines the results from Sections G.4.1 and G.4.2 to estimate the generic probability of consequential LOOP.

G.4.1 An Evaluation of the Generic Probability of Consequential LOOP Due to Plant-Centered Factors

The power sources for the safety buses during normal plant operation can be classified in two categories: 1) the safety buses are supplied by the main generator through a unit transformer and, 2) the safety buses are supplied by a preferred offsite power source. For plants in the first category, after the main generator has tripped, the power supply to the safety buses has to be transferred to an offsite power source.

Figure G.1 is a simplified one-line diagram showing the connection of the safety buses to offsite power for plants in the first category; it was adapted from a drawing in Regulatory Guide 1.155 [Ref. G.5]. For plants in the second category, the safety buses are directly fed from the start-up transformer during normal operation, and no transfer is required to get power from this offsite source to these buses. The initial conditions of the plant are that a LOCA has occurred, the reactor and main generator have tripped, and offsite power is available.

G.4.1.1 Developing a Model of Consequential LOOP Due to Plant-Centered Factors

The model considers two safety buses, and that a LOOP occurs when offsite power to both buses is disconnected. As Figure G.1 shows, for plants in the first category, the safety buses are supplied by the main generator through the auxiliary transformer during normal operation. After the main generator trips, the power supply to the safety buses is transferred from it to offsite power through the start-up transformer. To make this transfer, the transfer relays send signals to open the normally closed circuit breakers that feed the safety buses from the main generator, and to close the normally open circuit breakers that feed the safety buses from the start-up transformer. The undervoltage relays associated with these buses monitor their voltage. The safety buses are disconnected from offsite power when the post-LOCA voltage at the buses is at, or below, the settings of their undervoltage relays. These settings are expressed as pairs of percentages of nominal voltage and time delays. A hypothetical example would be two pairs as follows: 90% for 30 seconds and 65% for 1 second. This means that the Class 1E buses would be disconnected from the offsite sources if the post-LOCA voltage at these buses dropped to 90% for 30 seconds or to 65% for 1 second.

The following equipment was considered relevant and was included in the probabilistic model for plants in the first category: the start-up transformer, the (outgoing) circuit breakers feeding the safety buses from the auxiliary transformer, and the (incoming) circuit breakers that close to feed the safety buses from the start-up transformer. It was considered that the start-up transformer has a tap changer.

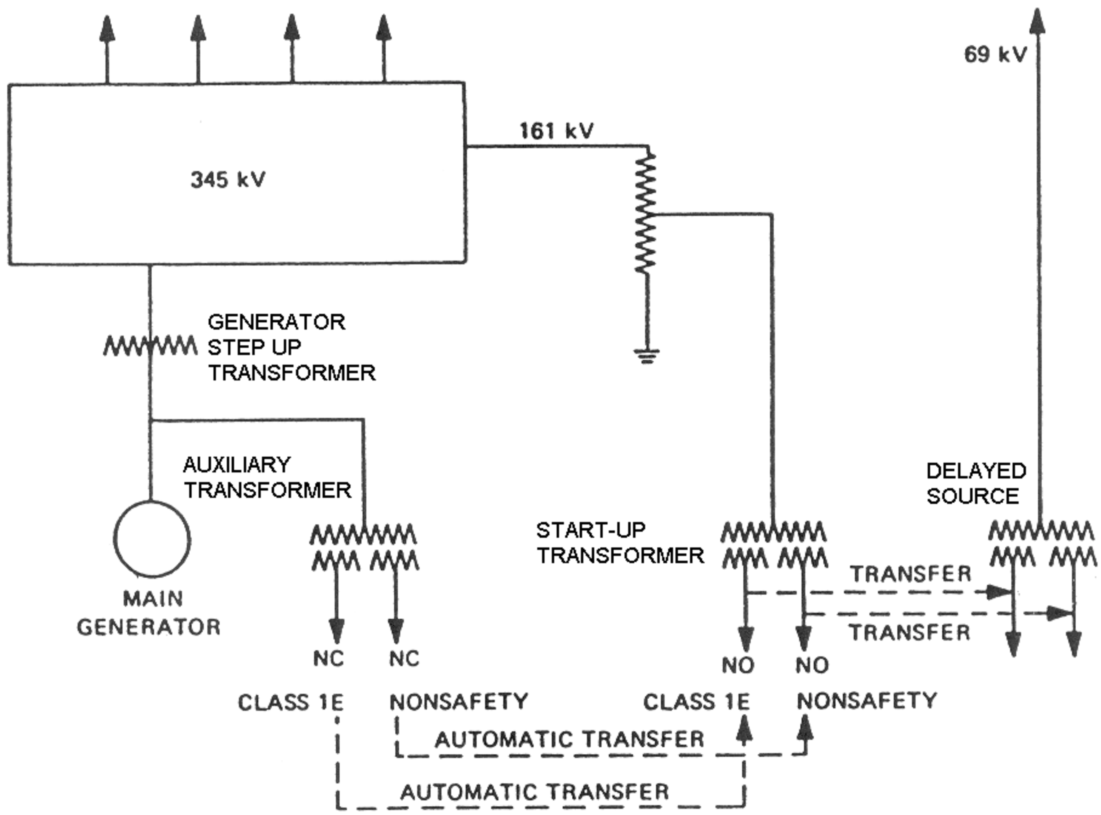

Figure G.1 Simplified One-Line Diagram

Figure G.1 does not include the following components which were also included in the model:

1. Undervoltage relays of safety buses, and the relays used for transferring the source of power from the auxiliary transformer to the start-up transformer. For both sets of relays, one of each is modeled per bus. In other words, the failure of a single undervoltage- or transfer-relay would cause the loss of the associated bus.

2. Time-delay relay. A single external timer for the undervoltage relays was assumed. The failure of the timer can cause the separation of the safety buses from offsite power.

The nine consequential LOOPs (one after a major ECCS actuation, and eight after a reactor trip) were reviewed to identify other plant-centered failures that can contribute to a consequential LOOP. The consequential LOOPs at Point Beach 2 (LER 301/89-002) and at Nine Mile Point 2 (LER 410/99-010) were triggered by the failure of a fault relay on the main generator output breaker. In both events, this failure left the plant with a single line of offsite power. According to LER 301/89-002, since the loads at Point Beach are at the end of the line when the unit is not generating, significant line losses happened, and a consequential LOOP followed. In this event, no other plant-centered failure, in addition to the failure of this fault relay, was required to cause the consequential LOOP. In light of these events, the probability of a consequential LOOP is increased after the failure of this relay (loss of a single line of offsite power). For the purpose of this evaluation, given the failure of this relay, the plant will be left with a single offsite line. Accordingly, for plants where the safety buses are supplied by the main generator through a unit transformer, this relay is included in the model, along with an event for the conditional loss of the second line, given the loss of the first line due to the failure of this relay.

In a consequential LOOP at Indian Point 2 (LER 247/99-015), the station auxiliary transformer tap changer remained in manual mode due to a defective voltage control relay. Accordingly, this relay is also included in the model.

A consequential LOOP at Robinson 2 (LER 261/86-005) was caused by a failure in the protective equipment of the startup transformer. This is modeled by including a relay associated with this transformer for plants where the safety buses are supplied by the main generator through a unit transformer. In this LER, the licensee indicated that several factors contributed to the failure of the protective equipment. One of the factors is that the freeze protection circuits were creating a higher than usual resistive load tending to slow down motors (inductive loads) more during the dead bus period at transfer. This appears to indicate that plants exposed to cold winters may be somewhat more vulnerable to a consequential LOOP during the winter due to the operation of the freeze protection circuits. On the other hand, this particular factor should be taken into account by the licensee's transient voltage analyses, and was therefore not included in the probabilistic model.

For the plants in the second category, the safety buses are supplied by offsite power through the start-up transformer during normal operation. After the main generator trips, the power supply to the safety buses remains the start-up transformer; no transfer of power source is required (unless the preferred offsite source has deteriorated or is not available). The equipment considered relevant and included in the probabilistic model for the plants in the second category are the same as those considered for the first category, except for those that are related to the transfer of power from the main generator to an offsite source, such as the transfer relays and the circuit breakers that close to feed the safety buses from offsite power (i.e., the start-up transformer).

For plants in both categories, the start-up transformer is energized on its primary side. During normal operation, failures in the transformer are usually alarmed in the control room, so they are expected to be detected promptly. However, after the initiating event, LOCA with its consequent reactor trip, safety and non-safety loads would be energized by the start-up transformer, and it may fail during the loading process.

Dependencies of the electrical components included in the probabilistic model on their support systems were also considered. The support systems identified were Class 1E DC power and heating, ventilation, and air conditioning (HVAC):

1. Class 1E DC power. It provides power for signals and actuation of equipment, such as circuit breakers opening and closing. At the time the initiator happens, LOCA with its consequent reactor trip, AC and DC power are available. However, the chargers associated with the Class 1E DC buses may not have enough capacity during the initial period when equipment is

starting. For this reason, it is considered conservatively that the batteries associated with the Class 1E DC buses have to operate to provide DC power.

2. HVAC. It provides ventilation to the rooms containing electrical equipment. The initiator, LOCA with its consequent reactor trip, is not expected to affect the HVAC system. In addition, the period of interest for a delayed LOOP is a few minutes after the LOCA, so even if the HVAC system fails due to random failures in this period, it would take some time beyond this period for the resulting increase in temperature to affect electrical equipment. Hence, failures in the HVAC system do not impact electrical equipment within the period of interest, and no dependency on this system was included in the probabilistic model.

G.4.1.2 Probabilistic Data Used in the Model of Consequential LOOP Due to Plant-Centered Factors

Table G.3 contains the probabilistic data used. As is commonly done in probabilistic assessments, the failure rates and beta factors were assumed to be lognormally distributed, and their error factors are included in the table.

Table G.3 Probabilistic Data Used in the Model of Consequential LOOP Due to Plant-Centered Factors

Component	Failure rate (per hour)	Test interval	Unavailability	Error factor	Source of data
Undervoltage relay fails	1.3E-6	Quarterly	1.4E-3	3.0	BNL, 94[1]
Common-cause failure of two undervoltage relays	6.0E-2 (beta factor)	Quarterly	8.4E-5	2.2	BNL, 94
Relay of start-up transformer fails	1.3E-6	Quarterly	1.4E-3	3.0	BNL, 94
Transfer relay fails	1.3E-6	24 months[2]	1.1E-2	3.0	BNL, 94
Common-cause failure of two transfer relays	6.0E-2 (beta factor)	Refueling cycle[3]	6.7E-4	2.2	BNL, 94
Time-delay relay	Not available	Not available	1.0E-4	5.0	EPRI, 1997[4]
Voltage control relay of start-up transformer's tap changer	1.3E-6	Quarterly[5]	1.4E-3	3.0	BNL, 94
Fault relay on the main generator's output breakers	1.3E-6	Yearly[6]	5.6E-3	3	BNL, 94
Conditional loss of the second line of offsite power given the failure of the fault relay on the main generator's output breakers	Not available	Not applicable	1.0E-1	20	Engineering judgment[7]
Start-up transformer fails	9.4E-7	Yearly[6, 8]	4.1E-3	6.7	BNL, 94

Table G.3 Probabilistic Data Used in the Model of Consequential LOOP Due to Plant-Centered Factors

Component	Failure rate (per hour)	Test interval	Unavailability	Error factor	Source of data
Automatic tap changer fails	4.7E-8	Yearly[6]	2.0E-4	4.3	EPRI, 2002 & IEEE-500[9]
(Normally open) circuit breaker fails to close	2.0E-6	Yearly[6]	8.6E-3	8	BNL, 94
Common cause failure of two (normally open) circuit breakers to close	3.9E-2 (beta factor)	Yearly[6]	3.3E-4	2.6	INEEL, 98[10]
(Normally closed) circuit breaker fails to open	3.7E-7	Yearly[6]	1.6E-3	8	BNL, 94
Common cause failure of two (normally closed) circuit breakers to open	3.9E-2 (beta factor)	Yearly[6]	6.2E-5	2.6	INEEL, 98[11]
Battery	2.7E-6	1 month[12]	9.5E-4	6.6[13]	IEEE-500
Common cause failure of two batteries	9.9E-3	1 month[12]	9.4E-6	3.6	INEEL, 98

Notes to Table G.3:

1. "BNL, 94" refers to a study [Ref. G.6] that combined probabilistic data from three sources (IEEE-500 [Ref. G.7], NUCLARR [Ref. G.8], and the Nuclear Power Reliability Data System [NPRDS]) to obtain updated data.
2. It is assumed that these relays will only be exercised during an automatic reactor trip. According to an NRC report [Ref. G.9], the current frequency of automatic reactor trips is approximately 0.5 per year, per plant.
3. The refueling cycle was assumed to be 24 months.
4. "EPRI, 1997" refers to [Ref. G.10]. This reference was not available; the value used was taken from a report documenting the results of an elicitation meeting [Ref. G.11] on the probability of LOOP given a large-break LOCA.
5. A quarterly test interval was assumed.
6. This component is exercised every time there is a reactor trip. According to an NRC report [Ref. G.9], on average there are approximately 90 automatic and manual reactor trips per year since 1997, and there are 103 units operating. Hence, it was assumed that there is one trip per year, per plant.
7. This conditional probability depends on many factors and is not available. This probability is related to the consequential LOOPs at Point Beach 2 (LER 301/89-002) and at Nine Mile Point 2 (LER 410/99-010). In both events, the failure of a fault relay on the main generator's output breakers left the plant with a single line of offsite power. In light of these events, the probability of a consequential LOOP is considered to be increased after the failure of this relay (loss of one line of offsite power). Given the loss of a single line, the second line is estimated to be lost in 1 out of 10 trials. There is large uncertainty in this estimate, so a large error factor is assigned.
8. After the initiating event, LOCA with its consequent reactor trip, safety and non-safety loads would be energized by the start-up transformer, and it may fail during the loading process. For this reason, it was considered that the transformer is tested when it is loaded.
9. The same failure rate used by [Ref. G.11] was used here. The error factor was obtained assuming that the low and high values from IEEE-500 [Ref. G.7] are the 5% and 95% confidence limits, respectively.
10. "INEEL, 98" refers to NUREG/CR-5497 [Ref. G.12].

Table G.3 Probabilistic Data Used in the Model of Consequential LOOP Due to Plant-Centered Factors

Component	Failure rate (per hour)	Test interval	Unavailability	Error factor	Source of data
Notes to Table G.3 (continued):					

Notes to Table G.3 (continued):

11. The beta factor for the two circuit breakers failing to open was not found in the literature. It was assumed that the beta factor for the failure mode "fails to close" applies to "fails to open."
12. A monthly test was assumed.
13. The error factor was obtained assuming that the high value from IEEE-500 [Ref. G.7] is the 95% confidence limit, and that the 5% confidence limit is 1.0E-6.

G.4.1.3 Human Reliability Analysis

Human errors before and after the initiating event (LOCA) are considered in the probabilistic model. The widely used THERP method [Ref. G.13] was used for evaluating the human-error probabilities (HEPs). This publication here is referred to as “the handbook.” The following human errors before the initiating event (Type 1) were taken into account:

1. Operator sets the settings of the undervoltage relays too high. An operator or team from the plant staff erroneously calibrates or manipulates the relays, so that their settings are too high. Then, a dip in the offsite voltage that is less than the design settings of the relays can disconnect the safety buses from offsite power. Using the handbook (Table 20-12, Item 10), this HEP was estimated as 3.0×10^{-3}, with an error factor of 3.

2. Operator sets the start-up transformer voltage regulators to control the output voltage at a level lower than the worst-case voltage assumed in the degraded grid study. An operator or team sets these regulators incorrectly, or the design requirements are not properly translated into these regulators. This human error happened in an event at Oyster Creek 1 (LER 219/97-010) in 1997. The error can be modeled as “writing an item incorrectly in a formal or ad hoc procedure or on a tag” that has an HEP of 3.0×10^{-3}, with an error factor of 3 (Table 20-5, Item 3).

3. Operator sets transfer settings incorrectly. An operator or team sets incorrectly the equipment involved in a transfer of power from the auxiliary transformer to the start-up transformer. Using the handbook (Table 20-12, Item 10), this HEP was estimated as 3.0×10^{-3}, with an error factor of 3.

For each of these human errors, credit is given for recovery by a checker. The HEP for failure of the checker to recover the initial error is estimated to be 0.1 with an error factor of 5 (Table 20-22, Item 1).

With regard to human errors after the initiating event (Type 3), no credit is given to actions to use the delayed offsite source. GDC 17 requires, as a minimum, that there are two physically independent circuit paths from the offsite power network to the plant’s onsite power distribution system. Accordingly, two offsite power sources are available to a plant. One of them must be available within a few seconds after a LOCA. However, the other power source may not be immediately available because the staff has to take manual actions to make it available. For this reason, this source is called the delayed offsite source (see Figure G.1).

The time required for the operators to diagnose the cause of a LOOP and implement corrective actions is likely to be at least several minutes after the onset of the LOOP. Since a large-break LOCA (LBLOCA) is the focus of this study, and mitigating it requires the ECCS equipment to respond quickly, no credit is given to the manual recovery of offsite power. The manual actions required to make the delayed offsite source available can take up to several minutes, so this source is not credited in this evaluation, and no human errors of Type 3 are included in the model.

A report documenting the results of an expert elicitation meeting [Ref. G.11] on the probability of LOOP given large LOCA considers a human error in the system voltage analysis. The expert panel report estimates an HEP of 0.003. The expert panel report states that this HEP is based on a 0.03 probability of errors being introduced by the originator of the analysis, and a 0.1 probability that those errors are not identified and corrected when checking and verifying the analysis. These two HEPs appear to be the result of expert judgment. There appears to be large uncertainty associated with these estimates. The expert panel report estimates an error factor of 30.

G.4.1.4 Evaluation of Model of Consequential LOOP Due to Plant-Centered Factors

Fault-tree analysis was used to build the probabilistic model of the generic conditional probability of LOOP due to plant-centered factors. The computer code SAPHIRE Version 7.17 was used to implement and evaluate the model. The fault tree developed is included in Attachment G-1. The probabilistic model yields the results shown in Table G.4. The uncertainty calculations were conducted using the Latin Hypercube Sampling method with 10,000 samples.

Table G.4 Generic Conditional Probability of LOOP Due to Plant-Centered Factors

Power supply during normal operation	Probability		
	5%	Mean	95%
Main generator through an auxiliary transformer	4.4E-3	1.2E-2	2.8E-2
Offsite power through a start-up transformer	2.3E-3	9.3E-3	2.5E-2

The mean probability of LOOP due to plant-centered factors for the design that is powered during normal operation by the main generator is about 30% higher than for the design powered by offsite power through a start-up transformer because of failures in the first design when the power source is transferred from the main generator to an offsite power source. Examples of failures affecting this transfer include human errors while manipulating the components involved in the transfer, failures of the relays that send a signal for the transfer, and failures of the circuit breakers that have to open and close to power the safety buses from offsite power.

The minimal cut sets (MCSs) of the fault tree are the unique causes of a conditional probability of LOOP due to plant-centered factors. Attachments G-2 and G-3 present the MCSs for plants that are powered during normal operation by the main generator and by offsite power, respectively.

The means of the generic probabilities of LOOP given a LOCA due to plant-centered factors (1.2×10^{-2} and 9.3×10^{-3}) are larger than the point estimate of generic probability of LOOP given a reactor trip (2.3×10^{-3}) that was obtained using the data-driven approach. The reason for this difference is that the events triggered by a LOCA are expected to impose a larger stress on the plant-centered electrical equipment than a reactor trip. An examination of the MCSs of the conditional probability of LOOP due to plant-centered factors (in Attachments G-2 and G-3) indicates that there are two MCSs with a single event, each having a larger probability than the point estimate of generic probability of LOOP given a reactor trip (2.3×10^{-3}):

1. Failure of the startup transformer (probability = 4.1×10^{-3}). This failure is important because the model assumes that its occurrence will cause a LOOP. It is considered that the loading of the ECCS loads after a LOCA may cause incipient failures or degradations of this transformer to become serious enough to make it fail at the time of the loading. This is a failure mode that is not fully tested after a reactor trip because the ECCS loads are not energized in this case. On the other hand, since the primary side of this transformer is normally energized, and some failures can be detected in the control room during normal operation, the failure rate to be used for this transformer should be the one resulting from undetected failures. The use of this failure rate is expected to decrease the probability of failure of the startup transformer. At the time of this study, the failure rate from only undetected failures was not available.

2. Human error in the system voltage analysis (probability = 3.0×10^{-3}). This error can cause failures in the onsite electrical equipment resulting in a LOOP. As mentioned earlier in this section, the estimate of its probability of occurrence was carried out by an expert panel [Ref. G.11], and is considered to have a large uncertainty.

G.4.2 An Evaluation of the Generic Probability of Consequential LOOP Due to Transient Factors

The generic probability of consequential LOOP due to transient factors is considered to be less than the generic probability of consequential LOOP due to plant-centered factors. This conclusion is based on the following observations:

1. There have been more consequential LOOPs due to plant-centered factors than due to grid-related factors. Table G.5 lists all consequential LOOPs following a major ECCS actuation (1986-2001) and following a reactor trip (1984-2001) with their apparent main type of cause (i.e., either plant-centered or grid-related) based on review of the LERs. A review of the main causes of all the consequential LOOPs indicates that eight consequential LOOPs have occurred due to plant-centered factors, and only one due to grid-related factors. This argument, however, is not completely conclusive because most of the data in Table G.5 is from

consequential LOOPs after a reactor trip. As discussed earlier in this report, the impact of a reactor trip on the mechanisms related to a consequential LOOP is somewhat less severe than that resulting from a LOCA.

Table G.5 Consequential LOOPs with Main Type of Cause

Plant	Manufacturer	Date of Event	Docket#/LER#	Main type of cause
Major ECCS Actuation - LOOP Events				
Salem 2	Westinghouse	08/26/86	311/86-007	Plant-centered
Reactor Trip - LOOP Events				
Robinson 2	Westinghouse	01/28/86	261/86-005	Plant-centered
Byron	Westinghouse	10/02/87	455/87-019	Plant-centered
Point Beach 2	Westinghouse	03/29/89	301/89-002	Plant-centered
V. C. Summer	Westinghouse	07/11/89	395/89-012	Grid-related
Dresden 2	General Electric	01/16/90	237/90-002	Plant-centered
Oyster Creek 1	General Electric	08/01/97	219/97010	Plant-centered
Nine Mile Point 2	General Electric	06/24/99	410/99010	Plant-centered
Indian Point 2	Westinghouse	08/31/99	247/99015	Plant-centered

2. The data on LOOP events in NUREG/CR-5496 [Ref. G.14] indicates that there are more LOOP events due to plant-centered failures than due to grid-related failures. NUREG/CR-5496 evaluates LOOP events at nuclear power plants during the period 1980 to 1996, and classifies the events in three categories:
   "Plant-centered events are those in which the design and operational characteristics of the plant itself play the major role in the cause and duration of the loss of offsite power.
   Grid-related events are those in which problems in the offsite power grid cause the [LOOP] and impact its duration."
   Severe-weather events are those resulting from "weather with forceful and non-localized effects."
   The data on LOOP events gathered by NUREG/CR-5496 indicate that there are 65 LOOP events due to plant-centered failures and 6 events due to grid-related failures. In other words, the number of LOOP events due to plant-centered failures is about one order of magnitude

larger than the number of events due to grid-related failures. The data on LOOP events gathered by NUREG/CR-5496 includes events with short duration. In addition, Atwood, et al., state "...Based on this experience, grid instability has not been an important contributor to [LOOP] frequency."

Since the generic probability of consequential LOOP due to transient factors (grid-related failures) is considered to be less than the generic probability of consequential LOOP due to plant-centered factors, and since there is a lack of sufficient data or a model to accurately determine the probability of consequential LOOP due to transient factors, the generic probability of consequential LOOP due to plant-centered factors is used as a bounding value for the probability of consequential LOOP due to transient factors. This approach results in a conservative estimate of the generic probability of consequential LOOP due to transient factors.

The generic probability of consequential LOOP due to plant-centered factors and the generic probability of consequential LOOP due to transient factors are used in the next section to obtain an estimate of the generic probability of a LOOP given a LOCA.

G.5 ESTIMATING THE GENERIC PROBABILITY OF A LOOP GIVEN A LOCA

As discussed at the beginning of the previous section, an approximation of the generic probability of a consequential LOOP given a LOCA can be obtained by adding the probability of LOOP due to plant-centered factors and the probability of a LOOP due to transient factors, as follows:

$$P(\text{LOOP given a LOCA}) \sim P(\text{LOOP due to plant-centered factors}) + P(\text{LOOP due to transient factors}) \quad (5)$$

Since P(LOOP due to plant-centered factors) is a function of the design of the plant, that is, whether the safety buses are supplied by the main generator through a unit transformer, or they are supplied by a preferred offsite power source, two evaluations of P(LOOP given a LOCA) were conducted. Table G.6 presents the resulting generic conditional probabilities of LOOP given a LOCA.

Table G.6 Generic Probability of LOOP Given a LOCA

Power supply during normal operation	Probability		
	5%	Mean	95%
Main generator through an auxiliary transformer	1.1E-2	2.4E-2	4.6E-2
Offsite power through a start-up transformer	8.6E-3	2.1E-2	4.3E-2

The uncertainty bounds of the generic probability of LOOP given a LOCA presented in Table G.6 represent the uncertainty in the estimate of this probability mainly due to data variability. It is considered that the estimate of the generic probability of LOOP given a LOCA presented in Table G.6 also has uncertainty due to incomplete knowledge about all the factors impacting this probability. This kind of uncertainty is called here epistemic uncertainty and is not included in the confidence limits presented in Table G.6.

Due to incomplete knowledge (epistemic uncertainty), several assumptions were made in evaluating the generic probability of consequential LOOP due to plant-centered factors and the generic probability of consequential LOOP due to transient factors. In addition, and with regard to the last probability, as mentioned in Section G.2, there is a concern that inadequate voltage in the offsite system can be caused by deregulation of the electrical industry. Deregulation is a relatively recent factor, and it is expected to keep growing.

Due to the epistemic uncertainty, it is suggested that the generic probabilities of LOOP given a LOCA presented in Table G.6 apply only to plants that have certain “good” characteristics that make them less susceptible to a LOOP given a LOCA. A set of candidate characteristics was developed using the insights gained during the following activities: (1) review of consequential LOOPs after a reactor trip or a major ECCS actuation, (2) discussions with NRC staff, and (3) work carried out to produce NUREG/CR-6538. The characteristics were classified into two groups. Those characteristics that are related to onsite equipment are classified as “plant-centered,” and those that are related to the interaction of the plant with the offsite grid are classified as “external.”

Plant-centered characteristics

1. Onsite voltage correcting means such as automatic tap changer transformer (recent vintage, high reliability, fast responding type) or static volt amperes reactive (VAR) compensator.

2. A plant with electrical, instrumentation, and control equipment that is well-designed, analyzed, operated, and maintained. This applies to equipment located both onsite and offsite (up to the switchyard).

3. Multiple-unit sites maintain their generators in automatic voltage regulate.

4. Loading of ECCS loads to offsite power by sequencing, as opposed to block-loading.

5. On a plant trip, zero or minimal balance of plant loads are transferred to the same transformer winding that feeds AC Class 1E buses.

Items 4 and 5 are not required if item 2 is fulfilled. However, item 2 cannot be verified directly.

As seen from the analysis in Section G.4.1, and as evidenced by operational experience, plants that power their Class 1E buses directly from the offsite source(s) have better reliability of offsite power to the plant than plants that power their Class 1E buses from the main generator (through an auxiliary transformer). For this latter class of plants, the reliability of offsite power to the plant can be improved by providing an automatic transfer to the delayed source of offsite power. With this change, if the automatic transfer to the preferred source of power fails, there would be an automatic transfer to an alternate source of offsite power, unless there is a common failure which affects both automatic transfers.

External characteristics

1. Voltage at the switchyard is kept close to nominal during normal operation of the plant.

2. Plant operators maintain protocols with their grid system operators that alert them to low switchyard voltages on a contingency, such as a plant trip or a LOCA.

A positive answer to the following questions related to deregulation [Ref. G.15]:

3. Has the nuclear plant voltage requirement been determined through rigorous evaluation of all relevant conditions including evaluating the effect of a generator trip?

4. Does the nuclear plant voltage remain constant or rise when the nuclear plant trips under all allowed operating and credible contingency conditions?

5. Has the timing of the plant voltage requirements been coordinated with the power system's ability to provide that voltage post-contingency?

6. Is the geographic scope of real-time data collection, control, and system operations sufficient to address all nuclear plant offsite power reliability concerns?

7. Are real-time data tools, including state estimation and on-line contingency analysis, used by the control area operator, adjacent control areas (if their operation can influence the nuclear plants voltage), and the regional security coordinator?

8. Are system operators well trained in nuclear plant offsite power requirements and methods/procedures to assure adequacy of offsite supply?

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Attachment G-1 Fault Tree to Estimate the Generic Probability of a Consequential LOOP due to Plant-Centered Factors

Attachment G-2 Minimal Cutsets for a Plant Powered by the Main Generator During Normal Operation

Attachment G-3 Minimal Cutsets for a Plant Powered by Offsite Power During Normal Operation