GENERIC PROBABILITY OF A LOOP AFTER A LARGE LOCA: AN EVALUATION

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Acronyms and Abbreviations

BWR	Boiling water reactor
CFR	Code of Federal Regulations
DBA	Design basis accident
ECCS	Emergency core-cooling system
EDG	Emergency diesel generator
GDC	General Design Criterion
HPCS	High pressure core spray
IN	Information Notice
LBLOCA	Large-break LOCA
LER	Licensee event report
LOCA	Loss of coolant accident
LOOP	Loss of offsite power
LPCI	Low-pressure coolant injection mode of the residual heat removal system
LPCS	Low-pressure core spray system
NPP	Nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PRA	Probabilistic risk assessment
PWR	Pressurized water reactor
SIS	Safety injection signal

1 INTRODUCTION

In SECY-01-0133 [NRC, 2001], 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 requirements for emergency core cooling system (ECCS) reliability. Its adoption by licensees would be a voluntary one, and it would include technical requirements to ensure that an ECCS's reliability is commensurate with the frequency of challenges to the system. Attachment 2 of SECY-01-0133 describes the proposed voluntary alternative to the ECCS reliability requirements. It is envisioned that this option would be offered in place of one of the current requirements in General Design Criterion (GDC) 35 of Appendix A to Title 10 of the *Code of Federal Regulations* (CFR) Part 50 indicating that the ECCS's safety function can be accomplished for a design basis accident (DBA) large break loss of coolant accident (LBLOCA) given the operation of the onsite electric power system (assuming offsite power is not available). In practice, this requirement usually was interpreted as demonstrating that the ECCS safety function can be accomplished given a loss of offsite power (LOOP) that occurs simultaneously with the LBLOCA.

If the product of the frequency of LBLOCA and the probability of LOOP given a LBLOCA is considered "very low,"[(1)] it may be possible to remove the current requirement that the ECCS safety function can be accomplished for a LBLOCA with the onsite electric power system operational (assuming offsite power is unavailable). An U.S. Nuclear Regulatory Commission (NRC) report [Thadani, 2002] identified two approaches for accomplishing a risk-informed alternative to GDC 35; a plant-specific approach, and a generic one. Generic means one applicable to the entire population of U.S. nuclear plants, or to a large group of them. The objective of this report is to assess the generic probability of a LOOP given a LBLOCA to support removing this requirement. Appendix D of the NRC report [Thadani, 2002] describes a method for estimating the plant-specific probability.

Martinez-Guridi et al [1997] introduced the concept of a consequential LOOP, i.e., a LOOP that occurs as a consequence of a LOCA, in NUREG/CR-6538. This document provided an initial estimate of the generic probability of this event. Subsequently, the estimate was updated and included in Appendix G of an NRC report [Thadani, 2002]. The work presented herein further updates the approach and results discussed in that appendix.

Section 2 describes the causes of a LOOP after a LOCA. Section 3 discusses an approach to evaluate the generic probability of LOOP given a LBLOCA, and obtains an estimate of this probability. Finally, Section 4 considers the applicability of the estimated probability for risk-informed applications.

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[1] A discussion of what frequency is considered "very low" is beyond the scope of this work.

2 CAUSES OF LOOP AFTER A LBLOCA

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 DBA.

However, an operational event shows that a LOOP has occurred after an event similar to a LOCA. Thus, in 1986, Salem Generating Station Unit 2 had a LOOP after actuation of the ECCS (and a reactor trip). Additional electrical loads that were added to the Salem Station electrical distribution system after a transient study was completed in 1981 contributed to this LOOP. At the time they were added, a static analysis of their effect on the system demonstrated that the system was more than adequate to handle the additional loads. However, the 1981 transient analysis for higher startup currents had not been updated to account for additional loads.

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

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's 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 it to the offsite transmission-system grid.

3. Loading of safety loads to Class 1E buses[(2)]. The pumps of the ECCS are started and aligned. The AC-powered ECCS loads are powered from the Class 1E buses that, 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 demand electric power from this grid to feed safety- and non-safety-loads. Starting these loads requires a motor-starting (inrush) current that, in turn, can induce undervoltage at the Class 1E buses. Thus, a LOCA can cause voltage instability in the offsite transmission-system grid because of the combined effect of losing electric-power generation and demanding electric power for safety and non-safety loads. This instability can downgrade voltage at the unit's switchyard, thereby actuating degraded voltage protection (relays) which then disconnects the Class 1E buses from the offsite grid. These buses subsequently are powered by the onsite emergency AC power sources, usually the EDGs.

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

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

be exacerbated by inadequate or degraded voltage conditions in the offsite transmission-system grid. NRC Information Notice 2000-06 [NRC, 2000] 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. It identifies several factors that could entail inadequate offsite voltages, such as line outages, high system demand, and unavailability of other local voltage support. More recently, NRC Generic Letter 2006-02 [NRC, 2006] discussed issues of grid stability and offsite power.

Summarizing, a LOOP may result as a consequence of a LOCA due to the combined effect of losing electric-power generation and demanding electric power for safety and non-safety loads; accordingly, it is called a consequential LOOP. Also, the LOOP does not occur simultaneously with the LOCA; rather, some time elapses during the subsequent electrical disturbance. For this reason, it also is called a delayed LOOP.

3 ESTIMATING THE GENERIC PROBABILITY OF A LOOP GIVEN A LARGE LOCA

The approach we used to assess the probability of a LOOP after an LBLOCA consisted of two major steps: 1) search the operational data for events that resemble a LBLOCA, and identify those in which a LOOP occurred as a result of the surrogate LBLOCA, and, 2) use these identified events to obtain a point estimate of this probability and the associated confidence limits.

Since this method samples operational data from the entire population of U.S. nuclear plants, it can be considered a data-driven approach that affords a generic estimate of the probability of a LOOP given a LBLOCA. Accordingly, this generic assessment is considered applicable to this population.

When a large LOCA occurs, the initiation of ECCS loading and the reactor trip are expected to happen very shortly afterwards. The combined effect of the loading of the ECCS loads and the reactor trip could trigger a LOOP. A consequential LOOP is a function of the response of the electrical systems at a plant, and their interactions with the external power grid. Hence, it is not expected to depend on the type of nuclear power plant. Accordingly, the data both for pressurized water reactors (PWRs) and boiling water reactors (BWRs) were considered in obtaining a single estimate of the probability of a consequential LOOP.

Since there have been no operational events of a LBLOCA with a consequential LOOP, it was necessary to identify operational events that match, as closely as possible, such an occurrence. Hence, we sought and identified operational events that can be considered surrogates of LBLOCA. They involve major actuation of the ECCS loads so they cause a reactor trip and, in addition, the loading of the ECCS loads to the safety buses; their combined effect could cause an undervoltage at these buses, ultimately causing a LOOP. We also assessed whether a LOOP had occurred after each surrogate. We assessed the generic probability of a consequential LOOP after these surrogate events using this information.

Subsection 3.1 defines a LOOP due to a LBLOCA and also a surrogate of a LBLOCA. We used these definitions when searching operational data to identify those events in which a surrogate LBLOCA happened and those in which a LOOP occurred due to the surrogate. Subsection 3.2 discusses the collection of operational data, and subsection 3.3 uses the identified events to assess the point estimate of this probability and the associated confidence limits.

3.1 Definitions of surrogate of LBLOCA, and of LOOP due to a LBLOCA

3.1.1 Definition of surrogate of LBLOCA

Since the DBA of concern is a large LOCA, an event that has not happened in operating commercial nuclear power plants, an appropriate surrogate is an event that is similar to such a LOCA. Hence, for an operational event to be considered a surrogate of a LBLOCA, it must fulfill all the following requirements:

1. A reactor trip occurred during the event. At the beginning of the event, and before the trip, the plant was operating at "high" power. For this study, we considered that this was the case when it was producing power at 85% or more of its nominal power because the probabilistic risk assessments (PRAs) for power operation typically assume that the plant is operating at full power.

2. A major ECCS actuation occurred during the event. This actuation involves the loading of several or all of the ECCS equipment to the safety buses. For this study, such actuation had to meet the following requirements:

   2.1 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, were not counted because the electrical load is less than that resulting from a full SIS that would occur after a LBLOCA.

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

3. The major ECCS actuation, such as a full SIS, either caused the reactor trip, or happened within 1 minute afterwards. The requirement that the major ECCS actuation occurs within this period is because the electrical disturbance to the onsite and offsite systems is expected to be greater when these two events happen close in time.

Since we are searching for surrogate LBLOCA events that may cause a consequential LOOP, an additional requirement is that no LOOP occurred before the major ECCS actuation. Should that have happened, then this event is not included in the surrogate LBLOCA events because the associated ECCS actuation could not have caused the LOOP.

In addition, in some cases the LER did not contain the information required to assess whether an event met these requirements. For example, some LERs clearly stated that a major ECCS actuation, such as a full SIS, had occurred during the event, but did not stipulate its timing. The LERs that lacked such essential information were not included in the database of surrogate LBLOCA events because we could not evaluate their compliance with the requirements.

3.1.2 Definition of LOOP due to a LBLOCA

A consequential LOOP due to a LBLOCA is defined as follows: a LOOP resulting from the occurrence of a LBLOCA (and associated reactor trip), and happening when the Class 1E buses are disconnected from the offsite transmission-system grid, so that they no longer can 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 involving several, but not all Class 1E buses 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.

A LBLOCA damages the core in a few minutes if not mitigated promptly. Hence, for the purpose of analyzing operational data, an event is considered to include a LOOP as long as the Class 1E buses are disconnected from offsite power, even though this source of power may actually be available, or it is recovered.

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 them, while the other has offsite power available. This type of event here is named a partial LOOP, and it has the potential to become a complete LOOP (i.e., loss of offsite power to both emergency buses). One possible way 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. However, the contribution of partial LOOPs is not expected to be significant in assessing the probability of a consequential LOOP; accordingly, they were not included in this evaluation.

The consequential LOOPs identified in the operational experience are due to the impact of the LBLOCA, such as the electrical disturbance triggered by the generator trip. A LOOP may also result from “external” events such as earthquakes and fires; an analysis of the impact of “external” events on the probability of consequential LOOP was outside the scope of this work.

3.2 Collection of operational data

The source of operational data was the LERs in the NRC's computerized "LER Search System." We searched this system for LERs meeting the requirements to identify surrogate LBLOCA events and LOOPs after such events. Our search of LERs covered the period 1/1/1986 to 7/31/2006, i.e., about the last twenty years and a half of operational experience of all commercial nuclear power plants.

This review yielded the following results:

Number of surrogate LBLOCA events = 49 events.

Number of consequential LOOPs after a surrogate LBLOCA event = 1 event.

Appendix A contains the database of the 49 LERs documenting events that were considered LBLOCA surrogates, i.e., those that met all the requirements described above.

The consequential LOOP occurred at the Salem unit 2 on August 26, 1986, and is documented in LER number 3111986007. Even though this event happened in 1986, i.e., at the beginning of the period evaluated, it is considered relevant for evaluating the probability of a consequential LOOP due to a LBLOCA because its mechanism of occurrence still is applicable to current nuclear power plants. This mechanism was that additional electrical loads were added to the electrical distribution system, but the transient analysis for higher startup currents was not updated to account for the additional loads. When the surrogate LBLOCA occurred, the electrical distribution system could not handle these loads appropriately, thus resulting in a LOOP.

3.3 Assessing the probability of LOOP given a LBLOCA

The point estimate and uncertainty due to variability in the data were assessed using a binomial distribution. This distribution was chosen 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 it.

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.

Using equations (1) through (3), the following results were obtained for the generic probability of LOOP given a LBLOCA:

Point estimate = 2.0E-2.

95% confidence limit = 9.3E-2.

5% confidence limit = 1.1E-3.

4 USING THE ESTIMATED PROBABILITY FOR RISK-INFORMED APPLICATIONS

The estimate of the generic probability of LOOP given a LBLOCA that we obtained in this study is applicable in any PRA of internal events at full power for risk-informed applications. As stated earlier, our specific objective was to assess this generic probability to support removing the current regulatory requirement that the ECCS safety function can be accomplished for a LBLOCA given onsite electric power system operation (assuming offsite power is not available). This section discusses the applicability of this probability to regulatory applications.

Several aspects of the assessment of this generic probability are relevant to this discussion:

1. Generic means an assessment that would apply to the entire population of nuclear plants in the United States. Using the binomial distribution, the point estimate of the generic probability of LOOP given a LBLOCA is 2.0E-2. A plant with good design and operation features and that is connected to a robust offsite grid is likely to be closer to the lower confidence limit (1.1E-3), while one with poor features and/or connected to a weak offsite grid is likely to be closer to the upper limit (9.3E-2).

2. Figure 1 presents a graph of the number of surrogate LBLOCA events per year versus time. The year 2006 was not included because data is available for only about half of this year.

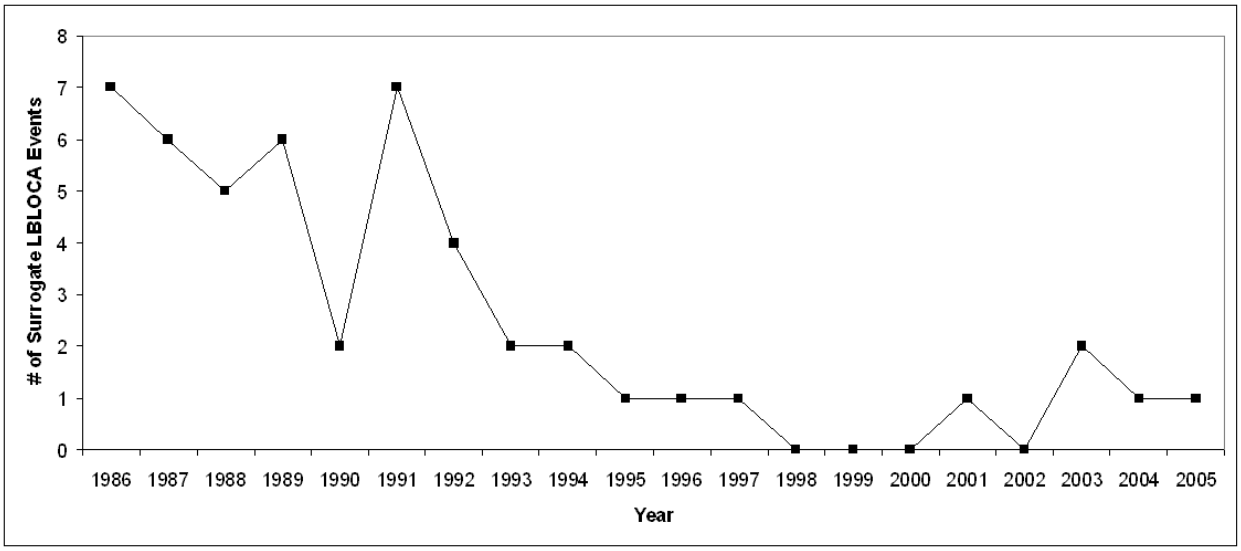

Figure 1 Number of surrogate LBLOCA events per year versus time

This graph indicates that the number of surrogate events per year was relatively high during the second half of the 80s and the beginning of the 90s, but since then has decreased. On average, there is about one surrogate event per year from 1993 to 2005. Hence, this graph suggests that there was an improvement in the performance of the industry in reducing the number of surrogate LBLOCA events per year. On the other hand, the data also indicate that most of the surrogate LBLOCA events happened before the middle 90s; in fact, almost 86% of the events occurred from the beginning of 1986 to the end of 1995.

3. The grid stability and offsite power issues mentioned in Section 2 may change over time. In addition, a plant's design and operation of its electrical systems evolve to some extent, e.g., to accommodate changes in the loads powered by specific electric buses. For these reasons, and related to the previous point, the estimated probability may not be used as a predictive tool of future probability.

These three points discuss relevant sources of uncertainty related to estimating the generic probability of LOOP given a LBLOCA. Due to these uncertainties, it does not appear judicious to use the point estimate of the probability because it may not be representative of the current probability of each plant throughout the country. Therefore, if the generic probability of LOOP given a LBLOCA will be used for changing regulatory requirements, it is advisable to establish some upper confidence limit, such as the 95% limit, for this probability.

In addition, we recommend evaluating periodically the generic probability of LOOP given a LBLOCA because it would help to determine if the considerations used to relax a regulatory requirement, such as the value of this probability, are still valid after this relaxation is granted. Such an evaluation could be incorporated into a performance-based monitoring program, such as the one described in Regulatory Guide 1.174 [NRC, 2002].

REFERENCES

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2. U.S. Nuclear Regulatory Commission (NRC), SECY-01-0133, “Status Report on Study of Risk-informed Changes to The Technical Requirements of 10 CFR Part 50 (Option 3) and Recommendations on Risk-informed Changes to 10 CFR 50.46 (ECCS Acceptance Criteria),” July 23, 2001.

3. NRC, “NRC Information Notice 2000-06: Offsite Power Voltage Inadequacies,” March 27, 2000.

4. NRC, “NRC Generic Letter 2006-02: Grid Reliability and the Impact on Plant Risk and the Operability of Offsite Power,” February 1, 2006.

5. NRC, “Regulatory Guide 1.174, An Approach for Using Probabilistic Risk Assessment In Risk-Informed Decisions On Plant-Specific changes to the Licensing Basis,” Rev. 1, November 2002.

6. Memorandum from Ashok C. Thadani, Director, Office of Nuclear Regulatory Research to Samuel J Collins, Director, Office of Nuclear Reactor Regulation, “Transmittal of Technical Work to Support Possible Rulemaking on a Risk-Informed Alternative to 10 CFR 50.46/GDC 35”, July 31, 2002.

APPENDIX A LBLOCA SURROGATES

Table A-1 of this appendix presents the database of the 49 LERs documenting events that were classified as LBLOCA surrogates. All the events happened in PWRs because, as discussed in Section 3, one of the requirements for an event to be classified as LBLOCA surrogate is that the event included a major ECCS actuation, i.e., a full SIS for a PWR. An ECCS actuation was identified in several LERs of BWRs, but it was not considered major in most cases mainly because it did not involve the starting (loading) of low-pressure ECCSs.

The column with the heading “Power Level (%)” is the percentage of the nominal power produced by a nuclear power plant at the start of an event.

Table A-1 LBLOCA Surrogates

Plant Name	Event Date	LER Number	Power Level (%)
Turkey Point 3	2/11/1986	2501986006	100
Diablo Canyon 1	3/14/1986	2751986004	98
North Anna 1	3/26/1986	3381986006	100
Prairie Island 2	5/19/1986	3061986001	100
Salem 2	8/26/1986	3111986007	100
Indian Point 2	9/16/1986	2471986031	100
Palo Verde 2	9/22/1986	5291986046	100
Wolf Creek	1/8/1987	4821987002	100
Indian Point 3	2/11/1987	2861987002	100
Diablo Canyon 2	3/21/1987	3231987003	100
Indian Point 3	4/17/1987	2861987004	100
North Anna 1	7/15/1987	3381987017	100
Surry 1	9/20/1987	2801987024	100
Surry 2	3/27/1988	2811988004	100
Summer	5/12/1988	3951988006	100
Surry 2	5/16/1988	2811988010	100
Beaver Valley 1	6/7/1988	3341988007	100
Arkansas Nuclear One 2	12/1/1988	3681988020	100
Palo Verde 2	2/16/1989	5291989003	100
Catawba 2	2/21/1989	4141989003	94
Palo Verde 3	3/3/1989	5301989001	98
Catawba 1	3/5/1989	4131989008	100
Beaver Valley 1	5/18/1989	3341989007	90
Diablo Canyon 1	10/6/1989	2751989009	100
Byron 2	1/18/1990	4551990001	99
Diablo Canyon 1	12/24/1990	2751990017	88
Point Beach 1	6/29/1991	2661991008	100
Surry 2	8/2/1991	2811991007	92
North Anna 1	8/8/1991	3381991017	100
Waterford 3	8/25/1991	3821991019	100
Palo Verde 1	10/27/1991	5281991010	100
Palo Verde 3	10/27/1991	5281991010	100
Waterford 3	11/17/1991	3821991022	100

Plant Name	Event Date	LER Number	Power Level (%)
Indian Point 2	1/27/1992	2471992002	100
North Anna 2	8/6/1992	3391992007	100
Sequoyah 2	8/21/1992	3281992011	100
Palo Verde 2	11/13/1992	5291992006	100
Beaver Valley 2	1/30/1993	4121993002	92
Palo Verde 2	3/14/1993	5291993001	98
Vogtle 1	2/2/1994	4241994001	100
Fort Calhoun	2/11/1994	2851994001	100
Harris	11/5/1995	4001995011	100
Comanche Peak 1	1/17/1996	4451996001	100
Diablo Canyon 2	10/24/1997	3231997005	100
Salem 2	12/31/2001	3112001008	100
Beaver Valley 1	2/24/2003	3342003001	100
Palo Verde 2	7/29/2003	5292003001	98
Vogtle 2	11/20/2004	4252004004	100
Millstone 3	4/17/2005	4232005002	100