Relay Chatter and Operator Response After a Large Earthquake

An Improved PRA Methodology With Case Studies

Manuscript Completed: June 1987
Date Published: August 1987

Prepared by
R. J. Budnitz, H. E. Lambert, E. E. Hill

Future Resources Associates, Inc.
Berkeley, CA 94704

Prepared for
Division of Reactor Accident Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN D1556
ABSTRACT

The purpose of this project has been to develop and demonstrate improvements in the PRA methodology used for analyzing earthquake-induced accidents at nuclear power reactors. Specifically, the project addresses methodological weaknesses in the PRA systems analysis used for studying post-earthquake relay chatter and for quantifying human response under high stress. An improved PRA methodology for relay-chatter analysis is developed, and its use is demonstrated through analysis of the Zion-1 and LaSalle-2 reactors as case studies. This demonstration analysis is intended to show that the methodology can be applied in actual cases, and the numerical values of core-damage frequency are not realistic. The analysis relies on SSMRP-based methodologies and data bases. For both Zion-1 and LaSalle-2, assuming that loss of offsite power (LOSP) occurs after a large earthquake and that there are no operator recovery actions, the analysis finds very many combinations (Boolean minimal cut sets) involving chatter of three or four relays and/or pressure switch contacts. The analysis finds that the number of min-cut-set combinations is so large that there is a very high likelihood (of the order of unity) that at least one combination will occur after earthquake-caused LOSP. This conclusion depends in detail on the fragility curves and response assumptions used for chatter. Core-damage frequencies are calculated, but they are probably pessimistic because assuming zero credit for operator recovery is pessimistic. The project has also developed an improved PRA methodology for quantifying operator error under high-stress conditions such as after a large earthquake. Single-operator and multiple-operator error rates are developed, and a case study involving an 8-step procedure (establishing feed-and-bleed in a PWR after an earthquake-initiated accident) is used to demonstrate the methodology. High-stress error rates are found to be significantly larger than those for no stress, but smaller than found using methodologies developed by earlier investigators.
TABLE OF CONTENTS

1.0 INTRODUCTION AND BACKGROUND

1.1 Project Scope
1.2 Background of the Project
1.3 Earlier Studies
1.4 Applicability of the Project Results
1.5 Format of This Report

2.0 RELAY AND CONTACT CHATTER: INTRODUCTION AND METHODOLOGY

2.1 General Approach
2.2 Previous Work
2.3 Scope of the Analysis Presented Here
2.4 Assumptions Made in Generating the Accident Sequences
2.5 Computational Approach
2.6 Fragility Values for the Chatter and LOSP Failure Modes
2.7 Earthquake Hazard Curves for the Zion and LaSalle Sites

3.0 DETAILS OF THE LIMITED-SCOPE SEISMIC PRA FOR ZION-1

3.1 Zion Electric Power System
3.2 Failure Mode Analysis for Chattering
3.3 Core-Damage Sequences for Zion-1
3.4 Generation of Min Cut Sets
3.5 Probabilistic Results
3.6 Sensitivity Studies
3.7 Operator Recovery Actions at Zion-1

4.0 DETAILS OF THE LIMITED-SCOPE SEISMIC PRA FOR LASALLE-2

4.1 Systems Analysis
4.2 Failure Mode Analysis for Chattering
4.3 LaSalle-2 Core Damage Sequence
4.4 Generation of Min Cut Sets
4.5 Probabilistic Results
4.6 Sensitivity Studies
4.7 Operator Recovery Actions at LaSalle-2
5.0 HUMAN RELIABILITY ANALYSIS UNDER HIGH-STRESS CONDITIONS

5.1 Introduction
5.2 Our Original Approach to the Problem
5.3 Development of a Model for Generating HEPs for High Stress Conditions
5.4 Results of Applying the Methodology
5.5 Conclusions and Insights

6.0 SUMMARY OF MAJOR TECHNICAL INSIGHTS

6.1 Introduction
6.2 Plant-Specific Insights for Zion-1: Vulnerabilities From Relay Chatter
6.3 Plant-Specific Insights for LaSalle-2: Vulnerabilities From Relay and Contact Chatter
6.4 Generic Insights: Analyzing Seismic Vulnerabilities From Relay and Contact Chatter
6.5 Generic Insights: Analyzing Human Reliability Under High-Stress Conditions

7.0 RESEARCH NEEDS EMERGING FROM THIS PROJECT

8.0 ACKNOWLEDGEMENTS

9.0 REFERENCES

APPENDIX A: Description of the X-Y Circuit Breaker Scheme for 4-kV Switchgear

APPENDIX B: Human Reliability Analysis Under High-Stress Conditions: Additional Figures and Tables

APPENDIX C: Accident Sequence Fault Trees for Zion-1

APPENDIX D: Accident Sequence Fault Trees for LaSalle-2

SECTION 1
INTRODUCTION AND BACKGROUND

1.1 Project Scope

The scope of this project has been a study of the following two issues:

- A detailed examination of the effect of earthquake-initiated chattering of relays and pressure switch contacts at two reactor plants: Zion-1 and LaSalle-2; this work has involved developing an improved PRA methodology for describing earthquake-induced relay chattering, contact closing and opening, circuit-breaker tripping, and related electrical and control circuit behavior.

- Developing an improved PRA-based methodology for describing how reactor operators respond under high-stress post-earthquake conditions, and applying this new methodology to a realistic case study example.

The relay-chatter and circuit-breaker study has used two specific reactor facilities as case studies, the Zion-1 and LaSalle-2 reactor stations owned and operated by Commonwealth Edison Company. Zion-1 is a Westinghouse PWR and LaSalle-2 is a General Electric BWR. Each has a twin unit on the same site.

The high-stress operator-response study has used a typical and generic post-earthquake operator-response problem --- the need to establish feed-and-bleed heat removal following loss of both normal and auxiliary feedwater to the steam generators in a PWR --- as a case study. (Originally, the project had planned to perform a detailed task analysis of this and other procedures for the Zion-1 station, but the generic feed-and-bleed study was performed instead due to inaccessibility to the Zion-1 control room or its simulator.)

For the part of the project dealing with earthquake-induced chattering of relays and pressure switches, the following questions, posed in laymen's terms, capture the objectives of the project:
1. Given an earthquake large enough to cause both loss-of-offsite power and chattering of relays and pressure switch contacts, and assuming no operator recovery actions, are there any combinations of relays and pressure switch contacts whose chattering, if they were to occur, could lead to a core-damage accident?

2. If so, what are these combinations of relays and pressure switches, and how many combinations are there?

3. What is the calculated overall core-damage frequency from this type of earthquake-initiated accident, assuming no operator recovery?

4. What is the effect on core-damage frequency of changes in the assumed fragility curves of relay chatter and pressure switch chatter, such as increasing the median capacity and/or decreasing the standard deviation?

5. What are the types and sizes of the uncertainties in this analysis?

For the part of the project dealing with earthquake-induced high stress for the operators, the following questions, in laymen's terms, capture the objectives of the project:

1. Under very high-stress (life-threatening) situations such as would occur after a major earthquake, what is the probability of human error, and how does it depend on factors such as the number of operators present?

2. What is the probability of error in executing an actual procedure (in our case study, an 8-step procedure to establish feed-and-bleed), and how does it depend on stress level?

1.2 Background of the Project

The idea for this project originated during the review of the state-of-the-art of PRA that was performed in early 1983 as part of NRC's "PRA Reference Document", report NUREG-1050 (Ref. NRC, 1984). The Principal Investigator on this project, R. J. Budnitz, was one of the team of NUREG-1050 authors, and carried out the NUREG-1050 review of external initiators. During this review, he became aware of certain specific weaknesses in the state-of-the-art of seismic PRA.
These weaknesses were the subject of a proposal to NRC in the spring of 1983 for a "Phase I project" under the auspices of NRC's "Small Business Innovation Research Program". The proposal was successful, and a 6-month scoping study of these issues in 1983-1984 produced a report (Ref. Budnitz and Lambert, 1984) that identified and analyzed the following weaknesses in the methodology of seismic PRA:

- seismic PRA methodology inadequately treats electrical and control system failures, such as earthquake-induced problems with circuit breakers, relays, and related equipment;
- seismic PRA methodology inadequately treats the possibility that operator performance after a large earthquake may be degraded due to higher than normal post-accident stress;
- seismic PRA methodology inadequately treats the issue of how failures of equipment located inside a structure are affected by the failure of the structure itself; specifically, the usual assumption in past PRAs has been that structural failure of a building automatically implies failure of all equipment within.

The identification of these three methodological weaknesses in seismic PRA led to the current project, which is a "Phase II project" under NRC's SBIR Program. In the current project, begun in the fall of 1984, we have examined the first two of the three weaknesses cited just above. Although there have been methodological advances in the intervening period, the weaknesses examined here still exist in current seismic PRAs.

1.3 Earlier Studies

1.3.1 Earlier Work on Relay Chatter

Other papers and research reports have identified various methodological weaknesses in seismic PRA methodology. An example is the review of seismic PRA accomplished as part of NRC's "seismic margins program" (Ref. Budnitz et al., 1986), which identified various inadequacies, and focussed attention on relay chattering and circuit-breaker tripping. Similar findings were reported by Budnitz (Ref. Budnitz, 1984) in his article reviewing the state-of-the-art based on the NUREG-1050 work. Conclusions along these same lines have been published in review papers under EPRI sponsorship by Ravindra, Kennedy, and their collaborators (Ref. Ravindra, 1984; Ravindra, 1985).
Relay chatter was not treated at all in the three important early utility-sponsored full-scope seismic PRAs, the Zion PRA (Ref. ZPSS, 1981), the Indian Point PRA (Ref. IPPSS, 1983), and the Limerick PRA (Ref. Limerick, 1981; Limerick, 1983), and of these three only the Limerick PRA made an effort to treat high-stress operator errors under earthquake conditions as a separate issue. The NRC-sponsored "Seismic Safety Margins Research Program" (SSMRP) at Lawrence Livermore National Laboratory produced a series of reports on PRA methodology that tried to cover the relay fragility topic in a preliminary way (Ref. SSMRP, 1981), and the SSMRP study of the Zion reactor (Ref. SSMRP, 1983) provided additional insights, but the assumption was made that relay chatter was always recoverable (which is equivalent to omitting its treatment entirely in the analysis). More recently, uncertainties in our understanding of the fragilities of relays and similar devices have been pointed out by the industry-sponsored SQUG effort (unpublished) and the NRC-sponsored work at LLNL (Ref. Holman et al., 1986) and Brookhaven National Laboratory (Ref. Bandyopadhyay et al., 1986; Hofmayer et al., 1986).

Over the last five years, a large number of plant-specific seismic PRAs have been done, most of which have treated the key issues of this project in only a cursory way. In the last two years, three ongoing projects have all identified these same methodological issues. These are the NRC-sponsored RMIEP project studying the LaSalle station, the NRC-sponsored seismic-margin trial review of Maine Yankee, and the EPRI-sponsored seismic margin review of Catawba. None of these three projects has been completed as of the writing of this report.

Although much effort is underway to develop and use seismic-PRA methodology, until this project there has not been any systematic and detailed published examination, in the context of a realistic PRA-based analysis, of the extent to which relay-chatter, breaker-trip, and related problems could affect the ability of a nuclear plant to shut down safely after a very large earthquake. Our work on this project is reported in Sections 2, 3, and 4 of this report.

Although this analysis is more realistic than earlier seismic PRAs, the authors acknowledge that its realism is limited in some key areas, most importantly because the information used about fragilities is generic and because a realistic analysis has not been done of how operator recovery actions could mitigate the accident sequences identified.
1.3.2 Earlier Work on Human Reliability Analysis Under High-Stress Conditions

On the issue of human high-stress response, there have been a few attempts to provide a PRA-type methodology for describing how operators might respond under high-stress conditions. The most well-known of these is the work of Swain as part of WASH-1400, which led later to the very important and influential report by Swain and Guttmann (Ref. Swain and Guttmann, 1983). Swain's work served almost as a "bible" for PRA human-factors analysts for many years. More recent studies by Bell and Swain (Ref. Bell, 1983), Hall et al. (Ref. Hall, 1982.), and Hannaman and Spurgin (Ref. Hannaman, 1984) have examined the high-stress issue further.

However, the work reported in Section 5 of this report seems to be the first attempt at a specific examination of how operators might respond under high-stress post-earthquake conditions.

1.4 Applicability of the Project Results

By a conscious decision, the project's work has focused in great detail on only a few specific technical issues. Later in this report (Section 6), the authors will discuss the extent to which the project's conclusions can be applied more generically. As a preview and summary of that discussion, it is useful to state here the authors' belief that the specific conclusions are probably not universally applicable, but that the methodologies developed and demonstrated surely are of wider applicability, as are the broader lessons learned.

It is important to note that this study has placed emphasis on the detail of the operation of circuit breakers, motor-operated valves, and signal actuation systems and the effect of relay and pressure switch chatter on these systems and components. Past seismic PRAs have typically given this matter only cursory treatment, if any. Literally thousands of circuits and drawings were analyzed for Zion-1 and LaSalle-2 to generate the fault trees presented here. Due to the complexity of the problem, we do not claim that we have included all possible failure modes caused by chattering.
1.5 Format of This Report

The four sections that follow this introduction contain the new research work in this report. The next three sections deal with the systems analysis of relay chatter after an earthquake: Section 2 covers our general approach, while Sections 3 and 4 describe our plant-specific studies of Zion-1 and LaSalle-2. Following these three sections comes Section 5 dealing with our work on human reliability analysis under high stress. Finally, Sections 6 and 7 contain our summary of technical insights and our recommendations for further research.

The main report is supplemented by several appendices containing back-up material. This appendix material presents in more detail some of the technical work and some of the background information that underlies the research reported in the main report.
SECTION 2

RELAY AND CONTACT CHATTER: INTRODUCTION TO METHODOLOGY

2.1 General Approach

The next three sections of this report (Sections 2, 3, and 4) describe limited-scope seismic Probabilistic Risk Assessments (PRAs) for the Zion Nuclear Power Station (ZNPS), Unit 1 and for the LaSalle County Station (LSCS), Unit 2. The phrase "limited scope" means that the PRA analyses have been limited to consideration of seismically-induced failures of relays, circuit breakers, instrumentation, control, and electrical systems. The results of these limited-scope PRAs are calculated frequencies of a core-damage accident. However, these frequencies are calculated based on several assumptions (see below) that are probably not entirely realistic, and hence the numerical values should not be interpreted as representing a realistic aspect of the risk profiles for either Zion-1 or LaSalle-2.

Section 2 (this section) describes that portion of the seismic risk assessment methodology that is common to both plants. Sections 3 (Zion) and 4 (LaSalle) will treat the plant-specific aspects, pertaining to anticipated plant behavior during a large earthquake, failure mode analysis, and accident sequence generation and analysis. Our discussion here will concentrate on generic methodological aspects and on technical issues that are common to Zion-1 and LaSalle-2.

2.2 Previous Work

As discussed in Section 1, a few previous publications have addressed seismically-induced failure modes. The most significant of this previous work for our purposes includes the following:

- The Seismic Safety Margins Research Program publications, including both the SSMRP methodological reports (Ref. SSMRP, 1981) and the SSMRP study of Zion-1 (Ref. SSMRP, 1983)
o The report for the first phase of the current project, entitled "Uncertainties in the Systems Analysis Part of Seismic PRA, Phase I Final Report" (Ref. Budnitz and Lambert, 1984)

o The study by Lambert for SSMRP on earthquake-induced electrical failures at Zion (Ref. Lambert, 1984).

These studies focused on methodology, and their applications all focused on seismically-induced loss-of-offsite-power (LOSP) transients at Zion-1. The research by Lambert for SSMRP (Ref. Lambert, 1984) arose as a result of the internal LLNL review of the Zion seismic PRA (Ref. SSMRP, 1983). Numerous unresolved technical issues were raised but not resolved during this earlier study. Many of these issues are being addressed here.

During a postulated strong-motion earthquake at Zion or LaSalle, numerous circuit breakers important to plant safety are expected to open and/or close during the strong earthquake motion. Here we will study (i) the operation of circuit breakers and (ii) potential electrical component failures during a major earthquake.

When the SSMRP conducted its seismic risk assessment of Zion (Ref. SSMRP, 1983), the study team assumed that circuit breakers would fail in the open-circuit position or would trip open as the result of mechanical failure modes, such as jarring the release trip mechanism, or physically removing the breaker from the cubicle resulting in an open circuit. The SSMRP study team also assumed that relay chatter would not affect circuit breaker operation, even though control circuits for circuit breakers contain numerous trip contacts that could cause breakers to trip open if there were chattering of these contacts.

We now know, as a result of this study, that these assumptions are not necessarily correct. Potential seismically-induced circuit breaker failure modes due to relay chatter were uncovered during the SSMRP study (Ref. Lambert, 1984). These failure modes include:

- circuit breaker failure to close;
- circuit breaker tripping open inadvertently;
- circuit breaker failure to reclose after it trips open.

The causes of these failure modes, which will be discussed in detail below in Sections 3.2 (Zion) and 4.2 (LaSalle), include:
The reason for the concern about chattering is, of course, its relatively low seismic fragility. As will be discussed below in Section 2.6, the relay chatter mode has a much lower seismic fragility than does the circuit-breaker-trip mode.

### 2.3 Scope of the Analysis Presented Here

In this project, limited-scope seismic PRAs have been conducted for Zion-1 and LaSalle-2. The limited-scope seismic PRAs consist of studying the effects of seismically-induced failure modes of relays, circuit breakers, motor-operated valves, instrumentation, control systems, and electrical systems. Specifically, the effects of chattering of relay contacts and pressure switch contacts during a major earthquake have been studied. Special emphasis has been placed on identifying circuits that could seal-in due to the effect of relay and contact chatter.

In addition, chattering of protective relay contacts can be important. Protective relays sense fault conditions such as overcurrent, undervoltage, reverse current and overvoltage. These relays work by sensing some parameter on an electrical bus, and actuating other relays such as lockout relays if the parameter does not agree with a standard or expected value.

This study focuses on the loss of offsite power (LOSP) accident sequence that is expected to occur following a strong motion earthquake due to the low median fragility value of ceramic insulators in the electrical grid. In the following discussion, we will briefly describe how AC power is restored using the auxiliary power system (the diesel generators). For the moment, we will assume that following LOSP no other failures occur such as a pipe break of the primary coolant boundary. We will also assume that the plant is at full power before LOSP.

When LOSP occurs, undervoltage is sensed on critical engineered safety feature (ESF) buses. Circuit breakers to loads that are normally operating will trip. Diesel generators, which serve as the auxiliary source of AC power, will start. When each diesel generator is at proper speed and voltage, its diesel generator circuit breaker should close (approximately 10 seconds to 15
seconds following LOSP) and supply 4.16 kV power to the ESF buses.

In the case of Zion-1, circuit breakers to important loads will close sequentially in time by the use of a load sequencer. These loads, which are important for shutting down the plant safely, include component cooling water pumps, service water pumps, and auxiliary feedwater pumps.

It is expected that the circuit breakers at Zion will operate during the period of strong motion, which we assume will last for at least 20 seconds.

In the case of LaSalle-2, circuit breakers to ESF loads are not expected to operate during strong motion. This is because ESF loads necessary for primary coolant makeup do not start until primary coolant level is boiled off to a specific set point (called "level 2"), after which two key systems are started: the reactor core isolation cooling system (RCIC) and the high pressure core spray system (HPCS). Given that no makeup systems are operating, boiloff to level 2 is expected to occur at LaSalle-2 by about 10 minutes after LOSP.

Both Zion-1 and LaSalle-2 have three ESF electrical divisions. One electrical division for each plant has a swing diesel shared by the twin unit (Zion-2 or LaSalle-1). In addition, each plant has a steam-driven pump that is used either for primary coolant makeup or for heat removal. At Zion this is the auxiliary feedwater pump, and at LaSalle it is the RCIC pump. Neither of these pumps has a dependency on AC power in the short term, except that the auxiliary feedwater pump at Zion-1 depends upon service water for cooling. The Zion service water pumps are supplied by 4.16 kV power.

Failure modes of these systems caused by chatter are described below in Sections 3.2 (Zion-1) and 4.2 (LaSalle-2). These systems are important because, for the accident sequences considered in this analysis, their operation or failure determines whether or not the sequences are safely terminated.

For seal-in circuits, the assumption was made that a normally closed set of relay contacts would remain closed in the circuit (otherwise the seal-in would drop out.) More generally, if the normal operation of a component leads to the fault event of interest, it was assumed that the component would operate normally. This implies that complementary logic was not used in the fault trees generated in this study. Based on the work of Holman (Ref. Holman et al., 1986), this assumption is conservative because Holman observed that contacts to normally closed relays will open due to chatter at a lower acceleration level than will contacts to normally open relays. This observation applies to armature-type relays that are unenergized (the type of relay that was generally encountered in this study at both Zion-1 and LaSalle-2). To assess the conservatism of this assumption, fault trees would need to be
generated with complementary logic, which was beyond the scope of this project.

2.4 Assumptions Made in Generating the Accident Sequences

Simplified fault trees have been used to generate various accident sequences that describe how a core-damage accident can occur. The following assumptions have been made for both plants in generating these sequences:

- we assume that loss of offsite power (LOSP) occurs with a certain probability due to earthquake-caused failure of the electrical grid's ceramic insulators, because their seismic capacity is generally much lower than that of any other components and structures; we use an SSMRP-derived fragility function for LOSP which is convoluted with a response function (see Sections 2.5 and 2.6 below);

- LOSP is the only earthquake-induced initiating event that we consider in this analysis; we assume that LOSP occurs whenever the ceramic insulators are damaged by the earthquake (see Section 2.6);

- we assume that the reactor protection system will shut down the fission chain reaction and keep it down after the earthquake;

- we assume that offsite power is not recovered --- therefore, the main feedwater system is not recovered and is unavailable for coolant makeup and/or heat removal;

- we pessimistically assume that there is no operator action, and in particular that operators do not reset circuit breakers and relays; thus no credit is taken for operator actions in the analysis;

- we assume that DC power is always available after the earthquake;

- we assume that the SSMRP "hazard curves" used in this analysis are correct (see Section 2.7 below);

- we consider only failure modes due to chatter of relay and pressure switch contacts.

It is important to note that we assume that there is no other transient event besides LOSP when the strong-motion earthquake occurs. For example, random pipe breaks, valve mechanical failures, and structural failures are not considered. Furthermore, as mentioned we assume that LOSP does not occur
with 100% probability: a seismic fragility function has been assigned for LOSP (see Section 2.6).

In the jargon of PRA, the "basic events" (that is, events or faults that are not developed further in the analysis) are limited to four generic types: loss of offsite power; swing diesel alignment to one or the other unit; chattering of relay contacts; and chattering of pressure switch contacts.

Another crucial assumption concerns operator recovery. Past seismic PRAs have assumed that the operator can always recover from failure modes induced by chattering of relay and pressure switch contacts. We assume here that there is no operator recovery action. However, we discuss operator recovery from these failure modes briefly in Sections 3.7 (Zion-1) and 4.7 (LaSalle-2).

2.5 Computational Approach

We now discuss the computational procedure that was used in the analysis of the accident sequences generated in this project.

2.5.1 Core Damage Sequences for Zion-1

In Section 3.3, we will describe in more detail two types of core melt sequences that were generated for Zion-1, assuming LOSP:

- a small LOCA through the reactor coolant pump seals, caused by failure of the component cooling water system (CCWS) and the high pressure makeup systems, i.e., safety injection and the charging system;
- failure of secondary heat removal because the auxiliary feedwater system fails, and failure of primary heat removal because feed and bleed fails.
For Zion-1, two generic types of min cut sets* were generated for these accident sequences. The first type was of order 5 and the second type was of order 6. Min cut sets of order 5 had the following form:

- loss of offsite power occurs
- swing diesel aligns to unit 1 or unit 2
- relay 1 contacts chatter
- relay 2 contacts chatter
- relay 3 contacts chatter.

Min cut sets of order 6 had the same form as those of order 5 except that one additional set of relay contacts must chatter, i.e.,

- loss of offsite power occurs
- swing diesel aligns to unit 1 or unit 2
- relay 1 contacts chatter
- relay 2 contacts chatter
- relay 3 contacts chatter
- relay 4 contacts chatter.

All together 94 relays were considered in the analysis of Zion-1. The phrase "relay contacts chatter" above means that the contacts touch each other long enough to cause energizing of a circuit-breaker trip coil or to cause a relay to seal in. It is important to note that at Zion-1 these relays are all located in the auxiliary building at the motor control center and will experience common floor motion during an earthquake. Therefore, we assume that they will share a common response during the postulated earthquake.

* A "min cut set", short for "minimal cut set", is the smallest combination of individual component ("basic event") failures that, if they all occur, will cause the overall system failure (the "top event") to occur. It is a combination of basic events sufficient for the top event. The combination is the "smallest" combination in that all of the failures are needed for the top event to occur; if one of the failures in the min cut set does not occur, then the top event will not occur from this combination of basic events.
2.5.2 Core Damage Sequence for LaSalle-2

As described in Section 4, one type of core damage-accident sequence was generated for LaSalle-2, following earthquake-caused LOSP:

- Failure to make up primary coolant within 80 minutes following LOSP (80 minutes corresponds to the time fuel damage is expected to begin if no coolant makeup is available following LOSP).

Four generic types of min cut sets were generated for these accident sequences. One type had order of 5 and the other three types had order of 6. Min cut sets of order 5 had the following form (which is very similar to the form for Zion-1):

- loss of offsite power occurs
- swing diesel aligns to unit 1
- relay 1 contacts chatter
- relay 2 contacts chatter
- relay 3 contacts chatter.

The three types of min cut sets of order 6 were:

- loss of offsite power occurs
- swing diesel aligns to unit 1
- pressure switch 1 contacts chatter
- pressure switch 2 contacts chatter
- relay 1 contacts chatter
- relay 2 contacts chatter.

- loss of offsite power occurs
- swing diesel aligns to unit 1
- pressure switch 1 contacts chatter
- relay 2 contacts chatter
- relay 3 contacts chatter
- relay 4 contacts chatter.

- loss of offsite power occurs
- swing diesel aligns to unit 1
- relay 1 contacts chatter
- relay 2 contacts chatter
- relay 3 contacts chatter
- relay 4 contacts chatter.
Altogether, there were 22 relays and 18 pressure switch contacts considered in the analysis of LaSalle-2. The phrase "pressure switch contacts chatter" means that the contacts touch each other long enough to cause a solenoid to energize.

2.5.3 SSMRP Methodology

In this analysis, we have used the methodology developed for the NRC by the Seismic Safety Margins Research Program (SSMRP) at Lawrence Livermore National Laboratory (LLNL). We summarize this methodology below. The reader is referred to the SSMRP reports (Ref. SSMRP, 1981) for more details about this methodology. LLNL conducted seismic risk assessments using the SSMRP methodology for both Zion-1 (Ref. SSMRP, 1983) and more recently for LaSalle-2 (Ref. Wells, 1986). In our analysis, we utilize data on fragilities and seismic hazards from these earlier studies. In addition, we used computer files generated by LLNL for both Zion-1 and LaSalle-2 to run the computer code SEISIM, which was used to perform the seismic risk assessment for this analysis.

The overall objective of the SSMRP was to develop improved methods for seismic safety assessment of nuclear power plants. To accomplish this, sophisticated models and computational methods were developed for all of the various aspects of the analysis.

Steps in the SSMRP Methodology

There are five steps in the SSMRP methodology, as shown in Figure 2.1 in flowchart form:

Step 1  Define local earthquake hazard (using the HAZARD code)

Step 2  Characterize the accident scenarios by their initiating events and event trees

Step 3  Determine failure modes for safety systems using system fault trees

Step 4  For each component or structure modeled in the fault trees, compute the following:

i) the distribution of response calculated (using the SMACS computer code)
ii) the distribution of strengths (fragilities data base)
Step 5  Combine all the data in Steps 1-4 to calculate the following risk measures (using the SEISIM code):

i) the probability of system failure
ii) the frequency of a core-damage accident
iii) frequency of a large release (not calculated in this analysis).

SSMRP Approach to Calculating Probabilities

The SSMRP methodology discretizes the earthquake hazard curve into six levels (see Section 2.7 below). In this analysis, we have used SEISIM to compute the probability of each min cut set for each earthquake level. The frequency per year of each min cut set is computed as the product of the following three terms:

\[ F(\text{earthquake}) \times P(\text{LOSP}) \times P(\text{min cut set}) \]

where:
- \( F(\text{earthquake}) \) = Frequency of the earthquake per year
- \( P(\text{LOSP}) \) = Probability of LOSP given the earthquake
- \( P(\text{min cut set}) \) = Probability of the min cut set given both the earthquake and LOSP

By summing over each min cut set and each earthquake level, we can obtain an upper bound (first order) approximation for the frequency of the accident sequence, \( F(\text{sequence}) \), using the following expression:

\[ F(\text{sequence}) = \sum_i \left[ F(\text{earthquake}) \times P(\text{LOSP}) \sum_j P(\text{min cut set}) \right] \]

where \( i \) represents the number of earthquake levels (6 for this study), and \( j \) represents the number of min cut sets.

If \( \sum_j P(\text{min cut set}) \) exceeds unity, then the first order approximation is set \( \sum_j \)equal to unity.
Convoluting the Capacity and Response Functions

The contingent probabilities represented by \( P(\text{LOSP}) \) and \( P(\text{min cut set}) \) are calculated by the stress-strength interference principle. In the SSMRP methodology, both stress and strength are random variables characterized by lognormal distributions. The strength (capacity) is represented by a fragility function and the stress (response) is calculated by the computer code SMACS. These distributions are specified by two parameters, a median value and a "beta value", which is a measure of dispersion about the median. (See Section 2.6 for a definition of "beta").

"Typical" fragility functions for circuit breaker trip and relay chatter are displayed in Figure 2.2, which shows the probability of failure versus spectral acceleration (g) at 8 hertz. Figure 2.3 displays typical distributions for response and for capacity. Variations in the response can be due to variations in soil properties, structural damping, and the like. Variations in capacity can be due to variations in manufacturing, material properties, and so on.

In our calculations of the probabilities, it is assumed (see detailed discussions in Sections 3 and 4) that the fragility functions for all relay-chattering events are independent, and that the responses are all 100% correlated. The betas of the response curves are taken from SSMRP data. In Sections 3.6 (for Zion-1) and 4.6 (for LaSalle-2) we will describe sensitivity studies that were done to explore the sensitivity of our results to the numerical magnitudes of the median and "beta" values for these fragility functions.

"Failure" is said to occur when the applied stress exceeds the capacity. If we let \( X \) represent stress, \( Y \) represent capacity, and \( F_X \) and \( F_Y \) their cumulative distribution functions, then the probability of failure, \( P(\text{failure}) \), is given by the following convolution integral, assuming that \( X \) and \( Y \) are independent random variables:

\[
P(\text{failure}) = P(X > Y) = \int_0^\infty (1 - F_X(z)) \, dF_Y(z)
\]

The single variant case is adequate for calculation of single event probabilities such as \( P(\text{LOSP}) \). However, for multiple events, such as the chattering

* Fragility curves are probability distributions that describe the probability of failure as a function of a critical response parameter such as local response. The median fragility value is the median acceleration at which the item will fail. A detailed discussion of fragility curves can be found in the NRC's "PRA Procedures Guide" (Ref. NRC, 1983).
of multiple relay contacts, we must use multivariate stress-strength probability distributions. In this analysis, we have assumed that the relays and pressure switches all experience the same response (that is, their responses are perfectly correlated random variables.) A valuable feature of SEISIM, which was employed in this project, is that the code can handle response-dependent as well as fragility-dependent failures, details of which are discussed by George (Ref. George, 1985).

2.6 Fragility Values for the Chatter and LOSP Failure Modes

The reason why this project is so relevant is that the chattering failure modes of relays and pressure switches are thought to possess much lower fragility curves than do other failure modes of the electrical equipment, such as the circuit-breaker-trip mode.

Our study team spent considerable time examining the fragility literature for relays, breakers, and related equipment. Among the fragility references studied were the Brookhaven compilation (Ref. Bandyopadhyay et al., 1986), the LLNL compilation done as part of NRC's seismic margins program (Ref. Campbell et al., 1985), and the SSMRP compilation (Ref. Cover, 1983). Conversations with experts associated with the SQUG ("Seismic Qualification Utility Group") project were also useful in indicating what the SQUG effort has yielded so far (Ref. Kennedy, 1986 and Kassawara, 1986). Our study team also had access to qualification data for some of the LaSalle relays through a private communication from Commonwealth Edison and Sargent & Lundy.

The project team realized from the start that it would not be possible to develop an independent set of fragility curves for the relays and contacts being studied here. In the course of the project, a more important conclusion has emerged: we have become convinced that fragility curves for the relays and contacts studied do not yet exist in a form that we could use for our PRA-type analysis here. We believe that this is true despite the existence of qualification test data, much of which we had access to through our contacts with Sargent & Lundy.

Therefore, the fragility values that we have used, mainly because they have been used in the past, are taken from the plant-specific SSMRP report for Zion-1 carried out for NRC by Lawrence Livermore National Laboratory (Ref. Cover, 1983).
The values used are as follows (here the median fragility is a spectral acceleration and is in g's):

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Median Fragility (g)</th>
<th>Beta*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay Chatter</td>
<td>2.60 g</td>
<td>1.5</td>
</tr>
<tr>
<td>Pressure Switch Chatter</td>
<td>1.51 g</td>
<td>1.5</td>
</tr>
<tr>
<td>Loss of Offsite Power</td>
<td>0.20 g</td>
<td>0.3</td>
</tr>
<tr>
<td>Circuit Breaker Trip</td>
<td>9.58 g</td>
<td>0.82</td>
</tr>
</tbody>
</table>

As the information here shows, the relay chatter mode has a much lower median capacity than does the circuit breaker trip mode. Also, the standard deviation (usually designated by "beta", defined as the standard deviation of the logarithm of the fragility) is much larger for the chatter mode than for the circuit breaker trip mode.

Of course, the lower median capacity and higher beta for the chatter mode results in a much higher probability of failure under earthquake motion than for the trip mode. This is made quantitative in Table 2.1, which is for the Zion site. The table shows, for the six earthquake levels used (see Section 2.7 below), that the probability of relay chatter given an earthquake is quite high while direct circuit-breaker trip is very unlikely. This table also shows that at all but the lowest levels the probability of ceramic insulator failure approaches unity. (We assume that ceramic insulator failure always leads to unrecoverable loss of offsite power.)

It is important to point out that these generic fragility values cannot possibly be correct in detail, because they do not differentiate among different relay types. Also, they do not differentiate between energized and deenergized states of relays, or between relays that are open or closed, even though it is known that these differences affect relay fragility in an important way (Ref. Holman et al., 1986).

* "Beta" as defined here is the standard deviation of the logarithm of the median fragility. The beta used here is "beta-total", which is obtained by combining in quadrature [square root of the sum of the squares] the values of "beta-R" (the uncertainty due to "randomness") and "beta-U" (the uncertainty due to less than complete knowledge, which is sometimes called "modeling uncertainty"). See the "PRA Procedures Guide" (Ref. NRC, 1983) for these definitions.
Furthermore, because the analysis uses the single parameter of peak ground acceleration, the frequency dependence of the relay fragility curves is probably not captured well enough in this analysis.

Because our knowledge of these fragilities is not very good, our analysis here has been done not only with "base case values" as above, but also using different values for the median and beta for chatter, in a set of "sensitivity studies". These sensitivity studies are reported in Section 3.6 (Zion-1) and Section 4.6 (LaSalle-2).

The fragility for LOSP (loss of offsite power) is another important parameter (see Table 2.1). As the information above indicates, the fragility curve for LOSP is very much lower than the curve for any other plant feature. Therefore, LOSP is almost sure to occur for any earthquake-initiated accident sequence of interest here. However, rather than assume that LOSP is 100% probable, the analysis has used an actual LOSP fragility curve, whose parameters are shown above.

The fragility values used in this analysis are convoluted with the earthquake hazard curve by the computer code SEISIM (see the discussion about SEISIM above in Section 2.5.3), to yield calculated frequencies of core-damage accidents.

2.7 Earthquake Hazard Curves for the Zion and LaSalle Sites

In order to simplify our analysis, we have chosen to use the SSMRP hazard curves for both the Zion and LaSalle sites as inputs to the SEISIM analysis. The SSMRP methodology (Ref. SSMRP, 1981) uses a discrete distribution of its hazard curve input, to approximate a smooth function.

The SSMRP-derived hazard curves for both sites are comprised of six earthquake levels, each associated with a frequency of recurrence. The Zion information is from (SSMRP, 1983) and the LaSalle information is from (Wells, 1986). The information we have used is in the following table:
<table>
<thead>
<tr>
<th>Zion Earthquake Level</th>
<th>Zion Earthquake Level</th>
<th>Bedrock</th>
<th>Zion, Frequency per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.06 - .10 g</td>
<td>5.48 E-4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>.10 - .20 g</td>
<td>2.66 E-4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>.20 - .32 g</td>
<td>1.32 E-5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>.32 - .42 g</td>
<td>1.62 E-6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>.42 - .53 g</td>
<td>4.18 E-7</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>.53 - .69 g</td>
<td>1.62 E-7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LaSalle Earthquake Level</th>
<th>LaSalle Earthquake Level</th>
<th>Bedrock</th>
<th>LaSalle, Frequency per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.18 - .27 g</td>
<td>1.07 E-4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>.27 - .36 g</td>
<td>2.87 E-5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>.36 - .46 g</td>
<td>1.08 E-5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>.46 - .58 g</td>
<td>4.71 E-6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>.58 - .73 g</td>
<td>2.12 E-6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>above .73 g</td>
<td>1.02 E-6</td>
<td></td>
</tr>
</tbody>
</table>

These frequencies/year for the 6 earthquake levels are used directly by the SEISIM code in its analysis.

It is important to note that these are point values, without any spread to account for uncertainties in our knowledge of the site-specific hazard. This means that our analysis using these values will not be able to provide results that capture this uncertainty.

In the SSMRP analysis of LaSalle-2 (Ref. Wells, 1986), it was assumed that the rock outcrop hazard curve was the same as was assumed for the earlier SSMRP analysis of Zion (Ref. SSMRP, 1983). However, for a given size of earthquake at the rock outcrop, Zion would experience larger local accelerations than would LaSalle. This is due in part to different soil column characteristics at the two sites. In addition, LaSalle is located on a single-slab foundation and would not experience differential building movement like that at Zion.
<table>
<thead>
<tr>
<th>Earthquake Level</th>
<th>Earthquake Accel. in Bedrock (g)</th>
<th>Earthquake Frequency Per Year</th>
<th>Probability of Relay Chatter Given Earthquake Level*</th>
<th>Probability of Breaker Trip Given Earthquake Level*</th>
<th>Prob. Ceramic Insulator Fail. Given Earthquake Level**</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>.06 - .10</td>
<td>5.4 E-4</td>
<td>0.095</td>
<td>7.9 E-8</td>
<td>0.27</td>
</tr>
<tr>
<td># 2</td>
<td>.10 - .20</td>
<td>2.7 E-4</td>
<td>0.15</td>
<td>3.1 E-5</td>
<td>0.79</td>
</tr>
<tr>
<td># 3</td>
<td>.20 - .32</td>
<td>1.3 E-5</td>
<td>0.26</td>
<td>3.2 E-4</td>
<td>1.00</td>
</tr>
<tr>
<td># 4</td>
<td>.32 - .42</td>
<td>1.6 E-6</td>
<td>0.33</td>
<td>1.7 E-3</td>
<td>1.00</td>
</tr>
<tr>
<td># 5</td>
<td>.42 - .53</td>
<td>4.2 E-7</td>
<td>0.37</td>
<td>4.1 E-3</td>
<td>1.00</td>
</tr>
<tr>
<td># 6</td>
<td>.53 - .69</td>
<td>1.6 E-7</td>
<td>0.42</td>
<td>9.2 E-3</td>
<td>1.00</td>
</tr>
</tbody>
</table>

* Response location: motor control center, auxiliary building

** Response location: free field at grade level
FIG. 2.1 -- A FLOW CHART OF THE SSMRP PROBABILISTIC COMPUTATIONAL PROCEDURE
Spectral acceleration (g) at 8 Hz

FIG. 2.2 -- TYPICAL FRAGILITY FUNCTION FOR CIRCUIT BREAKER TRIP AND RELAY CHATTER
Failure occurs when a random value of $R$ exceeds a random value of $F$.

FIG. 2.3 -- SEISIM METHOD FOR COMPUTING COMPONENT FAILURE PROBABILITIES
SECTION 3
DETAILS OF THE LIMITED-SCOPE SEISMIC PRA FOR ZION-1

As mentioned in the introduction, Zion-1 ("Zion Nuclear Power Station-1", or "ZNPS-1") is a pressurized water reactor rated at 1040 MWe, of Westinghouse design. It is owned by Commonwealth Edison Company, and has a twin unit (Zion-2) on the same site, which shares certain important equipment to be discussed below.

This Section describes the limited-scope seismic PRA that has been performed for Zion-1. The analysis here covers accident sequences in which a loss of offsite power (LOSP) occurs after a major earthquake. The analysis considers only failure modes involving the chatter of relay contacts after LOSP. As mentioned in Section 1, the authors recognize that this analysis is not fully realistic, and the numerical results should not be used as an indicator of Zion-1's seismic risk.

The basic assumptions used in this analysis, which were discussed above in Section 2, are as follows:

- we assume that loss of offsite power (LOSP) occurs with a certain probability due to earthquake-caused failure of the electrical grid's ceramic insulators, because their seismic capacity is generally much lower than that of any other components and structures; we use an SSMRP-derived fragility function for LOSP which is convoluted with a response function (see Sections 2.5 and 2.6);

- LOSP is the only earthquake-induced initiating event that we consider in this analysis; we assume that LOSP occurs whenever the ceramic insulators are damaged by the earthquake (see Section 2.6);

- we assume that the reactor protection system will shut down the fission chain reaction and keep it down after the earthquake;

- we assume that offsite power is not recovered --- therefore, the main feedwater system is not recovered and is unavailable;

- we pessimistically assume that there is no operator action, and in particular that operators do not reset circuit breakers and relays; thus no credit is taken for operator recovery;
o we assume that DC power is always available after the earthquake;

o we assume that the SSMRP "hazard curves" used in this analysis are correct (see Section 2.7);

o we consider only failure modes due to chatter of relay contacts.

It is important to note that we assume that there is no other transient event besides LOSP when the strong-motion earthquake occurs. For example, random pipe breaks, valve mechanical failures, and structural failures are not considered. Furthermore, as mentioned we assume that LOSP does not occur with 100% probability: a seismic fragility function has been assigned for LOSP (see Section 2.6).

Another crucial assumption concerns operator recovery. We assume here that there is no operator recovery action. However, we discuss operator recovery from these failure modes briefly in Section 3.7.

The end point of the analysis is the calculation using PRA methods of the frequency of a core-damage accident, based on the assumptions above. In order to accomplish this, the analysis requires two additional key inputs:

o the site-specific frequencies of earthquakes of various sizes must be known ---- this input is discussed in Section 2.7;

o fragilities for the chattering of relay contacts must be known ---- this input is discussed in Section 2.6.

We will begin with a description (Section 3.1) of the loss-of-offsite power (LOSP) transient at Zion-1. Next, the failure mode analysis will be covered (3.2), followed by discussions of the core-damage sequences identified (3.3), the min cut sets found (3.4), and our quantification of the core-damage frequency (3.5). Sensitivity analyses are described in Section 3.6.

Below we will discuss our finding that three key safety systems play major roles at Zion in responding to LOSP sequences after a large earthquake. These three are the component cooling water system (CCWS), the service water system (SWS), and the auxiliary feedwater system (AFWS). The ways that each of these might fail due to earthquake-induced chatter will be given detailed discussion.
3.1 Zion Electric Power System

In this section, we will concentrate on the seismically-induced LOSP transient at Zion. We will first describe the electric power system and circuit breaker operation following LOSP.

Since the CCWS and SWS are supplied by and serve both units, we need to describe the ESF bus configuration for both units 1 and 2 at Zion.*

The one line diagrams for units 1 and 2 are shown in Figures 3.1 and 3.2. Units 1 and 2 each have three major electrical divisions. For unit 1, these are divisions 17, 18 and 19 which include 4.16 kV buses 147, 148 and 149 respectively; for unit 2, these are divisions 27, 28 and 29 which include 4.16 kV buses 247, 248 and 249 respectively. Each division consists of a 4.16 kV engineered safety bus, a 480 V engineered safety bus, a 480 V motor control center, a 120 V instrumentation bus, and a 125 volt DC control bus. Each division can be fed from a 4.16 kV bus supplied by that unit's auxiliary transformer.

Each of the divisions 18, 19, 28 and 29 is connected to its own dedicated diesel generator which supplies emergency 4.16 kV power in the event of LOSP. Divisions 17 and 27 share a swing diesel, called DG-0. Upon LOSP there is an equal (50-50) chance that DG-0 will swing to one or the other division. The one-line diagrams in Figures 3.1 and 3.2 identify the ESF loads that are attached to each 4.16 kV bus. These loads are also described in the key diagram for buses 147 and 148 in Figure 3.3. Figure 3.4 is an enlargement of part of Figure 3.1 to show bus 148.

3.1.1 Loss of Offsite Power

We now describe the sequences of events following LOSP.

3.1.2 Assumptions About Events Just Prior to and After the Earthquake

Figure 3.5 shows the expected sequence of events following LOSP. We assume that the plant has been at full power prior to the earthquake. At time equals zero seconds (i.e., \( t = 0 \)), strong motion starts. At the Zion site,

* The Component Cooling Water System (CCWS) has 5 pumps, three of which are served by electrical buses from Zion-1, and two by buses from Zion-2. The outputs of all five pumps go to a common header, from which the water is distributed to both Zion-1 and Zion-2. The Service Water System (SWS) has 6 pumps, three of which are served by Zion-1 electrical buses and three by Zion-2 buses. The SWS also has a common header arrangement for its 6 pumps, from which water is distributed to both units.

3-3
strong motion can occur for as long as 20 seconds. Additional shaking of buildings, such as the auxiliary building where the motor control centers are located, can occur for as long as 60 seconds when a strong motion earthquake occurs.

At some small but finite time later, shown on the figure as "delta t", LOSP occurs due to ceramic insulator failures in the switchyard. We assume that the ceramic insulator failures occur instantaneously, at \( t = 0 \). In the following discussion, we assume that no further failures occur. (In section 3.2, we will consider additional failures that could result from the earthquake.)

3.1.3 Reapplication of Power and Engineered Safety Systems Loads

Again referring to Figure 3.5, an undervoltage signal generates a trip signal for all ESF breakers. For bus 148 shown in Figure 3.3, breakers to the service water pump 1B and component cooling water pump OD, which are normally closed because these pumps are normally up and running, will trip open. The FSAR states that within 10 seconds (\( t = 10 \) sec) the diesels should run at synchronous speed. At this time, each diesel generator breaker should close and the load sequencers should start.

There are two load sequencers for each division. These sequencers are timers with rotating cam shafts that close contacts to ESF circuit breakers as the shaft rotates. Figure 3.5 shows the closing sequence for ESF loads on buses 147, 148 and 149. The sequence that is shown is the so-called "safe shutdown sequence" (given the notation 'SD') that is produced by an undervoltage signal on the ESF buses. A similar kind of operation occurs for buses 247, 248 and 249 at unit 2.

3.1.4 Assumption That No LOCA Occurs

We have assumed that a loss of coolant accident (LOCA) does not occur due to a pipe break, valve mechanical problem, or other failure caused directly by the earthquake. A LOCA would produce a safety injection signal (SIS). An SIS would start the following loads at Zion (listed in order of time at which their respective circuit breakers are closed by the load sequencers):

- safety injection pump
- residual heat removal pump
- containment spray pumps
- service water pumps
- containment cooling fans.
Although the SIS sequence is important, we will assume in this analysis that it does not occur during the strong earthquake motion. Here we will only consider the "safe shutdown" sequence (SD) following LOSP.

3.1.5 Circuit Breaker Operation

In the next several sections, we will discuss the details of circuit breaker operation. For purposes of example, we focus our attention on the operation of two circuit breakers critical to plant safety at Zion-1:

- the breaker for service water pump 1B
- the breaker for diesel generator 1A.

Both of these electrical components are attached to bus 148 (see Figures 3.3 and 3.4).

The service water system is part of the ultimate heat sink for the plant and is a vital system required for both normal and emergency operation. The diesel generator 1A is required for reapplication of power following LOSP. Both circuit breakers are ITE-type circuit breakers using a typical X-Y breaker scheme, the details of which are discussed in the next subsection and also in Appendix A. A Sargent & Lundy standard describing the device function numbers and letters used on their electrical drawings can be found in Appendix E.

To help the reader find relays and contacts on figures, we will use a grid system for locating components by their row and column on the figures. We use letter-number designators to locate the lettered row and numbered column; for example, [D-4] represents location Row D and Column 4.

3.1.6 X-Y Circuit Breaker Scheme

Figure 3.6 shows the control circuit breaker of service water pump 1B. The circuit to the left of the dashed line in Figure 3.6 is the closing circuit; to the right is the tripping circuit. The lower lefthand corner of Figure 3.6 shows the X-relay [P-4], called the closing relay, and the Y relay [P-4], called the anti-pumping relay. The trip coil TC [P-7] opens the breaker on a "trip" signal if the breaker is in the closed position. Also shown in Figure 3.6 are numerous relay and auxiliary contacts.

The breaker itself is bounded by the disconnect symbols, >>, in the lower lefthand corner of Figure 3.6. All components and circuits found outside of the breaker boundary are control circuits.
When the breaker is in its closed position, a red light above the control switch is on, and when the breaker is in its open position a green light is on. When an automatic trip occurs, an amber light goes on and stays on until the breaker is reset.

The basic aspects of the circuit breaker operation involving these relays and contacts are:

- charging of the closing spring;
- closure of the circuit breaker by automatic control;
- recharging of the closing spring;
- trip of the circuit breaker by automatic control.

Each of these aspects of breaker operation will be covered in the next four subsections.

### 3.1.7 Charging of the Closing Spring

The circuit breaker is enclosed in a cabinet on wheels. When the circuit breaker is first racked into its cubicle, the LS/b contacts* (positions [M-3] and [N-5]) are closed, since the closing spring is not energized. The LS/b contacts are only open when the spring is fully wound, otherwise the LS/b contacts are closed. The LS/a contacts follow the opposite position of the LS/b contacts. If DC control power is available, the motor [O-3] will automatically wind the spring causing the LS/b contacts to open and the LS/a contacts to close. For this analysis, we will assume that DC power is always available.

### 3.1.8 Closure of the Circuit Breaker by Automatic Control

The 52/b contacts** (position [O-4], Figure 3.6) are closed because the breaker is open [the 52b contacts are open (closed) when the breaker is closed (open)]. Also, the Y/b contacts [M-3] are closed since the anti-pumping relay Y [P-4] is de-energized.

When the closing relay X [P-4] is energized, the relay releases a latch that causes the closing spring to discharge. With this discharge, the breaker closes. The X-relay can be energized if the operator manually closes the

* The notation "LS" denotes "limit switch", which follows the spring position.

** "52" is the device number denoting circuit breaker.
control switch in the control room causing the CS/C contacts [C-4] to close. Since all other contacts located in the current path in column 4 are closed, the X-relay [P-4] becomes energized.

When the closing spring discharges, the LS/b contacts [N-5] close, causing the Y-relay to energize and to seal itself in via the Y/a contacts [N-4]. The Y/b contacts [N-4] open, thereby preventing automatic reclosure against a faulted circuit. If this anti-pumping feature did not exist, the breaker could destroy itself by cycling back and forth from the closed to the open position continuously in the presence of a fault.

Automatic reclosure of the circuit breaker to service water pump 1B requires closure of the redundant set of contacts R6/18-1 [F-4], or R6/18-2 [F-5], in the circuit shown in Figure 3.6. Operation of the R6 relays will be discussed below in Section 3.1.14. The other current path located in row 1 (upper lefthand corner) is not available since the M427X contacts [G-1] are open when the 4.16 kV bus voltage is lost. Details will be discussed in Section 3.1.12.

3.1.9 Recharging of the Closing Spring

After the closing spring discharges, the LS/b contacts ([M-3] and [N-5]) close and the motor [O-3] starts rewinding the closing spring. It takes about 3 to 5 seconds to wind the spring. During this time, the circuit breaker cannot close since the LS/a contacts [N-4] are open. Also, it is important to note that the Y relay will remain energized if control power is available or becomes available while the motor is winding the spring. During this time, the LS/b [O-5] remains closed providing a current path to the Y relay [P-4]. As described in Section 3.1.8, the X relay [P-4] cannot be energized while the Y relay is energized because the Y/b contacts [N-4] are open. What this means is that the circuit breaker cannot be closed by an electrical signal (produced either automatically or manually) as long as the Y relay remains energized.

3.1.10 Trip of the Circuit Breaker by Automatic Control

The word "trip" describes the action when a closed breaker is opened by receipt of a signal. The tripping circuit in Figure 3.6 consists of numerous protective relay contacts. When any one of these contacts closes, it will energize the trip coil [P-7], provided that the breaker is closed. (When the
As described in Appendix E, these contacts are numbered according to the following scheme: the first number denotes the type of switchgear (for example, 1 denotes 345 kV switchgear, while 4 denotes 4.16 kV switchgear). The second and third numbers represent the type of protective relay.

** When voltage is restored, the OV contacts close and the seal in drops out.
Another breaker that will trip is the breaker to the component cooling pump OD. All of the other breakers to ESF loads are normally open and therefore do not trip. These loads include (see righthand side of Figure 3.7):

- auxiliary feedwater pump 1B
- safety injection pump 1B
- residual heat removal pump 1B.

LOSP also results in undervoltage on buses 142, 143 and 144 which causes M427X [K-5 in Figure 3.8] to energize.

3.1.13 Closure of the Diesel Generator 1A Circuit Breaker

Figure 3.9 shows the control circuit to the Diesel Generator 1A Feed Breakers. Automatic closure of the circuit breaker requires that the following sets of contacts be closed:

<table>
<thead>
<tr>
<th>Contacts</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>148-M/b</td>
<td>[A-6]</td>
<td>Incomplete sequence relay bus 143</td>
</tr>
<tr>
<td>486 - 148M</td>
<td>[D-4]</td>
<td>Interlock relay bus 143</td>
</tr>
<tr>
<td>148-R/b</td>
<td>[E-4]</td>
<td>Incomplete sequence relay bus 241</td>
</tr>
<tr>
<td>486-DG1A</td>
<td>[G-4]</td>
<td>Lockout device for the DG (normally closed)</td>
</tr>
<tr>
<td>DGX1A</td>
<td>[I-4]</td>
<td>DG proper voltage and frequency permissive relay</td>
</tr>
</tbody>
</table>

All contacts listed above close upon LOSP except 486 DG1A (which is normally closed). The contacts DGX1A close when the diesel 1A runs at synchronous speed and proper voltage.

Figure 3.10 shows the initiation logic for the relay DGX-1A [K-7]. Relay DGX-1A energizes when the 27/59 contacts [F-7] close and when the 81Y-1A contacts [E-7] close. The 27/59 contacts close when the diesel generator output voltage is within a proper range. 81Y-1A contacts close when the diesel is at proper frequency and voltage. As long as the diesel generator is at proper voltage and frequency, DGX-1A remains energized and the DGX1A contacts [I-3 in Figure 3.8] remain closed.

Relay 486DG1A [P-17 in Figure 3.9] is a WL device, which is a type of lockout relay. This relay is energized by a three-phase differential relay 487 [M-18] (a solid-state device). The 487 relay is energized when diesel genera-
tor differential current exists between phases (a fault condition). The 487 relay energizes a solenoid that physically turns a WL lock-out type switch to energize relay 486DG1A, which in turn closes the following contacts: 15-16, 17-18, and 19-20 [P-21 on Figure 3.9]. If this lockout device is energized, it must be manually reset at the cabinet.

3.1.14 Reclosure of the Service Water Pump 1B Circuit Breaker

Automatic reclosure of the circuit breaker to service water pump 1B requires closure of the redundant set of contacts R6/18-1 [F-4], or R6/18-2 [F-5], in the circuit shown in Figure 3.6.

We now discuss the initiation logic that causes the R6/18-1 contacts to close. (The logic for R6/18-2 contact closure is similar.)

Figure 3.11 shows the circuit which energizes the timer motor T-SD/18-1 [H-14]. Energizing the timer motor T-SD/18-1 requires two operations:

- energization of the timer circuit which requires bus MCC 1381B (see Figure 3.4) to energize;
- energization of the timer which requires a number of contacts to close in Figure 3.11.

We now discuss the first operation. The timer circuit energizes when the 4.16kV/480-volt feed breaker to transformer 138 closes (see Figures 3.3 and 3.4). The control circuit to this breaker is shown in Figure 3.12. As described in section 3.1.12, relay M427X [K-5 in Figure 3.8] energizes which causes the contacts 9-10 [G-6 in Figure 3.12] to close. When the diesel is at proper speed and voltage, the 5-6 contacts [D-6 in Figure 3.12] close which in turn energizes the X-relay [O-4] and closes the feed breaker.

We next discuss the contacts that must close in Figure 3.11 to energize the timer motor T-SD/18-1 [H-14]. These contacts are:

- 427X1/148 [C-2]
- M427/T18/INST [D-10]
- M427/T18/TDO [D-10]
- G1A [F-13]

(Here the M427 relays are Agastat relays, which are timing relays.)

When LOSP occurs, the first three sets of contacts listed above close. M427/T18/TDO contacts open in two minutes if prolonged undervoltage exists on
buses 142, 143 and 144 (2-out-of-3 logic in Figure 3.8). When contacts M427-
/T18/TDO open, timer T-SD/18-1 in Figure 3.11 is reset.
Contacts SIX6/A [C-9] remain closed since we assume (as was stated in
Section 3.1.4) that a safety injection signal (SIS) is not produced.* When
the breaker to diesel generator 1A closes, contacts G1A/a close, the timer
motor (also known as a load sequencer) starts, and the contacts close sequen-
tially in time as shown in the lower half of Figure 3.13 (the timing sequence
for all three 4.16 kV buses is shown in Figure 3.5). (The upper half of the
circuit in Figure 3.13 shows the safeguards sequence when a SIS is produced.)
As shown in Figure 3.13, the 2A-2B contacts on cam No. 2 close in five
seconds after the timer is energized. As shown in Figure 3.14, when the
contacts [F-4] close (Figure 3.6). The other set of parallel contacts in Figure
3.6, R6/18-2 [F-5], close by a redundant timer.

3.2 Failure Mode Analysis for Chattering

Based on the discussion of section 3.1, we now discuss potential failure modes
of the emergency AC power system at Zion-1.

3.2.1 Electric Power Failure Modes

Examining the control circuits to the circuit breakers in Figures 3.6, 3.9 and
3.12, we see that there are numerous protective relay contacts that can
chatter and thereby cause a breaker to trip open. For example, these con-
tacts for ESF loads include:

- undervoltage relay contacts
- instantaneous overcurrent relay contacts
- AC time overcurrent relay contacts.

In addition, Zion-1 has protective relays that would cause the diesel-generator
circuit breaker to trip open, such as lockout relays. With these observations
in mind, we have identified three ways by which an ESF load can fail to
receive AC power following LOSP:

1. There could be no AC power on the bus that feeds the load. This
can be caused by the diesel-generator circuit breaker tripping after
closure. Chattering of the overcurrent protective relays can cause the
breaker to trip. In the case of buses 147 or 247, no AC power on a bus

* If an SIS were generated, then the SIX6/A contacts open and the timer
motor T-SI/18-1 [I-8 in Figure 3.11] energizes. In this case, a "safeguards sequence" is produced, rather than a "safe shutdown" sequence.
can be caused by the swing diesel (DG-0) swinging to the other unit.

2. The supply breaker to the ESF load could fail to close because of a load sequencer failure. The load sequencer, which requires 480 volt power, can fail if the supply breaker from the 4.16kV bus to the 480-volt bus trips. This can occur due to chatter of the protective relay contacts in the trip circuit.

3. The supply breaker could trip open after closure, because of chattering of the protective relay contacts that cause the trip coil to energize.

The "generic" fault tree structure for the three failure modes listed above is depicted in Figure 3.15. This structure appears in the fault trees generated for the accident sequences as described in Section 3.3.

The above three failure modes imply the following scenario. All five diesels at Zion would start, but would not provide power to the ESF loads, either because the diesel-generator breaker fails to close or because the ESF circuit breaker fails to close or trips after closure. Also, for all diesels other than the swing diesel DG-0, if the DG circuit breaker were to trip due to relay chatter, the Y relay would seal-in and reclosure from the control room would not be possible. (Currently, Commonwealth Edison is making changes in their control switches and in the control circuits for other reasons, which changes will eliminate the seal-in problem.)

The circuit design in Figure 3.9 is such that the 148M/b contacts [B-5] bypass the control switch contacts. The circuit design for the swing diesel is different so that the seal-in is not possible, for the following reasons: There are two separate breakers for the swing diesel DG-0 that feed buses 147 and 247. The control circuit for breaker 147 is shown in Figure 3.16. The breakers are electrically interlocked so that both breakers cannot be closed at the same time. Let us suppose that DG-0 swings to unit 1. If the 147 breaker were to trip open due to relay chatter, the 247 breaker would attempt to close and the contacts labeled GO [J-3] would open, causing the control circuit to deenergize, which in turn would cause the seal-in to drop out (that is, to be eliminated). GO contacts are closed (open) when breaker 247 is open (closed).

3.2.2 AFWS Failure Modes

Any ESF load that depends upon AC power can fail due to the reasons stated in section 3.2.1. This includes the two electrically-driven auxiliary feedwater pumps 1B and 1C.
AFWS pump 1A is steam-driven. Our analysis carefully examined the control circuit to the steam stop valve to the pump 1A turbine. This valve supplies steam from either steam generator 1A and/or 1D. Though no failures due to relay chatter were found in this circuit, we will describe this circuit for the sake of completeness.

The control circuit to the AFWS pump 1A is shown in Figure 3.17. There is a six-second time delay in the circuit so that pump 1A can lubricate itself. The stop valve opens when the solenoid [Q-3] is unenergized. The 1-5 contacts in column 2 open upon loss of all AC and the solenoid opens, which causes the stop valve to open. A limit switch LS-O [D-7] closes when the stop valve is opened. Relay TDMS57X/TDE [O-7] energizes after a six second time delay, after which contacts TDMS57X [N-7] close. The self-lubricating lube oil pressure will build up, and contacts IPS [E-9] open, thereby deenergizing relay PSLX/OPER [O-9]. Contacts PSLX [E-7] open. Oil pressure should build before the six second time delay and the solenoid should remain unenergized.

Contacts R/PSLX [G-5] or contacts PSLX [E-7] can chatter close momentarily, but this should have no effect on the solenoid after chattering ceases, so that the solenoid should remain unenergized and the valve should remain open.

Self-lubrication of these pumps is an issue. The most recent FSAR states that all three AFWS pumps are self-lubricating. When the SSMRP study of Zion (Ref. SSMRP, 1983) was conducted, the AFWS pumps depended upon lube oil pumps for lubrication. The SSMRP study generated double event minimal cut sets for the AFWS which described failure of relays controlling the lube oil pumps. These relays were powered by two separate electrical divisions, which implies that doubles describing bus failures were also generated for AFWS failure.

For the purposes of this analysis, we assume that the AFWS pumps are all self-lubricating.

3.2.3 Excluded Failure Modes

Also, it is important to note that some failure modes were excluded in our analysis because they were judged very unlikely to occur. For example, refer to the control circuit to the diesel generator breaker in Figure 3.9. The devices labeled TS ([G-3] and [H-3]) are test switches which are protected behind screw down covers. These switches are used by relay test engineers

* In the figure, "ETC" means "energize to close".

3-13
during outages. The possibility of these switches flying open is highly unlikely, because they are restrained in closed position by glass covers. Also excluded were failure modes involving the simultaneous chattering of two or more normally-open contacts in series. This type of event could be included in a more complete analysis, but its omission here is judged not to be important.

Also, for seal-in circuits we made the assumption that a normally closed set of contacts would remain closed (otherwise the seal-in would drop out). More generally, if the normal operation of a component leads to the fault event of interest, we assumed that the component would operate normally. For example, refer to the diesel generator circuit in Figure 3.9. The Y-relay would drop out if any of the normally closed contacts in series in column 3 would chatter open.

Referring to Figure 3.9, it is important to note that the device which senses diesel-generator current, 487DG1A/SA-1 (M-18), is a solid-state device and does not exhibit failure modes due to relay chattering.

3.3 Core Damage Sequences for Zion-1

Two core melt sequences were considered for Zion-1:

- a small LOCA through the reactor coolant pump seals, caused by failure of the component cooling water system (CCWS) and the high pressure makeup systems, i.e., safety injection system and charging system;

- failure of secondary heat removal because the auxiliary feedwater system fails, and failure of primary heat removal because feed and bleed fails.

The fault trees for these two accident sequences are displayed in Appendix C, which consists of 6 sheets. Sheet 1 defines the top structure for the small LOCA sequence. Sheet 3 defines the top structure for the transient sequence.

3.3.1 Small LOCA Sequence at Zion-1

In the small LOCA sequence, failure of the CCWS will cause the reactor coolant pump seals to heat and subsequently leak. In addition, failure of the CCWS will fail the high pressure injection pumps due to pump overheating. Hence, failure of the CCWS is a single event leading to a core-damage accident.
The CCWS consists of 5 pumps, three served by unit 1 power and two served by unit 2 power. According to the Sandia review of the Zion PRA (Ref. Berry et al., 1983), 2 out of the 5 pumps must operate for successful heat removal after a LOCA. However recent communications with Sandia (Ref. Wheeler, 1986) indicate that only 1 out of the 5 pumps is required. In addition, 3 out of 6 service water pumps must operate for successful heat removal. As displayed on Sheet 1 of our fault tree in Appendix C, the success criterion implies that all 5 CCWS pumps must fail or 4 out of 6 service water pumps must fail to produce a pump-seal LOCA.

It is important to note that when the swing diesel aligns to one bus, the other bus is unavailable. This means that upon LOSP one service-water pump is always unavailable. In addition, one CCWS pump is unavailable if DG-0 swings to unit 2.

It is not known precisely when core damage is expected to occur by this small LOCA sequence since the leakage rate through the coolant pumps seals is unknown. The Sandia report on Zion (Ref. Berry et al., 1983) quotes a Seabrook nuclear power plant analysis that gives a time of 10 hours.

3.3.2 Failure of All Secondary and Primary Heat Removal

The second group of accident sequences considered in this analysis is failure to remove heat because the secondary heat removal system (the auxiliary feedwater system) has failed, and the primary heat removal system (feed and bleed) has also failed. The reader is referred to Sheet 3 in Appendix C.

Failure of the service water system can cause this sequence to occur, because such failure leads to overheating of the diesel generators and subsequently loss of all AC power. In addition, the steam-driven auxiliary feedwater pump fails because of overheating. The sequence takes approximately 1 to 1.5 hours for core damage. Sandia's review of the Zion PRA (Ref. Berry et al., 1983) quotes a success criterion of 2 out of 6 service water pumps, meaning that 5 out of 6 pumps must fail to cause a core damage accident.

3.4 Generation of Min Cut Sets

The computer code FTAP (Ref. Willie, 1978) was used to find the min cut sets to the two accident sequences being studied. It is important to note that one must find all of the min cut sets, because each min cut set by itself has a small probability. Taken all together, however, the total (actually, the Boolean union) of these cut sets can be risk-significant. (Section 3.5 demonstrates this.)
3.4.1 Need for Separate Runs for the Two Swing-Diesel Alignment Cases

Two separate FTAP runs were necessary for each accident sequence, depending upon whether the swing diesel aligns to unit 1 or unit 2. This approach is used because there is an asymmetry in the bus structure at Zion in the way the 5 CCWS pumps are supported. Unit 1's electrical system supports 3 CCWS pumps but unit 2's electrical system supports only 2 CCWS pumps, although the water pumped from these 5 CCW pumps all goes to a common header before distribution to various equipment at both units. This approach also avoided generating logically inconsistent min cut sets that would describe the swing diesel aligning to both units 1 and 2 simultaneously.

3.4.2 Description of the Min Cut Sets

As described in Section 2.5, two generic types of min cut sets were generated for Zion-1. The first type had order of 5 and the second type had order of 6. Min cut sets of order 5 had the following form:

- loss of offsite power occurs
- swing diesel aligns to unit 1 or unit 2
- relay 1 contacts chatter
- relay 2 contacts chatter
- relay 3 contacts chatter.

Min cut sets of order 6 had the same form as for min cut sets of order 5 except that one additional set of relay contacts must chatter, i.e.,

- loss of offsite power occurs
- swing diesel aligns to unit 1 or unit 2
- relay 1 contacts chatter
- relay 2 contacts chatter
- relay 3 contacts chatter
- relay 4 contacts chatter.

3.4.3 Reactor Coolant Pump Seal LOCA

Table 3-1 presents the number of min cut sets for three different cases:

- swing diesel aligns to unit 1
- swing diesel aligns to unit 2
- total number (sum of the previous 2 cases).
We see that the second case generates more min cut sets than the first case. A total of 27,648 min cut sets of order 5 and 17,192 min cut sets of order 6 are generated.

3.4.4 Transient Sequence

Table 3-2 displays the min sets for the transient sequence. We see that there are no min cut sets of order 5; only order-6 cut sets are found for this accident sequence group. This reflects that fact that more service water pumps must fail to produce this sequence than must fail to produce the pump-seal-LOCA sequence. The table shows that the two swing-diesel cases are symmetric. A total of 152,064 min cut sets are generated.

3.5 Probabilistic Results

As described in Section 2.5, the computer code SEISIM was run to determine the frequency of core damage accidents for the pump-seal-LOCA and the transient accident sequences. The fragilities used for chatter and LOSP are as presented in Section 2.6, and the site-specific hazard information used is as presented in Section 2.7.

The following assumptions were made in running SEISIM:

- it is assumed that relay fragilities are statistically independent of each other; this is believed to be a reasonable assumption on the basis that technical specifications require testing of most relays at specified intervals, and failed relays are replaced.
- it is assumed that all relay chatter fragilities are identical and all contact chatter fragilities are identical;
- it is assumed that each relay experiences the same response;
- it is assumed that there is zero response correlation coefficient between the free field response and the response at the motor control center. This implies that we can multiply the probability of LOSP times the probability of relay chatter given LOSP.

As described in Section 2.5, the probability of the Boolean union of all the min cut sets was calculated. The results are displayed in Table 3-3 for the LOCA sequence and in Table 3-4 for the transient sequence. Two response cases are considered:
o Case A: the relays experience the predicted plant response for that location;

o Case B: the relays experience the peak plant response, meaning the response for the plant location with the greatest motion.

The final risk measure (core damage frequency per year) computed in Tables 3-3 and 3-4 is unconditional, which means that the value in the last column includes the earthquake frequency.

The total unconditional core-damage frequency is the sum of the unconditional frequencies for each earthquake level. As indicated in footnote 2 on Tables 3-3 and 3-4, this is simply the sum of products from the number of min cut sets times the min cut set probability as was computed by SEISIM. The core-damage frequency for each min cut set is calculated as discussed in Section 2, as the convolution of the hazard curve and the fragility curves. These individual min cut sets have quite small core-damage frequencies. However, there are so many of them (about 200,000) that their Boolean sum is non-negligible: The value of core-damage frequency calculated by this analysis is about $4 \times 10^{-4}$ per year. This value is a "best-estimate value" or "point value", without any uncertainty analysis associated with it.

Of course, this number cannot be taken at face value, because a number of assumptions, many of them conservative, have been incorporated into this analysis. Section 6 discusses this issue, along with a discussion of various uncertainties in the analysis.

It is important to note that the unconditional core-damage frequency for each earthquake level cannot exceed the frequency of the earthquake times the probability of LOSP. For both response cases (the predicted-response case, Case A and the peak-response case, Case B), the sum of products for all the min cut sets exceeds this value. This means that the conditional probability that the sequence occurs given the occurrence of the earthquake and loss of offsite power is close to unity (100%). This is true because the number of min cut sets is so large. It must be emphasized again that operator recovery is not included in this evaluation.
3.6 Sensitivity Analysis ---- Zion-1

3.6.1 Variations in the Relay-Chatter Fragility Values

One of the principal unknowns that affects the relay-chatter analysis is the fragility curve for the chatter mode. In this Section, we will discuss a sensitivity analysis that has been performed for this issue.

Specifically, we will describe four cases (a "base case" and three "sensitivity cases") that have been considered for the relay-chatter fragility function. Each of the three sensitivity cases represents a relay chatter fragility function substantially stronger than Case # 1, the base case:

<table>
<thead>
<tr>
<th>Case</th>
<th>Median Fraility</th>
<th>Beta</th>
<th>Small LOCA Sequence</th>
<th>Transient Seq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(BASE CASE)</td>
<td>2.6 g</td>
<td>1.5</td>
<td>Table 3-3</td>
<td>Table 3-4</td>
</tr>
<tr>
<td>2</td>
<td>2.6 g</td>
<td>0.4</td>
<td>Table 3-5</td>
<td>Table 3-8</td>
</tr>
<tr>
<td>3</td>
<td>5.0 g</td>
<td>1.5</td>
<td>Table 3-6</td>
<td>Table 3-9</td>
</tr>
<tr>
<td>4</td>
<td>5.0 g</td>
<td>0.4</td>
<td>Table 3-7</td>
<td>Table 3-10</td>
</tr>
</tbody>
</table>

Case # 1 is the base case, representing the fragility curve used in the main body of this analysis. In Case # 2, the median fraility remains at 2.6 g, but the beta value is smaller, meaning that the overall fragility curve is higher (the lower-side tails of the curve do not extend as far down). Cases # 3 and 4 represent median frailities of 5.0 g, with wider beta (1.5) and narrower beta (0.4), respectively.

The assumptions that were made in the main analysis all apply to the sensitivity runs as well. Specifically, the relay frangilities are assumed to be statistically independent, and the relay responses are assumed to be perfectly correlated.

3.6.2 Discussion

For both the small-LOCA sequence and the transient sequence, the core-damage frequency varies in the same way from case to case. Our discussion below will cover the small-LOCA sequence ---- that is, the reader should study Tables 3-5, 3-6, and 3-7. These should be compared to the base-case.
results in Table 3-3 for the small-LOCA sequence. Our conclusions apply equally to the transient sequence.

Recall that for the base case two different analyses were done, one assuming a "peak response" and the other assuming a "predicted response", taken to be the response at the motor control center.

**Predicted response case:** For the predicted-response case, we see that for Case #2 (same median, smaller beta) the probability of relay chatter and the probability of the min cut sets have decreased (see Table 3-5). However, the probability value is still large enough so that, when multiplied by the large number of min cut sets, the total core-damage frequency is still the same—that is, there is still an essentially 100% likelihood of at least one min cut set occurring. Table 3.6 shows that this conclusion is also true for Case #3 (median raised to 5.0 g, beta value still large at 1.5).

For Case #4 (see Table 3-7), in which the median is 5.0 g and the beta is narrow (0.4), we see that the small-LOCA core-damage sequence frequency is reduced by a factor of 4.

**Peak response analysis:** Because the peak response is so large, even sensitivity Case #4 (the sensitivity case with the strongest relay-chatter capacity) still generates the maximum value for core-damage frequency. That is, even Case #4 still produces a 100% likelihood that at least one of the min cut sets will be present. In technical terms, the probability of the Boolean union for Case #4 is still unity, as it was for Case #1. For the peak-response analysis, this conclusion is likewise true for Cases #2 and #3.

**Conclusions from the sensitivity analysis:** We conclude from these sensitivity analysis runs that the relay-chatter median fragility value must be approximately doubled (2.6 to 5.0) and the beta value must be substantially decreased (1.5 to 0.4) in order to produce even the modest difference in core-damage frequency of a factor of 4. Increasing only one of these parameters at a time produces essentially no effect.

3.6.3 **Effect of Modifying the Response Correlation**

Our analysis assumes that the response correlation is unity—specifically, it is assumed that the responses of all relay chattering events are perfectly correlated. What this means in laymen's terms is that their motions are all
identical. If response correlations were zero, then the basic chattering events would be statistically independent of each other, in which case we would simply multiply the individual probabilities separately in each min cut set to obtain the overall min cut set probability.

We recall here the discussion in Section 2.5, pointing out that the response curves used in this analysis have "beta values". For example, for the six earthquake levels at Zion, the response betas are all between 0.346 and 0.463. For our base case analysis (Case # 1), the fragility "beta value" is 1.5, which is so much broader than these response beta values that in calculating the min cut set probabilities we can simply multiply the basic event probabilities together as if these basic events were statistically independent of each other. (In laymen's terms, if the fragility beta is much greater than the response "beta", response correlation has little or no effect on min cut set probabilities.)

However, for sensitivity Case # 2, the fragilities "beta values" are 0.4, comparable in magnitude to the response beta values. The impact of this is shown for Case # 2 on Table 3-5, in which the individual min cut set probability is considerably larger than for Case # 1. Because of response correlation, the min cut set probability is considerably greater than if we assumed that the basic event probabilities were independent (see our example in the paragraph below). While the numerical values should not be taken as valid on their face, because of various assumptions, this sensitivity analysis demonstrates that the numerical results for min cut set probability are sensitive in detail to what is assumed for the widths of the various fragility and response distributions.

To demonstrate the effect of response correlation on the calculation of min cut set probabilities, consider as an example the small-LOCA sequence and examine Case # 1 (see Table 3.3) and Case # 2 (see Table 3.5). The difference between these two cases is the assumed "beta" value, which is 1.5 and 0.4, respectively.

As an example, consider earthquake level 1 in both tables. Assuming statistical independence of basic events, the probability of the min cut set in column (5), Table 3.3, is 1.05 E-4, as follows:
\[ P(\text{LOSP}) \times P(\text{Swing Diesel}) \times P(\text{Relay Chatter})^3 \]

\[ = (2.6 \times 10^{-1}) \times (0.5) \times (9.3 \times 10^{-2})^3 \]

\[ = 1.05 \times 10^{-4}. \]

This is almost exactly the value computed by SEISIM, which shows that even though SEISIM assumes full response correlation that assumption does not affect the numerical result.

In Table 3.5 (for Case # 2), the probability of this min cut set, assuming independence, would be $2.7 \times 10^{-14}$, as follows:

\[ (2.6 \times 10^{-1}) \times (0.5) \times (5.94 \times 10^{-5})^3 \]

\[ = 2.7 \times 10^{-14}. \]

This value is about 5 orders of magnitude smaller than the $4.35 \times 10^{-9}$ calculated by SEISIM, whose algorithm takes into account the full response correlation that we have assumed in our analysis. Thus in Case # 2 the response correlation has an important bearing on the numerical result.

3.7 Operator Recovery Actions at Zion-1

We now discuss briefly the operator actions that would be necessary to recover from the failure modes described above. Discussion with Commonwealth Edison Company engineers indicates that the Zion operators are well-trained on the X-Y circuit-breaker scheme. If loss of offsite power were to occur at Zion, the operators would follow the emergency operating instructions to restore AC power. These instructions clearly specify that the operators must close the DG circuit breakers and the circuit breakers to the ESF loads.

If breakers to ESF loads have tripped open due to relay chatter of protective relay contacts, the operator can reclose these breakers by simply closing the control switch in the control room. Closing the control switch manually will cause a momentary open circuit that will cause the Y relay to drop out,
permitting reclosure of the circuit breaker. This is true for all such breakers except the breakers to the dedicated diesels (not the swing diesel), which require manual operator action at the motor control center rather than the control room. In this case, the Y relay seals in.

Commonwealth Edison has indicated that at the next refueling outage changes will be made to the control circuits for other reasons, which changes will allow the seal-in to be dropped out from the control room according to emergency operating procedures.

In our analysis, the assumption has been made that there is no operator recovery. Although this is clearly quite pessimistic, we do not know how to perform a more accurate analysis without doing a detailed "task analysis" on each important recovery operation, which is beyond the scope of the current project.

3.8 Conclusions and Insights from the Zion-1 Analysis

The conclusions and insights from the analysis of Zion-1 are presented in Section 6.2, and generic insights based on both the Zion-1 and LaSalle-2 analyses are presented in Section 6.4.
Table 3-1
Reactor Coolant Pump Seal LOCA
Min Cut Set Summary

CASE 1 — Diesel DG-0 Swings to Unit 1
Number of Min Cut Sets of Order 5 13,824
Number of Min Cut Sets of Order 6 6,388

CASE 2 — Diesel DG-0 Swings to Unit 2
Number of Min Cut Sets of Order 5 13,824
Number of Min Cut Sets of Order 6 10,804

TOTAL (Sum of Cases 1 AND 2)
Number of Min Cut Sets of Order 5 27,648
Number of Min Cut Sets of Order 6 17,192
Table 3-2
Transient Sequence
Min Cut Set Summary

<table>
<thead>
<tr>
<th>CASE</th>
<th>Description</th>
<th>Number of Min Cut Sets of Order 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE 1</td>
<td>Diesel DG-0 Swings to Unit 1</td>
<td>76,032</td>
</tr>
<tr>
<td>CASE 2</td>
<td>Diesel DG-0 Swings to Unit 2</td>
<td>76,032</td>
</tr>
<tr>
<td>CASE 3</td>
<td>TOTAL (Sum of Cases 1 and 2)</td>
<td>152,064</td>
</tr>
</tbody>
</table>
## TABLE 3-3 -- SEISIM RUNS FOR ZION UNIT 1 -- SMALL LOCA SEQUENCE (CASE 1)

<table>
<thead>
<tr>
<th>COLUMN (1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EARTHQUAKE FREQUENCY</td>
<td>Earthquake Level</td>
<td>P(LOS)</td>
<td>P(RELAY CHATTER, R)</td>
<td>P(LOS)x P(RELAY CHATTER, R)</td>
<td>P(LOS)x P(RELAY CHATTER, R)</td>
<td>UNCONDITIONAL RISK (YR-1)</td>
</tr>
<tr>
<td>1</td>
<td>5.48 E-4</td>
<td>2.60 E-1</td>
<td>9.30 E-2</td>
<td>1.05 E-4</td>
<td>9.75 E-6</td>
<td>*1.42 E-4</td>
</tr>
<tr>
<td>2</td>
<td>2.66 E-4</td>
<td>7.35 E-1</td>
<td>1.44 E-1</td>
<td>1.11 E-3</td>
<td>1.60 E-4</td>
<td>*(1.96 E-4)</td>
</tr>
<tr>
<td>3</td>
<td>1.32 E-5</td>
<td>9.92 E-1</td>
<td>2.61 E-1</td>
<td>8.82 E-3</td>
<td>2.30 E-3</td>
<td>*(1.31 E-5)</td>
</tr>
<tr>
<td>4</td>
<td>1.62 E-6</td>
<td>1.00 E+0</td>
<td>3.92 E-1</td>
<td>1.78 E-2</td>
<td>5.98 E-3</td>
<td>*(1.62 E-6)</td>
</tr>
<tr>
<td>5</td>
<td>4.18 E-7</td>
<td>1.00 E+0</td>
<td>3.77 E-1</td>
<td>2.68 E-2</td>
<td>1.01 E-2</td>
<td>*(4.18 E-7)</td>
</tr>
<tr>
<td>6</td>
<td>1.62 E-7</td>
<td>1.00 E+0</td>
<td>4.19 E-1</td>
<td>3.68 E-2</td>
<td>1.54 E-2</td>
<td>*(1.62 E-7)</td>
</tr>
</tbody>
</table>

**TOTAL UNCONDITIONAL RISK (YR-1)**: 3.73 E-4

**NOTES:**

1. Columns (5) and (6) represent individual MIN cut set probabilities
2. Unconditional risk (for each earthquake level) = Column (2) x [27,648 x Column (5) + 17,192 x Column (6)]
3. Maximum unconditional risk = Prob(Earthquake Per Year) x P(LOS)
4. P(SWING) = 0.5
5. Fragility (Chatter): Relay -- Median capacity = 2.60 g, Beta = 1.5
6. Assumptions:
   - Relay responses are assumed to be perfectly correlated
   - All fragilities are assumed to be statistically independent
### TABLE 3-4 -- SEISIM RUNS FOR ZION UNIT 1 -- TRANSIENT SEQUENCE (CASE 1)

152,064 MIN CUT SETS (ORDER 6)

<table>
<thead>
<tr>
<th>COLUMN (1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTUAL (PEAK)</td>
<td>P</td>
<td>ACTUAL (PEAK)</td>
<td>P</td>
<td>ACTUAL (PEAK)</td>
<td>P</td>
</tr>
<tr>
<td>EARTHQUAKE LEVEL</td>
<td>EARTHQUAKE Freq</td>
<td>P(LOS P)</td>
<td>P(RELAY CHATTER, R)</td>
<td>P(SWING)</td>
<td>P(R-1 AND R-2 AND R-3 AND R-4)</td>
</tr>
<tr>
<td>UNCONDITIONAL RISK (YR-1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. **5.48 E-4** 2.60 E-1 9.30 E-2 (1.00 E+0)P 9.75 E-6 (1.30 E-1)P *1.42 E-4 *(1.42 E-4)P

2. **2.66 E-4** 7.35 E-1 1.44 E-1 (1.00 E+0)P 1.60 E-4 (3.68 E-1)P *1.96 E-4 *(1.96 E-4)P

3. **1.32 E-5** 9.92 E-1 2.61 E-1 (1.00 E+0)P 2.30 E-3 (4.96 E-1)P *1.31 E-5 *(1.31 E-5)P

4. **1.62 E-6** 1.00 E-0 3.92 E-1 (1.00 E+0)P 5.98 E-3 (5.00 E-1)P *1.62 E-6 *(1.62 E-6)P

5. **4.18 E-7** 1.00 E-0 3.77 E-1 (1.00 E+0)P 1.01 E-2 (5.00 E-1)P *4.18 E-7 *(4.18 E-7)P

6. **1.62 E-7** 1.00 E-0 4.19 E-1 (1.00 E+0)P 1.54 E-2 (5.00 E-1)P *1.62 E-7 *(1.62 E-7)P

**TOTAL UNCONDITIONAL RISK (YR-1)** 3.73 E-4 (3.73 E-4)P

**NOTES:**

1. COLUMN (5) REPRESENTS INDIVIDUAL MIN CUT SET PROBABILITIES
2. UNCONDITIONAL RISK (FOR EACH EARTHQUAKE LEVEL) = COLUMN (2) x 152,064 x COLUMN (5)
   * MAXIMUM UNCONDITIONAL RISK = PROB(EARTHQUAKE PER YEAR) x P(LOS P)
3. TOTAL UNCONDITIONAL RISK = UNCONDITIONAL RISK SUMMED OVER ALL SIX EARTHQUAKE LEVELS
4. P(SWING) = 0.5
5. FRAGILITY (CHATTER):
   RELAY -- MEDIAN CAPACITY = 2.60 g, BETA = 1.5
6. ASSUMPTIONS:
   RELAY RESPONSES ARE ASSUMED TO BE PERFECTLY CORRELATED
   ALL FRAGILITIES ARE ASSUMED TO BE STATISTICALLY INDEPENDENT
### Table 3-5 -- Seisim Runs for Zion Unit 1 -- Small LOCA Sequence (Case 2)

<table>
<thead>
<tr>
<th>Earthquake Level</th>
<th>Earthquake Frequency</th>
<th>YR-1</th>
<th>Actual (Peak) P</th>
<th>Actual (Peak) P</th>
<th>Actual (Peak) P</th>
<th>Actual (Peak) P</th>
<th>Actual (Peak) P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>5.48E-4</td>
<td>2.60E-1</td>
<td>5.94E-5</td>
<td>4.75E-9</td>
<td>5.39E-10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1.00 E+0)P</td>
<td>(1.30 E-1)P</td>
<td>(1.30 E-1)P</td>
<td>(1.30 E-1)P</td>
<td>(1.30 E-1)P</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>2.66E-4</td>
<td>7.35E-1</td>
<td>3.24E-3</td>
<td>4.05E-5</td>
<td>1.71E-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1.00 E+0)P</td>
<td>(3.68 E-1)P</td>
<td>(3.68 E-1)P</td>
<td>(3.68 E-1)P</td>
<td>(3.68 E-1)P</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>1.32E-5</td>
<td>9.92E-1</td>
<td>3.60E-2</td>
<td>1.24E-3</td>
<td>5.80E-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1.00 E+0)P</td>
<td>(4.96 E-1)P</td>
<td>(4.96 E-1)P</td>
<td>(4.96 E-1)P</td>
<td>(4.96 E-1)P</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>1.62E-6</td>
<td>1.00E+0</td>
<td>1.07E-1</td>
<td>7.89E-3</td>
<td>4.50E-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>4.18E-7</td>
<td>1.00E+0</td>
<td>1.89E-1</td>
<td>2.17E-2</td>
<td>1.36E-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>1.62E-7</td>
<td>1.00E+0</td>
<td>4.66E-1</td>
<td>5.06E-2</td>
<td>3.17E-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
</tr>
</tbody>
</table>

**Notes:**

1. Columns (5) and (6) represent individual min cut set probabilities.
2. Unconditional risk (for each earthquake level) = Column (2) x [27,648 x Column (5) + 17,192 x Column (6)]
3. Maximum unconditional risk = Prob(Earthquake per year) x P(LOS)
4. P(SWING) = 0.5
5. Fragility(CHATTER): Relay -- Median capacity = 2.60 g, Beta = 0.4
6. Assumptions: Relay responses are assumed to be perfectly correlated; all fragilities are assumed to be statistically independent.
<table>
<thead>
<tr>
<th>EARTHQUAKE LEVEL</th>
<th>EARTHQUAKE FREQUENCY</th>
<th>P(LOSP)</th>
<th>P(RELAY CHATTER, R)</th>
<th>P(SWING1 X)</th>
<th>P(SWING1 X)</th>
<th>P(LOSP) X</th>
<th>P(LOSP) X</th>
<th>UNCONDITIONAL RISK (YR-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>YR-1</td>
<td>5.48 E-4</td>
<td>2.60 E-1</td>
<td>4.02 E-2</td>
<td>8.49 E-6</td>
<td>3.42 E-7</td>
<td>1.32 E-4</td>
<td>*(1.42 E-4)P</td>
</tr>
<tr>
<td>2</td>
<td>YR-1</td>
<td>2.66 E-4</td>
<td>7.35 E-1</td>
<td>6.97 E-2</td>
<td>1.24 E-4</td>
<td>8.67 E-6</td>
<td>*1.96 E-4</td>
<td>*(1.96 E-4)P</td>
</tr>
<tr>
<td>3</td>
<td>YR-1</td>
<td>1.32 E-5</td>
<td>9.92 E-1</td>
<td>1.44 E-2</td>
<td>1.47 E-3</td>
<td>2.12 E-4</td>
<td>*1.31 E-5</td>
<td>*(1.31 E-5)P</td>
</tr>
<tr>
<td>4</td>
<td>YR-1</td>
<td>1.62 E-6</td>
<td>1.00 E+0</td>
<td>1.93 E-1</td>
<td>3.60 E-3</td>
<td>6.96 E-4</td>
<td>*1.62 E-6</td>
<td>*(1.62 E-6)P</td>
</tr>
<tr>
<td>5</td>
<td>YR-1</td>
<td>4.18 E-7</td>
<td>1.00 E+0</td>
<td>2.31 E-1</td>
<td>6.13 E-3</td>
<td>1.41 E-3</td>
<td>*4.18 E-7</td>
<td>*(4.18 E-7)P</td>
</tr>
<tr>
<td>6</td>
<td>YR-1</td>
<td>1.62 E-7</td>
<td>1.00 E+0</td>
<td>4.04 E-1</td>
<td>1.41 E-1</td>
<td>1.35 E-1</td>
<td>*1.62 E-7</td>
<td>*(1.62 E-7)P</td>
</tr>
</tbody>
</table>

TOTAL UNCONDITIONAL RISK (YR-1) = 3.63 E-4

NOTES:

[1] COLUMNS (5) AND (6) REPRESENT INDIVIDUAL MIN CUT SET PROBABILITIES
[2] UNCONDITIONAL RISK (FOR EACH EARTHQUAKE LEVEL) = COLUMN (2) x [27,648 x COLUMN (5) + 17,192 x COLUMN (6)]
[3] MAXIMUM UNCONDITIONAL RISK = PROB(EARTHQUAKE PER YEAR) x P(LOSP) * MAXIMUM UNCONDITIONAL RISK = PROB(EARTHQUAKE PER YEAR) x P(LOSP)
[4] TOTAL UNCONDITIONAL RISK = UNCONDITIONAL RISK SUMMED OVER ALL SIX EARTHQUAKE LEVELS
[5] P(SWING) = 0.5
   RELAY -- MEDIAN CAPACITY = 5.00 g, BETA = 1.5
[7] ASSUMPTIONS:
   RELAY RESPONSES ARE ASSUMED TO BE PERFECTLY CORRELATED
   ALL FRAGILITIES ARE ASSUMED TO BE STATISTICALLY INDEPENDENT
<table>
<thead>
<tr>
<th>COLUMN (1)</th>
<th>EARTHQUAKE LEVEL</th>
<th>EARTHQUAKE FREQUENCY</th>
<th>YR-1</th>
<th>COLUMN (2)</th>
<th>MIN CUT SETS</th>
<th>ORDER 5</th>
<th>COLUMN (3)</th>
<th>ACTUAL PEAK P</th>
<th>COLUMN (4)</th>
<th>ACTUAL PEAK P</th>
<th>COLUMN (5)</th>
<th>ACTUAL PEAK P</th>
<th>COLUMN (6)</th>
<th>ACTUAL PEAK P</th>
<th>COLUMN (7)</th>
<th>ACTUAL PEAK P</th>
<th>UNCONDITIONAL RISK (YR-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.48 E-4</td>
<td>2.60 E-1</td>
<td>&lt;1.00 E-8 (1.00 E+0)P</td>
<td>&lt;1.00 E-15 (1.30 E-1)P</td>
<td>&lt;1.00 E-15 (1.30 E-1)P</td>
<td>&lt;2.46 E-14 *(1.42 E-4)P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.66 E-4</td>
<td>7.35 E-1</td>
<td>7.46 E-5 (1.00 E+0)P</td>
<td>1.42 E-7 (3.68 E-1)P</td>
<td>3.65 E-8 (3.68 E-1)P</td>
<td>1.21 E-6 *(1.96 E-4)P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.32 E-5</td>
<td>9.92 E-1</td>
<td>1.40 E-3 (1.00 E+0)P</td>
<td>5.90 E-6 (4.96 E-1)P</td>
<td>1.63 E-6 (4.96 E-1)P</td>
<td>2.52 E-6 *(1.31 E-5)P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.62 E-6</td>
<td>1.00 E+0</td>
<td>7.49 E-3 (1.00 E+0)P</td>
<td>9.38 E-5 (5.00 E-1)P</td>
<td>3.40 E-5 (5.00 E-1)P</td>
<td>1.62 E-6 *(1.62 E-6)P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.18 E-7</td>
<td>1.00 E+0</td>
<td>1.94 E-2 (1.00 E+0)P</td>
<td>4.52 E-4 (5.00 E-1)P</td>
<td>1.92 E-4 (1.00 E+0)P</td>
<td>4.18 E-7 *(4.18 E-7)P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.62 E-7</td>
<td>1.00 E+0</td>
<td>3.97 E-1 (1.00 E+0)P</td>
<td>1.45 E-1 (5.00 E-1)P</td>
<td>6.16 E-2 (5.00 E-1)P</td>
<td>1.62 E-7 *(1.62 E-7)P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

1. Columns (5) and (6) represent individual min cut set probabilities.
2. Unconditional risk (for each earthquake level) = Column (2) * [27,648 x Column (5) + 17,192 x Column (6)]
3. Maximum unconditional risk = Prob(Earthquake per year) x P(LOSP)
4. P(SWING) = 0.5
5. Fragility (chatter):
   - Relay: Median capacity = 5.00 g, Beta = 0.4
6. Assumptions:
   - Relay responses are assumed to be perfectly correlated.
   - All fragilities are assumed to be statistically independent.
**TABLE 3-8 -- SEISIM RUNS FOR ZION UNIT 1 -- TRANSIENT SEQUENCE (CASE 2)**

<table>
<thead>
<tr>
<th>COLUMN (1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>ACTUAL</td>
<td>ACTUAL</td>
<td>ACTUAL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(PEAK)P</td>
<td>(PEAK)P</td>
<td>(PEAK)P</td>
</tr>
<tr>
<td>EARTHQUAKE LEVEL</td>
<td>EARTHQUAKE FREQUENCY</td>
<td>P(LOSP)</td>
<td>P(RELAY P(LOSP)x R)</td>
<td>P(RELAY P(LOSP)x R-1 AND R-2 AND R-3 R-4)</td>
<td>UNCONDITIONAL RISK (YR-1)</td>
</tr>
<tr>
<td>1</td>
<td>5.48 E-4</td>
<td>2.60 E-1</td>
<td>5.94 E-5</td>
<td>5.39 E-10</td>
<td>4.49 E-8</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(1.30 E-1)P</td>
<td>(1.30 E-1)P</td>
<td>(1.30 E-1)P</td>
<td>*(1.42 E-4)P</td>
</tr>
<tr>
<td>2</td>
<td>2.66 E-4</td>
<td>7.35 E-1</td>
<td>3.24 E-3</td>
<td>1.71 E-5</td>
<td>*(1.96 E-4)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(3.68 E-1)P</td>
<td>(3.68 E-1)P</td>
<td>(3.68 E-1)P</td>
<td>*(1.96 E-4)P</td>
</tr>
<tr>
<td>3</td>
<td>1.32 E-5</td>
<td>9.92 E-1</td>
<td>3.60 E-2</td>
<td>5.80 E-4</td>
<td>*(1.31 E-5)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(4.96 E-1)P</td>
<td>(4.96 E-1)P</td>
<td>(4.96 E-1)P</td>
<td>*(1.31 E-5)P</td>
</tr>
<tr>
<td>4</td>
<td>1.62 E-6</td>
<td>1.00 E-0</td>
<td>1.07 E-1</td>
<td>4.50 E-3</td>
<td>*(1.62 E-6)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>*(1.62 E-6)P</td>
</tr>
<tr>
<td>5</td>
<td>4.18 E-7</td>
<td>1.00 E-0</td>
<td>1.89 E-1</td>
<td>1.36 E-2</td>
<td>*(4.18 E-7)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>*(4.18 E-7)P</td>
</tr>
<tr>
<td>6</td>
<td>1.62 E-7</td>
<td>1.00 E-0</td>
<td>4.66 E-1</td>
<td>3.17 E-2</td>
<td>*(1.62 E-7)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>(5.00 E-1)P</td>
<td>*(1.62 E-7)P</td>
</tr>
</tbody>
</table>

**TOTAL UNCONDITIONAL RISK (YR-1)**

2.31 E-4

(3.73 E-4)P

**NOTES:**

1. COLUMN (5) REPRESENTS INDIVIDUAL MIN CUT SET PROBABILITIES
2. UNCONDITIONAL RISK (FOR EACH EARTHQUAKE LEVEL) = COLUMN (2) x 152,064 x COLUMN (5)
3. MAXIMUM UNCONDITIONAL RISK = PROB(EARTHQUAKE PER YEAR) x P(LOSP)
4. TOTAL UNCONDITIONAL RISK = UNCONDITIONAL RISK SUMMED OVER ALL SIX EARTHQUAKE LEVELS
5. P(SWING) = 0.5
6. FRAGILITY(CHATTER):
   - RELAY -- MEDIAN CAPACITY = 2.60 g, BETA = 0.4
7. ASSUMPTIONS:
   - RELAY RESPONSES ARE ASSUMED TO BE PERFECTLY CORRELATED
   - ALL FRAGILITIES ARE ASSUMED TO BE STATISTICALLY INDEPENDENT
Table 3-9 -- Seisim Runs for Zion Unit 1 -- Transient Sequence (Case 3)

<table>
<thead>
<tr>
<th>Column (1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4) Actual Peak/P</th>
<th>(5) Actual Peak/P</th>
<th>(6) Actual Peak/P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake Frequency</td>
<td>Earthquake</td>
<td>P(LOSP)</td>
<td>P(RELAY CHATTER, R)</td>
<td>P(LOSP)x R-1 AND R-2 AND R-3 R-4</td>
<td>Unconditional Risk (YR-1)</td>
</tr>
<tr>
<td>Yr-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.48 E-4</td>
<td>2.60 E-1</td>
<td>4.02 E-2</td>
<td>3.42 E-7</td>
<td>2.85 E-5</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(1.30 E-1)P</td>
<td>*(1.42 E-4)P)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.66 E-4</td>
<td>7.35 E-1</td>
<td>6.97 E-2</td>
<td>8.67 E-6</td>
<td>*(1.96 E-4)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(3.68 E-1)P</td>
<td>*(1.96 E-4)P)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.32 E-5</td>
<td>9.92 E-1</td>
<td>1.44 E-2</td>
<td>2.12 E-4</td>
<td>*(1.31 E-5)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(4.96 E-1)P</td>
<td>*(1.31 E-5)P)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.62 E-6</td>
<td>1.00 E-0</td>
<td>1.93 E-1</td>
<td>6.96 E-4</td>
<td>*(1.62 E-6)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>*(1.62 E-6)P)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.18 E-7</td>
<td>1.00 E-0</td>
<td>2.31 E-1</td>
<td>1.41 E-3</td>
<td>*(4.18 E-7)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>*(4.18 E-7)P)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.62 E-7</td>
<td>1.00 E-0</td>
<td>4.04 E-1</td>
<td>1.35 E-1</td>
<td>*(1.62 E-7)P</td>
</tr>
<tr>
<td></td>
<td>(1.00 E+0)P</td>
<td>(5.00 E-1)P</td>
<td>*(1.62 E-7)P)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total unconditional risk (YR-1) = 2.60 E-4 (3.73 E-4)P

Notes:

[1] Column (5) represents individual min cut set probabilities.
[2] Unconditional risk (for each earthquake level) = column (2) x 152,064 x column (5)
    * Maximum unconditional risk = prob(earthquake per year) x P(LOSP)
[3] Total unconditional risk = unconditional risk summed over all six earthquake levels
[4] P(SWING) = 0.5
[5] Fragility (chatter): relay -- Median capacity = 5.00 g, Beta = 1.5
[6] Assumptions:
    Relay responses are assumed to be perfectly correlated
    All fragilities are assumed to be statistically independent
<table>
<thead>
<tr>
<th>EARTHQUAKE LEVEL</th>
<th>EARTHQUAKE FREQUENCY</th>
<th>ACTUAL (PEAK) P</th>
<th>ACTUAL (PEAK) P</th>
<th>ACTUAL (PEAK) P</th>
<th>UNCONDITIONAL RISK (YR-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>YR-1</td>
<td>5.48 E-4</td>
<td>2.60 E-1</td>
<td>&lt;1.00 E-8 (1.00 E+0)P</td>
<td>1.00 E-15 (1.30 E-1)P</td>
</tr>
<tr>
<td>2</td>
<td>YR-1</td>
<td>2.65 E-4</td>
<td>7.35 E-1</td>
<td>7.46 E-5 (1.00 E+0)P</td>
<td>3.65 E-8 (3.68 E-1)P</td>
</tr>
<tr>
<td>3</td>
<td>YR-1</td>
<td>1.32 E-5</td>
<td>9.92 E-1</td>
<td>1.40 E-3 (1.00 E+0)P</td>
<td>1.63 E-6 (4.96 E-1)P</td>
</tr>
<tr>
<td>4</td>
<td>YR-1</td>
<td>1.62 E-6</td>
<td>1.00 E-0</td>
<td>7.49 E-3 (1.00 E+0)P</td>
<td>3.40 E-5 (5.00 E-1)P</td>
</tr>
<tr>
<td>5</td>
<td>YR-1</td>
<td>4.18 E-7</td>
<td>1.00 E-0</td>
<td>1.94 E-2 (1.00 E+0)P</td>
<td>1.92 E-4 (5.00 E-1)P</td>
</tr>
<tr>
<td>6</td>
<td>YR-1</td>
<td>1.62 E-7</td>
<td>1.00 E-0</td>
<td>3.97 E-1 (1.00 E+0)P</td>
<td>6.16 E-2 (5.00 E-1)P</td>
</tr>
</tbody>
</table>

**NOTES:**

1. COLUMN (5) REPRESENTS INDIVIDUAL MIN CUT SET PROBABILITIES
2. UNCONDITIONAL RISK (FOR EACH EARTHQUAKE LEVEL) = COLUMN (2) x 152,064 x COLUMN (5)
3. MAXIMUM UNCONDITIONAL RISK = PROB(EARTHQUAKE PER YEAR) x P(LOSP)
4. TOTAL UNCONDITIONAL RISK = UNCONDITIONAL RISK SUMMED OVER ALL SIX EARTHQUAKE LEVELS
5. P(SWING) = 0.5
6. FRAGILITY(CHATTER):
    RELAY -- MEDIAN CAPACITY = 5.00 g, BETA = 0.4
7. ASSUMPTIONS:
    RELAY RESPONSES ARE ASSUMED TO BE PERFECTLY CORRELATED
    ALL FRAGILITIES ARE ASSUMED TO BE STATISTICALLY INDEPENDENT
FIG. 3.3 -- KEY DIAGRAM FOR 4.16 KV ESF BUSES 147 AND 148
FIG. 3.4 -- SINGLE LINE DIAGRAM
DIVISION 18
Figure 3.5 Possible Sequence of Events Following a Strong-Motion Earthquake
FIG. 3.8 -- 2-OUT-OF-3
UNDERVOLTAGE
LOGIC CIRCUIT
FIG. 3.9 -- CONTROL CIRCUIT FOR
DIESEL GENERATOR 1A
FEED BREAKER
FIG. 3.10 -- UNDervoltage/OVER-VOLTAGE RELAYS FOR DIESEL GENERATOR
FIG. 3.12 -- CONTROL CIRCUIT FOR 480 V FEED BREAKER TO TRANSFORMER 138
### FIG. 3.13 -- CLOSING SEQUENCE FOR TIMER MOTOR T-SD/18-1

<table>
<thead>
<tr>
<th>Cam No.</th>
<th>Contact</th>
<th>Service</th>
<th>Schem. Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IA-1B</td>
<td>Safety Injection Pump 1B</td>
<td>RP9</td>
</tr>
<tr>
<td>2</td>
<td>2A-2B</td>
<td>Residual Heat Removal Pump 1B</td>
<td>RP10</td>
</tr>
<tr>
<td>3</td>
<td>3A-3B</td>
<td>Containment Spray Pump 1B &amp; Auxiliaries</td>
<td>RP10</td>
</tr>
<tr>
<td>4</td>
<td>4A-4B</td>
<td>Containment Spray Pump 1B &amp; Auxiliaries</td>
<td>RP10</td>
</tr>
<tr>
<td>5</td>
<td>5A-5B</td>
<td>Containment Cooling Fans 1A &amp; 1D</td>
<td>RP11</td>
</tr>
<tr>
<td>6</td>
<td>6A-6B</td>
<td>Service Water Pump 1B</td>
<td>RP11</td>
</tr>
<tr>
<td>7</td>
<td>7A-7B</td>
<td>Auxiliary Feedwater Pump 1B</td>
<td>RP11</td>
</tr>
<tr>
<td>8</td>
<td>8A-8B</td>
<td>Component Cooling Pump 00</td>
<td>RP12</td>
</tr>
<tr>
<td>9</td>
<td>9A-9B</td>
<td>Spare</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10A-10B</td>
<td>Spare</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>11A-11B</td>
<td>Spare</td>
<td></td>
</tr>
</tbody>
</table>

### CAM DEVELOPMENT - PART 3

<table>
<thead>
<tr>
<th>Cam No.</th>
<th>Service</th>
<th>Schem. Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Component Cooling Pump 00</td>
<td>RD12</td>
</tr>
<tr>
<td>2</td>
<td>Service Water Pump 1B</td>
<td>RP11</td>
</tr>
<tr>
<td>3</td>
<td>Auxiliary Feedwater Pump 1B</td>
<td>RP11</td>
</tr>
<tr>
<td>4</td>
<td>Containment Cooling Fans 1A &amp; 1D</td>
<td>RP11</td>
</tr>
<tr>
<td>5</td>
<td>Spare</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Spare</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Spare</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Spare</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Spare</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Spare</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Spare</td>
<td></td>
</tr>
</tbody>
</table>

### Schematic Diagram

ZION STATION UNIT 1 COMMONWEALTH EDISON CO CHICAGO ILLINOIS
FIG. 3.14 -- CONTROL CIRCUIT FOR R6/18-1 RELAY [K-10]
FIG 3.15  GENERIC FAULT TREE FOR ENGINEERED SAFETY LOADS

COMPONENT COOLING WATER
OR SERVICE WATER PUMP
Fails to start or run

* OR *

*********************************************************************************
* SUPPLY BREAKER TRIPS OPEN *
THIS SHEET TRIP COIL IS INADVERTANTLY ENERGIZED
* OR *

*********************************************************************************
* 427, UNDervoltage Relay Contacts
Relay Chatter
* 450/451 Co-5 OA, Overcurrent Contacts, Chatter
* 450/451 Co-5 OC, Overcurrent Contacts, Chatter
* 450 G/PJc, Overcurrent Contacts, Chatter

*********************************************************************************
* SUPPLY BREAKER TRIPS OPEN *
THIS SHEET TRIPS OPEN
* *

*********************************************************************************
* SUPPLY BREAKER TRIPS OPEN *
INSUFFICIENT POWER ON 4.16 KV BUS
* *

*********************************************************************************
* 427, UNDERVOLTAGE RELAY CONTACTS
CHATTER
* 450/451 CO-5 OA, OVERCURRENT CONTACTS, CHATTER
* 450/451 CO-5 OC, OVERCURRENT CONTACTS, CHATTER
* 450 G/PJC, OVERCURRENT CONTACTS, CHATTER

--------- THIS SHEET --------- SHEET 2 --------- SHEET 3 ---------
FIGURE 3.15 CONTINUED

SUPPLY BREAKER FAILS TO CLOSE
* CLOSING COIL IS NOT ENERGIZED
* CLOSE SIGNAL NOT GENERATED
* LOAD SEQUENCERS NOT ENERGIZED
* NO POWER ON 480V BUS 137, 138, 139, 237, 238, 239
* 4.16KV/480V FEED BREAKER TRIPS
* TRIP COIL IS INADVERTANTLY ENERGIZED
* OR
*

******************************************************************************************************
* 427, UNDervoltage Relay Contacts Chatter 450/451 CO-11 Contact, Chatter 450/451 CO-11 Contact, Chatter 450 G/PJC, OverCurrent Contacts, Chatter
FIGURE 3.15 CONTINUED

FAULT TREE FOR 4.16KV BUSES WITH DEDICATED DIESELS

NO AC POWER
ON 4.16 KV BUS 148, 149, 248, 249
* DG SUPPLY BREAKER TRIPS
* TRIP COIL IS INADVERTANTLY ENERGIZED (CAUSES Y RELAY TO SEAL-IN)
* OR
*
**********************************************************************************
*
*
486-1 486-2 486-DG 451 CO-6 451 CO-6
LOCKOUT RELAY LOCKOUT RELAY LOCKOUT RELAY OC, OVERCURRENT OC, OVERCURRENT
CONTACTS, CHATTER CONTACTS, CHATTER CONTACTS, CHATTER CONTACTS, CHATTERCONTACTS, CHATTER

FAULT TREE FOR NO AC POWER ON BUSES 147 OR 247 (SHARE SWING DIESEL)

NO AC POWER ON 4.16 KV BUS 147 (247)
* DIESEL GENERATOR DG-0 SWINGS TO OTHER UNIT

(ASSUME TO OCCUR WITH PROBABILITY 0.5)
FIG. 3.16 -- CONTROL CIRCUIT FOR DIESEL GENERATOR FEED BREAKER

DIESEL GENERATOR O FEED BREAKER

SCHEMATIC DIAGRAM
ZION STATION
UNIT 1
COMMONWEALTH EDISON CO
CHICAGO ILLINOIS

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

REV: A 3-1-76
REVISIONS

1 B 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

FIG. 3.16 -- CONTROL CIRCUIT FOR DIESEL GENERATOR FEED BREAKER

DIESEL GENERATOR O FEED BREAKER

SCHEMATIC DIAGRAM
ZION STATION
UNIT 1
COMMONWEALTH EDISON CO
CHICAGO ILLINOIS

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

REV: A 3-1-76
REVISIONS

1 B 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

FIG. 3.16 -- CONTROL CIRCUIT FOR DIESEL GENERATOR FEED BREAKER

DIESEL GENERATOR O FEED BREAKER

SCHEMATIC DIAGRAM
ZION STATION
UNIT 1
COMMONWEALTH EDISON CO
CHICAGO ILLINOIS

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

REV: A 3-1-76
REVISIONS

1 B 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
SECTION 4
DETAILS OF THE LIMITED-SCOPE SEISMIC PRA FOR LASALLE-2

As mentioned in the introduction, LaSalle-2 is a boiling water reactor (General Electric BWR/5, Mark II design), rated at 1100 MWe. LaSalle-2 (or "LSCS-2" for "LaSalle County Station, Unit 2") is owned by Commonwealth Edison Company, and has a twin unit (Unit 1) on the same site, which shares certain important equipment to be discussed below.

This Section describes the limited-scope seismic PRA that has been performed for LaSalle-2. The analysis here covers accident sequences in which a loss of offsite power (LOSP) occurs after a major earthquake. The analysis considers only failure modes involving the chatter of relays and pressure-switch contacts after LOSP. As mentioned in Section 1, the authors recognize that this analysis is not fully realistic, and the numerical results should not be used as an indicator of LaSalle's seismic risk.

The basic assumptions used in this analysis, which were discussed above in Section 2, are as follows:

- we assume that loss of offsite power (LOSP) occurs with a certain probability due to earthquake-caused failure of the electrical grid's ceramic insulators, because their seismic capacity is generally much lower than that of any other components and structures; we use an SSMRP-derived fragility function for LOSP which is convoluted with a response function (see Sections 2.5 and 2.6);

- LOSP is the only earthquake-induced initiating event that we consider in this analysis; we assume that LOSP occurs whenever the ceramic insulators are damaged by the earthquake (see Section 2.6);

- we assume that the reactor protection system will shut down the fission chain reaction and keep it down after the earthquake;

- we assume that offsite power is not recovered --- therefore, the main feedwater system is not recovered and is unavailable for coolant makeup and/or heat removal;

- we pessimistically assume that there is no operator action, and in particular that operators do not reset circuit breakers and relays; thus
no credit is taken in our analysis for operator recovery;

- we assume that DC power is always available after the earthquake;
- we assume that the SSMRP "hazard curves" used in this analysis are correct (see Section 2.7);
- we consider only failure modes due to chatter of relay and pressure switch contacts.

It is important to note that we assume that there is no other transient event besides LOSP when the strong-motion earthquake occurs. For example, random pipe breaks, valve mechanical failures, and structural failures are not considered. Furthermore, as mentioned we assume that LOSP does not occur with 100% probability: a seismic fragility function has been assigned for LOSP (see Section 2.6).

Another crucial assumption concerns operator recovery. We assume here that there is no operator recovery action. However, we discuss operator recovery from these failure modes briefly in Section 4.7.

In the analysis, we have excluded failure modes involving the simultaneous chattering of two or more normally-open contacts in series, although we recognize that a more complete analysis would need to include these events. We do not believe that this omission is important for the analysis done here.

The end point of the analysis is the calculation using PRA methods of the frequency of a core-damage accident, based on the assumptions above. In order to accomplish this, the analysis requires two additional key inputs:

- the site-specific frequencies of earthquakes of various sizes must be known ---- this input is discussed in Section 2.7.
- fragilities for the chattering of relay and pressure-switch contacts must be known ---- this input is discussed in Section 2.6.

The accident sequence that was identified as important for LaSalle-2 is the following:

Failure to makeup primary coolant within 80 minutes following loss of offsite power (LOSP). (80 minutes corresponds to the time fuel damage is expected to occur if no coolant makeup is available following LOSP.)
As described in Section 2, circuit breakers to ESF loads should not operate at LaSalle-2 during the strong earthquake motion. This is because loads necessary for primary coolant makeup will not be started until the primary coolant level has boiled off to a specific set point (called "level 2"), after which two key systems are started: the reactor core isolation cooling (RCIC) system and the high pressure core spray (HPCS) system. Given that no makeup systems are operating, boiloff to level 2 is expected to occur at LaSalle-2 by about 10 minutes following LOSP.

However, if LOSP occurs, the diesel generators are expected to start and their supply breakers should close within 10 to 15 seconds.

4.1 Systems Analysis

In Sections 4.1.1, 4.1.2 and 4.1.3, we will describe the following systems which were found in this study to have failure modes that would occur following chattering of relay contacts and pressure switch contacts:

- the Electric Power System
- the Automatic Depressurization System (ADS)
- the Reactor Core Isolation Cooling System (RCIC).

4.1.1 LaSalle Electric Power System

A simple single-line diagram of the overall electric power system at LaSalle is given in Figure 4.1. This shows the output of the unit 1 and unit 2 main generators, which are connected to the grid system through a ring bus arrangement. Also shown are each unit's auxiliary transformers (UAT's 241 and 141) and station auxiliary transformers (SAT's 242 and 142).* These transformers provide power for the 6900-volt and 4160-volt major switch groups which supply power for all plant auxiliaries.

For each unit, all ESF equipment important to plant safety is divided among the three divisions of that unit's Class 1E AC power system switchgear. Divisions 1, 2 and 3 at unit 2 consist of the following switchgear:

* Note that in Figure 4.1 components associated with LaSalle unit 1 are identified by numbers starting with "I" while unit 2 components are identified by numbers starting with "2".

4-3
Division 1:
- 4160-volt bus 241Y.
- 480-volt buses 235X and 235Y.

Division 2:
- 4160-volt bus 242Y.
- 480-volt buses 236X and 236Y.
- 480-volt MCCs 236X-1, 236X-2, 236X-3, 236Y-1 and 236Y-2.
- 120-volt AC distribution panels in 480-volt MCCs 236X-1, 236X-2, 236X-3 and 236Y-2.

Division 3:
- 4160-volt bus 243.
- 480-volt MCC 243-1.
- 120-volt AC distribution panels in 480-volt MCC 243-1.

The loads on each of the 4.16 kV ESF buses for unit 2 are displayed in Table 4-1.

In the event of the total loss of offsite and main auxiliary power, the power required for safe shutdown is supplied from the diesel generators. Two ESF groups (Divisions 2 and 3) are supplied by the two unit 2 diesel generators while the third group (Division 1) is supplied by the shared or "swing" DG, called DG-0, which also supplies those same loads at unit 1, as follows:

- Division 1: diesel generator DG-0 (the "swing diesel")
- Division 2: diesel generator DG-2A
- Division 3: diesel generator DG-2B (called the "HPCS diesel")

Each diesel generator is rated for 4160 volts, 2700 kVA, continuous, and has a minimum rated starting time of 23 seconds from admission of air to rated voltage and frequency. The anticipated starting time is 10 to 15 seconds. The capacity of each diesel generator is sufficient to carry its assigned engineered safeguard system loads and still drive additional motor-operated valves.

The auxiliaries associated with each diesel generator are powered and controlled by the AC train served by that generator or by the corresponding power train. Each diesel generator is served by its own fuel system and supply and each has its own air starting system. Field flashing is required
for generator start.

Upon LOSP, all three diesels will automatically start. In addition, all 4.16 kV loads in divisions 1 and 2 are shed. Division 3 loads are not shed. After each diesel generator has attained its nominal frequency and voltage, its breaker closes.

Table 4-2 displays the status of the relevant circuit breakers following LOSP.

There are numerous conditions that can cause a diesel to go into an emergency shutdown while it is starting and assuming load. As described below, numerous relays are used to sense these abnormal conditions. These relays can chatter after an earthquake, and can cause an emergency shutdown of the diesels. For DG-0 and DG-2A (called non-HPCS diesels), emergency shutdown is initiated by the energizing of a lockout relay* (see Figures 4.2 and 4.3).

The non-HPCS 86 lockout relay energizes on any of several faults:

- engine overspeed (electrical) > 1035 RPM
- high water temperature > 208 F
- engine start failure after 45 second time delay
- low lube oil pressure < 16 psi within 5 sec after reaching 150 RPM
- reverse power
- generator differential current
- overcurrent with voltage restraint (backup)
- loss of exciter (with breaker shut)
- neutral ground (neutral overvoltage)
- emergency stop button, or
- under frequency, < 55 Hz (with breaker shut).

Actuation of the 86 lockout relay stops the engine and locks out the start signal, trips the DG field breaker and shunts the exciter field, and trips and locks out the DG output breaker.

On a loss-of-coolant-accident, all (non-HPCS) diesel trips are bypassed except three: overspeed, differential current, and the emergency stop button.

HPCS uses relays K1 and K15 together to accomplish the same functions as does the 86 device for the non-HPCS circuit, except that HPCS has no under-frequency or neutral ground protection. All other trip signals are identical.

* The lockout relays for the non-HPCS diesels carry the designation "86".
The K1 lockout relay energizes on generator differential current, loss of excitation, reverse power, or overcurrent with voltage restraint. K1 stops the engine and locks out the start signal, trips the DG field breaker and shunts the exciter field, and trips and locks out the DG output breaker. The K15 lockout relay energizes on the emergency stop pushbutton, failure to start after 45 seconds, overspeed > 1035 RPM, low lube oil pressure < 16 psi within 50 seconds after reaching 150 RPM, or high engine cooling water with temperature > 208 F.

Relay K15 stops the engine and trips and locks out the DG output breaker. On LOCA signal all HPCS diesel trips are bypassed except mechanical overspeed, differential current, and emergency stop pushbutton.

4.1.2 The Automatic Depressurization System (ADS)

The major purpose of the ADS system is to provide automatic depressurization for small breaks in the primary coolant boundary, so that the Low Pressure Core Spray (LPCS) System and the Low Pressure Coolant Injection System (LPCI) mode of RHR can operate to protect the core. ADS is part of the ECCS and acts as a backup to the High Pressure Core Spray System (HPCS).

At LaSalle-2, there are eighteen safety/relief valves. These valves perform a safety/relief function if the primary coolant pressure becomes too high. Seven of the eighteen SRVs at LaSalle-2 are assigned to the ADS.

Figure 4.4 shows a simplified circuit of the ADS/SRV initiation logic. An ADS valve will automatically actuate if any of the A, B or C solenoids are energized.

Trip system "A" in Figure 4.4 energizes all A solenoids to ADS valves when all of the following conditions exist:

- high drywell pressure
- reactor vessel low water level
- confirmed reactor vessel low water level
- time delay timed out
- low pressure pumps running.

In this case, both the $K_A$ and $K_C$ relays will energize, causing the A solenoid to energize. Trip system B (not shown in Figure 4.4) energizes solenoid B in a similar manner.

The C solenoid energizes (for both the ADS valves as well as the SRVs) when reactor coolant pressure is too high. Each SRV has its own pressure switch.
When the pressure contacts close, the \( K_z \) relay in Figure 4.4 energizes, which causes the respective C solenoid to energize.

4.1.3 The Reactor Core Isolation Cooling System (RCIC)

When the primary (RCS) is isolated from its normal coolant source, the RCIC system cools the core and reduces reactor vessel pressure following a reactor shutdown. Reactor vessel water is maintained or supplemented by RCIC under any of the following conditions:

- when the reactor vessel is isolated and maintained in the hot standby condition.
- when the reactor vessel is isolated accompanied by a loss of normal coolant flow from the reactor feedwater system.
- when a complete plant shutdown following a loss of normal feedwater is started before the reactor is depressurized enough to allow operation of the reactor shutdown cooling mode of RHR.

The RCIC system may also be used to back up the HPCS system or to operate in conjunction with other ECCS systems if desired.

The RCIC turbine-driven pump operates on steam generated by decay heat. It takes suction water from either the suppression pool or the condensate storage tank (CST). The pump can also be aligned to take suction on the RHR heat exchanger for shutdown cooling. The system consists of one turbine-driven pump discharging to the head spray nozzle inside the reactor vessel. Figure 4.5 is a simplified P&ID of the RCIC system at LaSalle-2.

The RCIC system is normally lined up to draw water from the CST through the normally-open valve MOV 2E51-F010. Should the CST become depleted, the RCIC pump suction will automatically shift to the suppression pool by opening the normally-closed valve MOV 2E51-F031 and closing MOV 2E51-F010.

The RCIC pump discharge is directed to the reactor vessel through the normally-closed injection valve MOV 2E51-F013, or diverted for full flow tests to the CST through normally-closed MOVs 2E51-F022 and 2E51-F059. When the pump discharge is directed to the reactor vessel through 2E51-F013, the flow passes through a testable check valve 2E51-F065, penetrates the containment, and then passes through another testable check valve 2E51-F066. RCIC flow then enters the reactor vessel through the head spray nozzle. In the Hot
Standby Mode, the water suction may be from either the RHR heat exchangers or the CST.

Steam is drawn off the reactor vessel from the "B" main steam line (MSL), through valve 2E51-F063, penetrates the containment, and then passes through valve 2E51-F008 to the RCIC turbine steam supply stop valve F045. From the steam supply stop valve it is routed through the turbine stop and governor valves into the RCIC turbine. The turbine exhaust is directed to the suppression pool.

Concerning the RCIC isolation signal, the RCIC steam supply valves F063, F067 and F008 will shut automatically on any of the following conditions:

- High steam flow, > 290 %, indicating a steam line rupture.
- High temperature, in either the RCIC equipment room or the RCIC pipe routing area, indicating a steam leak.
- High RCIC equipment area or steam line tunnel differential temperature > 117 F.
- A high pressure of 10 psig between rupture discs on the RCIC turbine exhaust line, indicating blockage of the normal exhaust path.
- A low steam supply pressure, < 57 psig, sensed between Main Steam Line B and F063, which increases the potential for airborne activity release through the turbine seals.
- Manual pushbutton depressed (only closes F008).

4.2 Failure Mode Analysis for Chattering

Based on the discussion of Section 4.1, we now discuss the potential failure modes of the crucial systems for our analysis: the electric power system and RCIC.

As discussed earlier, we consider only failure modes due to chattering of relay contacts or pressure switch contacts.

Failure of electric power for each division is due either to the DG supply breaker failing to close or to its tripping open after closure. This in turn can be caused by lockout relays inadvertently energizing. In addition, the swing diesel (DG-0) may align with unit 1, causing bus 241-Y to be unenergized. Complete failure of the 4.16 kV electric system can fail all coolant makeup systems other than RCIC.
For the purposes of this analysis, RCIC failure or inadequacy can be due to either of two causes:

- inadvertent generation of an RCIC isolation signal;
- inadvertent ADS actuation (2 or more SRVs) which causes a LOCA with area greater than 0.1 square feet, which produces inventory loss larger than RCIC can keep up with.

For the remainder of this Section, we shall refer to LaSalle-2 drawings in our Figures. Each drawing is segregated into two halves -- the lefthand side of the drawing is given a figure number ending with the letter A; the righthand side is given a figure number ending with the letter B. For example, Figure 4.6 is the control circuit to the DG-2A diesel generator breaker 2423. The lefthand side of this drawing is designated Figure 4.6A, and the righthand side is designated Figure 4.6B. Also, as in the earlier Sections, we will use designators to locate a position on a drawing by a lettered row and numbered column.

4.2.1 Failure Modes of the Electric Power System

We now discuss the failure modes of the following three circuit breakers individually:

- 2423 (DG-2A supply breaker)
- 2413 (DG-0 supply breaker)

Each of these circuit breakers has a standard X-Y circuit breaker scheme as discussed in Section 3.1.6 and in Appendix A. In the discussion that follows, we assume that a LOCA signal has not been generated.

Figure 4.6A displays the "close" portion of the control circuit to circuit breaker 2423, the DG-2A feed breaker. Figure 4.6B displays the "trip" portion of the breaker. If lockout relay 86DG2A (shown in Figure 4.7) energizes, it trips the breaker by closing the 5-5c contacts [E-7 in Figure 4.6B], and prevents reclosure of the breaker by opening contacts 15-15c [K-9 in Figure 4.6A]. As described above in Section 4.1.1, energizing of the 86DG2A relay causes shutdown of diesel DG-2A.
Figure 4.6 displays the control circuit to the 86DG2A relay which is shown in Figure 4.7A [M-10]. We see that 86DG2A could be energized by chattering of any one of the following set of relay contacts:

- K10 [E-6], Figure 4.7A, auxiliary relay
- 87X [E-7], Figure 4.7A, differential current relay
- 59 [G-11], Figure 4.7A, overvoltage relay
- 81X [E-12], Figure 4.7A, underfrequency relay
- 51X [E-13], Figure 4.7A, overcurrent, phase A, B or C relay
- K25 [E-14], Figure 4.7A, DG field relay
- K9 [E-15], Figure 4.7A, low engine RPM relay
- K11 [E-1], Figure 4.7B, low lube oil pressure relay
- K12 [E-2], Figure 4.7B, high engine temperature relay
- K32 [E-3], Figure 4.7B, reverse power relay.

We assume that the normally closed contacts K-98 [I-14 in Figure 4.7A] remain closed since we assume that a LOCA signal is not generated.

In addition, the K9, K10, K11 and K12 relays (as shown in the M row of Figure 4.7B) have seal-in contacts (as shown in the H row of Fig. 4.7B). These contacts can chatter and can cause seal-in of these relays. The contacts whose closure can energize relays 51VX, 87X and 81X are shown in Figure 4.8B. The fault tree analysis explicitly allows for chattering of these contacts, as described in Section 4.3.

The supply breaker to the swing diesel, breaker 2413, has basically the same failure modes as those for breaker 2423. If these failure modes do not occur, then there is a 50% probability that breaker 1413 (unit 1 breaker to bus 141-Y) will close before breaker 2413, thereby aligning the swing diesel to the other unit. In other words, the probability that the swing diesel does not align to unit 2 has two components: either one of the 17 relays in the supply breaker circuit can chatter, or if chatter does not occur there is a 50-50 chance of alignment to the other unit.

The control circuit to the HPCS breaker, 2433, is shown in Figure 4.9 which is analogous to the control circuit to breaker 2423 as shown in Figure 4.6. The only exception is that the K1 and the K15 lockout relays perform the same function as the lockout relay 86DG2A.

The K1 [D-8] and K-15 [E-6] relay contacts are shown in the trip portion of the control circuit Figure 4.9B. These contacts are shown in locations [D-6] and [F-7] in the close portion of the breaker control circuit, Figure 4.9A. Energizing of either the K1 relay or the K15 relay causes shutdown of the HPCS diesel DG-2B.
Figure 4.10 shows the circuit that energizes the K1 lockout relay [K-9 in Figure 4.10A]. We see that K1 could be energized by any one of the following set of contacts chattering:

- K3 [C-6], Figure 4.10A, loss of excitation relay
- K32 [D-8], Figure 4.10A, HPCS DG reverse power relay
- K30 [E-11], Figure 4.10A, current differential phases A, B and C
- K35 [D-16], Figure 4.10A, overcurrent phase A, B, C.

Figure 4.11 shows the circuit that energizes lockout relay K15 [N-2 in Figure 4.11B]. We see that K15 can be energized by any one of the following set of contacts chattering:

- K10 [C-13], Figure 4.11A, HPCS DG overspeed relay
- K9 [C-14], Figure 4.11A, HPCS DG underspeed relay
- K11 [C-16], Figure 4.11A, HPCS DG low pressure
- K12 [C-1], Figure 4.11B, HPCS DG high temperature.

In addition, relays K9, K10, K11 and K12 have seal-in contacts that can chatter. These seal-in contacts are shown in row D of Figure 4.11A.

Examining Figures 4.2 and 4.3, we see that the lockout relays will eventually drop out were low water level to be reached in the reactor. However, if the lockout relays were to seal-in during the earthquake strong motion, the diesel generators would be shut down and would need to be restarted even if the sealed-in relays drop out.

4.2.2 Failure Modes of RCIC

In this section, we describe failure modes due to chattering of relay or pressure switch contacts that involve RCIC.

*Inadvertent ADS actuation*

Figure 4.4 shows the simplified ADS/SRV initiation logic. Energizing of the A or B solenoids requires 2 or more sets of contacts to chatter simultaneously. For this reason, we do not consider inadvertent energizing of these solenoids. The C solenoid energizes (for both ADS valves as well as SRVs) when reactor coolant pressure is high. Each SRV has its own pressure switch. When the pressure switch contacts close, the K2 relay in Figure 4.4 energizes.

Figure 4.12 shows an actual control circuit for ADS valves and SRV valves. Specifically, let us examine ADS valve F013E and SRV F013H in Figure 4.12A.
We will assume that the ADS control switch in the control room is placed in the "auto" position (see Figure 4.12B [S-2]).

The C solenoid [K-7 in Figure 4.12A] for the ADS valve F013E could energize when the K70A contacts chatter [C-12 in Figure 4.12A]. In addition, inadvertent energizing of K70 could be caused by chattering of the pressure switch contacts N039E [T-9 in Figure 4.12A]. We do not consider chattering of K52A [C-13] as a possibility, because its contacts are in series with itself, one set of contacts normally closed and one set normally open.

The C solenoid for SRV [V-6 in Figure 4.12A], F013H, could energize due to chattering of pressure switch N039E [T-9 in Figure 4.12A].

RCIC Isolation Signal

Inadvertent generation of an RCIC isolation signal will close the outboard isolation valve F008 and cause shutdown of RCIC (see Figure 4.5). The control circuit to F008 is shown in Fig. 4.13. The "open" and "close" contacts are shown in the N row in Figure 4.13A. Reversal of phases A and C causes the motor to run in the reverse direction. The close coil C [P-15 in Figure 4.13A] closes when relay contacts K-15 close. (The circuit is interlocked so that the close and open coil cannot be simultaneously energized.) Figure 4.14 shows the control circuit for relay K-15 [N-10 in Figure 4.14A]. K-15 could seal in from chatter of its contacts 1-2 [C-1 in Figure 4.14B]. In addition, closure of the K5 contacts [M-10 in Figure 4.14A] causes K-15 to energize. K5 could seal in due to chatter of its contacts 9-10 [B-13 in Figure 4.15A].

It is important to note that valve F008 is normally open and is AC-powered. Upon loss of AC, F008 fails as is (open). What this implies is that the timing of loss-of-offsite-power is important. If either relay K5 or K15 seals-in prior to loss of AC power, then valve F008 will close ---- otherwise it will remain open. In Section 4.5, we will discuss the effect on the core-damage frequency if we exclude the effect of these relays sealing-in.

4.3 LaSalle-2 Core-Damage Sequence

Appendix D displays the simplified fault trees that were generated for LaSalle-2. Appendix D consists of five sheets. The following assumptions were made in generating these fault trees:

- loss of offsite power occurs after a large earthquake due to failure of the ceramic insulators;
as described below all coolant makeup systems fail, which results in core damage within 80 minutes. This can occur for one or three reasons:

- RCIC can have inadequate makeup capability if two or more SRVs inadvertently open, causing a medium-sized LOCA to occur; or

- RCIC can fail if the steam supply to the RCIC turbines is cut off because the outboard isolation valve F008 closes, due to seal-in from chattering of either relay K15 or relay K3; or

- high pressure systems (HPCS) and low pressure systems (LPCS and RHR) can fail due to loss of all AC power.

The following assumptions are made with regards to the construction of the fault tree:

- only failure modes due to chatter of relay and pressure switch contacts are considered in the fault tree

- no operator recovery is assumed.

We assume that chatter can occur long enough to cause electrical continuity, which in turn causes a relay to seal-in or a solenoid to energize.

Below we describe the failure of RCIC separately from the description of all other coolant makeup systems. This is because RCIC does not depend upon AC power during the first 80-minute period required for coolant boiloff and subsequent core damage.

**RCIC Failure (Sheet 2, Appendix D)**

RCIC can successfully make up inventory for a LOCA size less than a 0.1 sq. ft. steam line break, which is defined as a "small LOCA" in the RMIEP analysis (Ref. Wells et al., 1986). If two or more SRVs open, it creates a steam-line LOCA greater than 0.1 sq. ft. equivalent, which is an inventory loss too great for RCIC to make up.

Sheet 2 displays the 2-out-of-18 logic which can cause two or more SRVs to actuate. The logic describes the double combination of contact pair chattering of relay and/or pressure switch contacts, i.e., the following three combinations: (1) two pairs of pressure switch contacts chattering, (2) one set of
relay contacts chattering and one set of pressure switch contacts chattering and (3) two pairs of relay contacts chattering.

In addition, RCIC could fail if steam supply to the turbine closes on a RCIC isolation signal. This can occur if outboard valve F008 closes when either one of the seal-in relays K15 or K5 chatters closed.

LOSS of All AC (Sheets 3, 4 and 5 of Appendix D)

As shown below and in Table 4-1, there are three ESF 4.16 kV buses at unit 2, whose respective diesel generators and pump loads used for makeup are as follows:

<table>
<thead>
<tr>
<th>4.16 kV Bus</th>
<th>Diesel</th>
<th>Pump Load(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>241Y</td>
<td>DG-0 (swing diesel)</td>
<td>LPCS, RHR A</td>
</tr>
<tr>
<td>242Y</td>
<td>DG-2A</td>
<td>RHR B, RHR C</td>
</tr>
<tr>
<td>243</td>
<td>DG-2B</td>
<td>HPCS</td>
</tr>
</tbody>
</table>

DG-0 is the swing diesel shared by both units. Upon loss of offsite power, circuit breakers to the respective diesels should close thereby restoring emergency AC power.

Sheets 3 through 5 show the logic for failure of these circuit breakers to close or failure to remain closed. Sheet 4 shows the logic for the DG-0 breaker failing to close, which is caused in part by the possibility that the diesel swings to the other bus, and in part by other causes as shown for breaker 2423 on Sheet 5. Sheets 3 and 5 show the logic for failure of the DG-2B and DG-2A breakers to close, respectively. As shown on these two sheets, there are lockout relays to the breaker control circuits that when energized prevent closure of the circuit breakers or trip the breakers. These lockout relays are energized when abnormal diesel generator conditions exist or when there is a bus fault.

As shown on Sheet 3, chattering of 12 possible sets of contacts will simulate these conditions and seal in lockout relays K1 or K15. Sealing-in of these lockout relays will prevent closure of the DG-2B (HPCS) circuit breaker. As shown on Sheet 5, the control circuit to DG-2A circuit breaker contains one lockout relay, 86 DG2A. There are 17 contact pairs that when closed will seal-in relay 86 DG2A. Chattering of any one of 17 contact pairs can energize relay 86 DG2A and thus prevent closure of the DG-2A circuit breaker.
4.4 Generation of Min Cut Sets

Figure 4.16 displays the core-damage sequence in a simplified fault tree form. Each branch of the tree is independent of each other branch with regards to relay/pressure switch contacts chattering. That is, no relays are in common and hence there are no repeated basic events other than the swing diesel.

For failure or insufficiency of RCIC, 2 single min cut sets are generated that describe relay contact pairs chattering. In addition, there are 293 double event min cut sets. Failure of HPCS involves 12 singles. Failure of LPCS and LPCI is due to a one-event min cut set (swing diesel aligns to unit 1). Failure of LPCI pumps B & C involves 17 single-event minimal cut sets.

When we perform a Boolean expansion of the fault tree in Figure 4.16, we generate the following number of min cut sets according to order and generic type indicated:

<table>
<thead>
<tr>
<th>Order</th>
<th>No. Min Cut Sets</th>
<th>Generic Description*</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>408</td>
<td>LOSP, Swing Diesel, Relay-1, Relay-2, Relay-3</td>
</tr>
<tr>
<td>6</td>
<td>31,212</td>
<td>LOSP, Swing Diesel, P-Switch 1, P-Switch-2, Relay-1, Relay-2</td>
</tr>
<tr>
<td>6</td>
<td>24,276</td>
<td>LOSP, Swing Diesel, P-Switch-1, Relay-1, Relay-2, Relay-3</td>
</tr>
<tr>
<td>6</td>
<td>4,284</td>
<td>LOSP, Swing Diesel, Relay-1, Relay-2, Relay-3, Relay-4</td>
</tr>
</tbody>
</table>

The total in this table is 60,180 min cut sets.

If we exclude the failure mode of valve F008 inadvertently closing due to relay chatter (see Section 4.2.2 above), then the 408 min cut sets of order 5 would be eliminated.

* "Relay-1" means "one relay chattering", "Relay-2" means "a second relay chattering", "P-Switch-1" means "one pressure switch chattering", and so on.
4.5 Probabilistic Results

This Section is similar in scope to Section 3.5 for Zion-1. The computer code SEISIM was run to determine the core-damage frequency for the accident sequence described in Section 3.4, i.e., failure to makeup within 80 minutes. The fragilities used for chatter and LOSP are as presented in Section 2.6, and the site-specific hazard curve used for LaSalle is as presented in Section 2.7.

The following assumptions were made in running SEISIM:

- it is assumed that relay and pressure switch fragilities are statistically independent of each other (zero correlation in the capacities);
- it is assumed that each relay experiences the same response and that each pressure switch experiences the same response. The response correlation between relays and pressure switches is assumed to be zero (that is, they are statistically independent of each other);
- it is assumed that there is zero correlation coefficient between the free field response and the response at the motor control center. This means that we can multiply the probability of LOSP times either the probability of relay chatter or the probability of pressure switch chatter.

As described in Section 2.5, the core-damage frequency per year is calculated as the Boolean union of all the min cut sets described in Figure 4.16. The results are displayed in Table 4-3. Two response cases are considered:

- Case A: the relays and pressure switches experience the predicted plant response for that location;
- Case B: the relays and pressure switches experience the peak plant response, meaning the response for the plant location with the greatest motion.

The final risk measure computed is the unconditional core-damage frequency per year, which means that the value in the last column includes the earthquake frequency.

The total unconditional core-damage frequency is the sum of the unconditional frequencies for each earthquake level. As indicated in footnote 2 on the Table, this is simply the sum of products from the number of min cut sets times the min cut set probability as was computed by SEISIM. The core-damage frequency for each min cut set is calculated as discussed in Section 2,
as the convolution of the hazard curve and the fragility curves. These individual min cut sets have quite small core-damage frequencies. However, there are so many of them (over 60,000) that their Boolean sum is non-negligible: The value of core-damage frequency calculated by this analysis is about $5 \times 10^{-8}$ per year. This value is a "best estimate" value or "point value", without any uncertainty analysis associated with it.

Of course, this number cannot be taken at face value, because a number of assumptions, many of them conservative, have been incorporated in this analysis. Section 6 discusses this issue, along with a discussion of various uncertainties in the analysis.

It is important to note that the unconditional core-damage frequency for each earthquake level cannot exceed the frequency of the earthquake times the probability of LOSP. For the peak-response case (Case B), the sum of products for all the min cut sets exceeds this value. This means that for the peak-response case (Case B) the conditional probability that the sequence occurs given the occurrence of the earthquake and loss of offsite power is essentially unity (100%). This is true because the number of min cut sets is so large. For the predicted-response case (Case A), the core-damage frequency is a factor of about 3 less than the maximum value that would be obtained if chattering occurred every time. It must be emphasized again that operator recovery is not included in this evaluation.

Column 6 in Table 4-3 displays the 408 min cut sets of order 5, which are the min cut sets involving valve F008 inadvertently closing. Examining this column reveals that this specific chatter mode represents about 6% of the total core-damage frequency; hence eliminating this one failure mode (see Section 4.2.2) would only reduce core-damage frequency by about 6%.

4.6 Sensitivity Analysis ---- LaSalle-2

4.6.1 Variations in the Fragility Values

One of the principal unknowns that affects the analysis of relay and pressure switch chatter is the fragility curve for the chatter mode. In this Section, we will discuss a sensitivity analysis that has been performed for this issue.

Specifically, we will describe four cases (a "base case" and three "sensitivity cases") that have been considered for the chatter fragility functions for relays and pressure switches. Each of the three sensitivity cases represents a fragility function substantially stronger than Case #1, the base case:
Case # 1 is the base case, representing the fragility curves used in the main body of this analysis. It is important to emphasize that Case # 1 does not necessarily represent the actual situation at LaSalle-2, because the use of generic fragility values cannot possibly be correct in detail as representing the responses of all of LaSalle-s relays and switches. In Case # 2, the median fragilities remain at 2.6 g and 1.51 g, but the beta values are smaller, meaning that the overall fragility curves are higher (the lower-side tails of the curves do not extend as far down). Cases # 3 and 4 represent median fragilities of 5.0 g, with wider beta (1.5) and narrower beta (0.4), respectively.

The assumptions that were made in the main analysis all apply to the sensitivity runs as well. Specifically, the relay and pressure-switch fragilities are assumed to be statistically independent, and the responses are assumed to be perfectly correlated.

4.6.2 Discussion

The reader should study Tables 4-4, 4-5, and 4-6. These should be compared to the base-case results in Table 4-3.

Recall that for the base case two different analyses were done, one assuming a "peak response" and the other assuming a "predicted response", taken to be the response at the locations of the relays and switches.

Predicted response case: For the predicted-response case at LaSalle-2, recall first that the "base-case" analysis finds that the core-damage frequency is about 30% of the "maximum" amount that would be found if chattering occurred every time (more technically, the "maximum" is the value if the
Boolean union of the chattering min cut sets has an essentially 100% probability of occurring given LOSP).

Compared to the base case, the tables show that the calculated core-damage frequencies are reduced for each of the sensitivity cases --- and dramatically for Cases # 2 and # 4. We also see that only reducing the betas (Case # 2, see Table 4-4) has a much more dramatic effect than only increasing the median capacities (Case # 3, see Table 4-5). Specifically, reducing the beta values (Case # 2) reduces calculated core-damage frequencies by about 8 orders of magnitude; increasing the median capacities (Case # 3) produces a reduction factor of about 150; and making both changes together (Case # 4) produces a reduction factor of about 10 orders of magnitude. (Of course, the numerical values here are not to be taken too seriously, because they are so sensitive to the details of the fragility curves and of the analysis algorithm). *

Peak response analysis: The same qualitative conclusions are found for the peak-response case. Recall that for the "base case" analysis, the core-damage frequency was at its maximum ---- that is, there is a 100% likelihood that at least one min cut set would occur, given LOSP. For Case # 3 here (reducing only the beta values), a reduction is produced of about two orders of magnitude (factor of about 60). For Cases # 2 and # 4, reductions of over 4 orders and 10 orders of magnitude are produced, respectively.

Conclusions from the sensitivity analysis: We conclude from these sensitivity analysis runs that increasing the median capacities for both relay chatter and pressure-switch chatter, while keeping the beta values the same, produces a change in calculated core-damage frequency of about two orders of magnitude. This is found for both the peak-response cases and the predicted-response cases. Decreasing only the beta values (that is, narrowing the width of the curves) produces a much more dramatic effect, essentially eliminating these sequences as important. This tells us that for LaSalle-2 the "bottom-line" results are quite sensitive to the fragility values assumed.

* The computer code SEISIM will not generate individual component failure probabilities less than $1 \times 10^{-8}$, or min cut set probabilities less than $1 \times 10^{-15}$. For our sensitivity runs, if component or min cut set probabilities are less than these cut-off values, our analysis has conservatively set them equal to the cut-off values.
4.6.3 Effect of Modifying the Response Correlation

The conclusions on response correlations are the same for LaSalle-2 as for Zion-1 (discussed in Section 3.6.3). As for Zion-1, the base-case analysis for LaSalle-2 has assumed that the response correlation is unity --- specifically, it is assumed that the responses of all relay chattering events are perfectly correlated. What this means in laymen's terms is that their motions are all identical. If response correlations are zero, then the chattering events are statistically independent of each other, in which case we would simply multiply the individual probabilities separately in each min cut set to obtain the overall min cut set probability.

We recall here the discussion in Section 2.5, pointing out that the response curves used in this analysis have "beta values" or widths. For our base case analysis (Case # 1), the fragility "beta value" is 1.5, which is so much broader than these response beta values that in calculating the min cut set probabilities we can simply multiply the basic event probabilities together as if these basic events were statistically independent of each other. (In laymen's terms, if the fragility "beta" is much greater than the response "beta", response correlation has little or no effect on min cut set probabilities.)

However, for sensitivity Case # 2, the fragilities "beta values" are 0.4, comparable in magnitude to the response beta values. The impact of this is shown for Case # 2 on Table 4-4, in which the individual min cut set probability is considerably larger than for Case # 1. Because of response correlation, the min cut set probability is considerably greater than if we assumed that the basic event probabilities were independent. While the numerical values should not be taken as valid on their face, because of various assumptions, this sensitivity analysis demonstrates that the numerical results for min cut set probability are sensitive in detail to what is assumed for the widths of the various fragility and response distributions.

In Section 3.6 (the discussion of sensitivity studies for Zion-1), an example was given of how the response correlation can affect the numerical values of calculated min cut set probabilities. This numerical example will not be repeated here --- the interested reader is referred to the end of Section 3.6 for details.
4.7 Operator Recovery Actions at LaSalle-2

Almost all seal-ins described for LaSalle-2 can be dropped out by operation of reset switches in the control room. The only exceptions are the lockout relays to the diesel generators, which can only be reset on the lower floor of the diesel generator room.

If the operator resets RCIC first, then the operators will have several hours to get the diesels started. If the operators fail to reset RCIC in the control room, then reset of the diesel-generator lockout relays must be accomplished within 80 minutes.

In our fault-tree/event-tree analysis, we have assumed that there is no operator recovery. This is obviously a pessimistic assumption. Unfortunately, the performance of a more realistic analysis would require a detailed "task analysis" of the recovery actions of the operators, which is beyond the scope of the current project.

4.8 Conclusions and Insights From the LaSalle-2 Analysis

The conclusions and insights from the analysis of LaSalle-2 are presented in Section 6.3, and generic insights based on both the LaSalle-2 and Zion-1 analyses are presented in Section 6.4.
Table 4-1

Major Loads on Class 1E AC Electrical System

**Bus 241Y**

1. LPCS Pump
2. RHR Pump 1A
3. SWGR 235X & 235Y
4. D/G "0"
5. Bus tie to 241X
6. Bus tie to 141Y
7. CRD Pump 1A
8. SWGR 233
9. Recirc MG set A
10. Primary Containment Water Chiller A
11. Suppression Pool C/U Pump B

**Bus 242Y**

1. D/G 2A
2. RHR Pump 1B & 1C
3. SWGR 236X & 236Y
4. Bus tie to 242X
5. Bus tie to 142Y
6. Sup Pool C/U Pump A
7. CRD Pump 1B
8. SWGR 234X and 234Y
9. Recirc MG Set B
10. Primary Containment Water Chiller B

**Bus 243**

1. D/G B (HPCS)
2. HPCS Pump
3. MCC 243-1

The diesel generators supply these buses:

a) D/G "0" supplies buses 141Y (unit 1) and 241Y.

b) D/G "2A" supplies bus 242Y.

c) D/G "2B" supplies bus 243.
Table 4-2

Automatic Circuit Breaker Status

<table>
<thead>
<tr>
<th>Breaker</th>
<th>Connects</th>
<th>Status Following LOSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2511</td>
<td>UAT 241/BUS 251</td>
<td>Open</td>
</tr>
<tr>
<td>2512</td>
<td>SAT 242/BUS 251</td>
<td>Open</td>
</tr>
<tr>
<td>2521</td>
<td>UAT 241/BUS 252</td>
<td>Open</td>
</tr>
<tr>
<td>2522</td>
<td>SAT 242/BUS 252</td>
<td>Open</td>
</tr>
<tr>
<td>2412</td>
<td>SAT 242/BUS 241Y</td>
<td>Open</td>
</tr>
<tr>
<td>2411</td>
<td>UAT 241/BUS 241X</td>
<td>Open</td>
</tr>
<tr>
<td>2421</td>
<td>UAT 241/BUS 242X</td>
<td>Open</td>
</tr>
<tr>
<td>2422</td>
<td>SAT 242/BUS 242Y</td>
<td>Open</td>
</tr>
<tr>
<td>2415</td>
<td>BUS 241Y/BUS 241X</td>
<td>Open</td>
</tr>
<tr>
<td>2425</td>
<td>BUS 242Y/BUS 242X</td>
<td>Open</td>
</tr>
<tr>
<td>2413</td>
<td>BUS 241YDG 0</td>
<td>Closed</td>
</tr>
<tr>
<td>2423</td>
<td>BUS 242Y/DG 2A</td>
<td>Closed</td>
</tr>
<tr>
<td>2433</td>
<td>BUS 243/DG 2B</td>
<td>Closed</td>
</tr>
<tr>
<td>2432</td>
<td>SAT 242/BUS 243</td>
<td>Open</td>
</tr>
<tr>
<td>------------------</td>
<td>----------------------</td>
<td>---------</td>
</tr>
<tr>
<td>1</td>
<td>1.07 E-4</td>
<td>5.57 E-1</td>
</tr>
<tr>
<td>2</td>
<td>2.37 E-5</td>
<td>6.74 E-1</td>
</tr>
<tr>
<td>3</td>
<td>1.08 E-5</td>
<td>7.65 E-1</td>
</tr>
<tr>
<td>4</td>
<td>4.71 E-6</td>
<td>8.33 E-1</td>
</tr>
<tr>
<td>5</td>
<td>2.12 E-6</td>
<td>8.95 E-1</td>
</tr>
<tr>
<td>6</td>
<td>1.02 E-6</td>
<td>9.43 E-1</td>
</tr>
</tbody>
</table>

TOTAL UNCONDITIONAL RISK (YR-1) = 3.16 E-5 (9.40 E-5)P

NOTES:

[1] COLUMNS (6), (7), (8) AND (9) REPRESENT INDIVIDUAL MIN CUT SET PROBABILITIES
[2] UNCONDITIONAL RISK (FOR EACH EARTHQUAKE LEVEL) = COLUMN (2) x (408 x COLUMN(6) + 31,212 x COLUMN (7) + 24,276 x COLUMN(8) + 4,284 x COLUMN(9))
[3] TOTAL UNCONDITIONAL RISK = UNCONDITIONAL RISK PER YEAR x P(LOSP) = COLUMN(2) x COLUMN(3)
  PRESSURE SWITCH -- MEDIAN CAPACITY = 1.31 g, BETA = 1.5
  RELAY -- MEDIAN CAPACITY = 2.60 g, BETA = 1.5
[5] ASSUMPTIONS:
  RELAY AND PRESSURE SWITC RESPONSES ARE ASSUMED TO BE PERFECTLY CORRELATED
  ALL FRAGILITIES ARE ASSUMED TO BE STATISTICALLY INDEPENDENT
[6] P(SWING1) = 17 x P(RELAY CHATTER) + (1 - 17 x P(RELAY CHATTER))/2
  = 17 x COLUMN(4) + (1 - 17 x COLUMN(4))/2
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>1.07 E-4</td>
<td>5.57 E-1</td>
<td>3.14 E-5</td>
<td>1.85 E-3</td>
<td>6.36 E-10 P</td>
<td>1.87 E-9 P</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.07 E-5</td>
<td>6.74 E-1</td>
<td>4.52 E-5</td>
<td>2.44 E-3</td>
<td>1.54 E-9 P</td>
<td>4.48 E-9 P</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.08 E-5</td>
<td>7.65 E-1</td>
<td>6.35 E-5</td>
<td>3.14 E-3</td>
<td>9.63 E-9 P</td>
<td>1.38 E-9 P</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>4.71 E-6</td>
<td>8.33 E-1</td>
<td>9.07 E-5</td>
<td>4.10 E-3</td>
<td>7.07 E-9 P</td>
<td>3.07 E-9 P</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>2.12 E-6</td>
<td>8.95 E-1</td>
<td>1.35 E-4</td>
<td>5.51 E-3</td>
<td>8.56 E-9 P</td>
<td>3.42 E-9 P</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>1.02 E-6</td>
<td>9.43 E-1</td>
<td>2.20 E-3</td>
<td>7.88 E-3</td>
<td>5.14 E-9 P</td>
<td>3.36 E-9 P</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
<td>1.00 E-15</td>
</tr>
</tbody>
</table>

**NOTES:**

[1] **COLUMNS (6), (7), (8) AND (9)** REPRESENT INDIVIDUAL MIN CUT SET PROBABILITIES

[2] **UNCONDITIONAL RISK (FOR EACH EARTHQUAKE LEVEL) = COLUMN (2) x [408 x COLUMN (6) + 31,212 x COLUMN (7) + 24,276 x COLUMN (8) + 4,284 x COLUMN (9)]

[3] **TOTAL UNCONDITIONAL RISK** = **UNCONDITIONAL RISK SUMMED OVER ALL SIX EARTHQUAKE LEVELS**

[4] **FRAGILITIES (CHATTER):**

PRESSURE SWITCH -- MEDIAN CAPACITY = 1.51 g, BETA = 0.4
RELAY -- MEDIAN CAPACITY = 2.60 g, BETA = 0.4

[5] **ASSUMPTIONS:**

RELAY AND PRESSURE SWITCH RESPONSES ARE ASSUMED TO BE PERFECTLY CORRELATED ALL FRAGILITIES ARE ASSUMED TO BE STATISTICALLY INDEPENDENT

[6] **P(SWING) = 17 x P(RELAY CHATTER) + (1 - 17 x P(RELAY CHATTER))/2

= 17 x COLUMN (4) + (1 - 17 x COLUMN (4))/2**
### Table 4-5: Seismic Runs for LaSalle Unit 2 (Case 3)

<table>
<thead>
<tr>
<th>Earthquake Frequency YR-1</th>
<th>Actual (Peak)</th>
<th>Actual (Peak)</th>
<th>Actual (Peak)</th>
<th>Actual (Peak)</th>
<th>Actual (Peak)</th>
<th>Actual (Peak)</th>
<th>Actual (Peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.07 E-4</td>
<td>5.57 E-1</td>
<td>1.21 E-2</td>
<td>1.21 E-2</td>
<td>4.94 E-7</td>
<td>5.60 E-9</td>
<td>5.60 E-9</td>
</tr>
<tr>
<td>2</td>
<td>2.87 E-5</td>
<td>6.74 E-1</td>
<td>1.42 E-2</td>
<td>1.42 E-2</td>
<td>9.61 E-7</td>
<td>1.36 E-8</td>
<td>1.36 E-8</td>
</tr>
<tr>
<td></td>
<td>(4.51 E-2)P</td>
<td>(4.51 E-2)P</td>
<td>(3.08 E-5)P</td>
<td>(3.08 E-5)P</td>
<td>(1.39 E-6)P</td>
<td>(1.39 E-6)P</td>
<td>(1.39 E-6)P</td>
</tr>
<tr>
<td>3</td>
<td>1.08 E-5</td>
<td>7.65 E-1</td>
<td>1.63 E-2</td>
<td>1.63 E-2</td>
<td>1.67 E-6</td>
<td>2.13 E-8</td>
<td>2.13 E-8</td>
</tr>
<tr>
<td></td>
<td>(4.77 E-2)P</td>
<td>(4.77 E-2)P</td>
<td>(4.14 E-5)P</td>
<td>(4.14 E-5)P</td>
<td>(1.98 E-6)P</td>
<td>(1.98 E-6)P</td>
<td>(1.98 E-6)P</td>
</tr>
<tr>
<td>4</td>
<td>4.71 E-6</td>
<td>8.33 E-1</td>
<td>1.88 E-2</td>
<td>1.88 E-2</td>
<td>2.76 E-6</td>
<td>5.23 E-8</td>
<td>5.23 E-8</td>
</tr>
<tr>
<td></td>
<td>(5.06 E-2)P</td>
<td>(5.06 E-2)P</td>
<td>(3.39 E-5)P</td>
<td>(3.39 E-5)P</td>
<td>(2.73 E-6)P</td>
<td>(2.73 E-6)P</td>
<td>(2.73 E-6)P</td>
</tr>
<tr>
<td>5</td>
<td>2.12 E-6</td>
<td>8.95 E-1</td>
<td>2.19 E-2</td>
<td>2.19 E-2</td>
<td>4.70 E-6</td>
<td>1.03 E-7</td>
<td>1.03 E-7</td>
</tr>
<tr>
<td></td>
<td>(5.41 E-2)P</td>
<td>(5.41 E-2)P</td>
<td>(7.08 E-5)P</td>
<td>(7.08 E-5)P</td>
<td>(3.82 E-6)P</td>
<td>(3.82 E-6)P</td>
<td>(3.82 E-6)P</td>
</tr>
<tr>
<td>6</td>
<td>1.02 E-6</td>
<td>9.43 E-1</td>
<td>2.61 E-2</td>
<td>2.61 E-2</td>
<td>1.53 E-5</td>
<td>6.67 E-7</td>
<td>6.67 E-7</td>
</tr>
<tr>
<td></td>
<td>(5.87 E-2)P</td>
<td>(5.87 E-2)P</td>
<td>(1.54 E-4)P</td>
<td>(1.29 E-5)P</td>
<td>(1.29 E-5)P</td>
<td>(1.29 E-5)P</td>
<td>(1.29 E-5)P</td>
</tr>
</tbody>
</table>

**Notes:**

1. Columns (6), (7), (8) and (9) represent individual min cut set probabilities.
2. Unconditional risk (for each earthquake level) = Column (2) x 408 x (Column (6) + 31,212 x Column (7) + 24,276 x Column (8) + 4,284 x Column (9))
3. Maximum unconditional risk = P(Earthquake Per Year) x P(LOSP) = Column (2) x Column (3)
4. Total unconditional risk = Unconditional Risk summed over all six earthquake levels
5. Fragilities (Chatter):
   - Pressure Switch -- Median Capacity = 5.00 g, Beta = 1.5
   - Relay -- Median Capacity = 5.00 g, Beta = 1.5
6. Assumptions:
   - Relay and pressure switch responses are assumed to be perfectly correlated
   - All fragilities are assumed to be statistically independent
7. P(SWING) = 17 x P(RELAY CHATTER) + (1 - 17 x P(RELAY CHATTER))/2
8. Total unconditional risk (YR-1) = 1.87 E-7 (1.25 E-6)P
### TABLE 4-6 SEISMIC RUNS FOR LASALLE UNIT 2 (CASE 4)

<table>
<thead>
<tr>
<th>Earthquake Frequency Level</th>
<th>Min Cut Sets (Order 5)</th>
<th>Min Cut Sets (Order 6)</th>
<th>Min Cut Sets (Order 6)</th>
<th>Min Cut Sets (Order 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>408</td>
<td>31,212</td>
<td>24,276</td>
<td>4,204</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column</th>
<th>Actual</th>
<th>Actual</th>
<th>Actual</th>
<th>Actual</th>
<th>Actual</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
</tr>
<tr>
<td>2</td>
<td>(8)</td>
<td>(9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Notes:

1. Columns (6), (7), (8) and (9) represent individual min cut set probabilities.
2. Unconditional risk (for each earthquake level) = Column (2) * (408 x Column(6) + 31212 x Column(7) + 24276 x Column(8) + 4204 x Column(9))
3. Total unconditional risk = Unconditional risk summed over all six earthquake levels
4. Fragilities (chatter): Pressure switch -- Median capacity = 5.00 g, Beta = 0.4
   Relay -- Median capacity = 5.00 g, Beta = 0.4
5. Assumptions:
   Relay and pressure switch responses are assumed to be perfectly correlated. All fragilities are assumed to be statistically independent.
6. \( P(SWING) = 17 \times P(RELAY CHATTER) + (1 - 17 \times P(RELAY CHATTER))/2 \)

---

#### Colloquial Text:  

The table presents seismic runs for Lasalle Unit 2 (Case 4) with various min cut sets. The data includes earthquake frequencies and their corresponding probabilities. The table also notes that the fragilities (chatter) for pressure switches and relays are assumed with specific median capacities and betas. All fragilities are assumed to be statistically independent.
FIG. 4.1 -- SINGLE LINE DIAGRAM FOR LASALLE, UNITS 1 AND 2
CONTACT OPENS WHEN REACTOR VESSEL LOW WATER LEVEL OR HIGH DRYWELL PRESSURE CONDITION EXISTS

Closes on REVERSE POWER
Closes on OVER-CURRENT
Closes on LOSS OF EXCITER
Closes on DIFFERENTIAL CURRENT

Closes when DG LOCKOUT RELAY ENERGIZES

TRIP LOCKOUT DIESEL GENERATOR OUTPUT BREAKER 1433
STOP ENGINE AND LOCKOUT START SIGNAL
TRIPS DIESEL GENERATOR FIELD BREAKER
Figure 4.4 - Simplified ADS/SRV initiation logic
Fig. 4.5 -- Reactor Core Cooling Isolation System Simplified Drawing
FIG. 4.6B -- CONTROL CIRCUIT TO DIESEL GENERATOR 2A FEED BREAKER

NOTES:
1. FOR SYMBOLS SEE 54L STANDARDS--EC-N3, EC-N3.1, & EC-N3.2.
2. SYMBOLS:
   A—INDICATES CONNECTION TO GROUND BUS
   B—INDICATES CONNECTION TO 54L STANDARD 6-10-A 460V
   C—RELAY TERMINALS, AS SHOWN
   D—WIRE CONNECTIONS, AS SHOWN

NUCLEAR SAFETY RELATED EQUIPMENT IS SHOWN ON THIS DRAWING.
SCHEMATIC DIAGRAM
460V 60HZ GRAY DIESEL GENERATOR FEED AC BUS
SYSTEM 54L P.1
LA SALLE COUNTY STATION UNIT 2
COMMONWEALTH EDISON CO.
CHICAGO, ILLINOIS

A R. H. SARGENT & LUCY

16-34
FIG. 4.7A -- CONTROL CIRCUIT TO LOCKOUT RELAY 86 DG2A (SAFETY SHUTDOWN)
FIG. 4.7B -- CONTROL CIRCUIT TO LOCKOUT RELAY 86 DG2A (SAFETY SHUTDOWN)
FIG. 4.8A -- SPEED CONTROL CIRCUIT
DIESEL GENERATOR 2A
FIG. 4.9A -- CONTROL CIRCUIT TO DIESEL GENERATOR 2B FEED BREAKER
FIG. 4.9B -- CONTROL CIRCUIT TO DIESEL GENERATOR 2B FEED BREAKER
FIG. 4.10A -- CONTROL CIRCUIT FOR DG 2B K1 LOCK-OUT RELAY
FIG. 4.10B -- CONTROL CIRCUIT FOR DG 2B K1 LOCK-OUT RELAY
FIG. 4.11A -- CONTROL CIRCUIT
FOR DG 2B K15
LOCKOUT RELAY
FIG. 4.11B -- CONTROL CIRCUIT FOR DG 2B K15
LOCKOUT RELAY
FIG. 4.13A -- CONTROL CIRCUIT
FOR RCIC OUTBOARD ISOLATION VALVE F008
FIG. 4.13B -- CONTROL CIRCUIT
FOR RCIC OUTBOARD ISOLATION VALVE FO08
FIG. 4.14A -- CONTROL CIRCUIT FOR GENERATION OF RCIC ISOLATION SIGNAL

4-49
FIG. 4.148 -- CONTROL CIRCUIT FOR GENERATION OF RCIC ISOLATION SIGNAL
FIG. 4.15A -- CONTROL CIRCUIT
FOR GENERATION OF
RCIC ISOLATION SIGNAL
FIG. 4.15B -- CONTROL CIRCUIT FOR GENERATION OF RCIC ISOLATION SIGNAL
LASALLE UNIT 2

CORE DAMAGE CAUSED
A SEISMIC EVENT

FAILURE TO MAKE UP WITHIN
70 MINUTES

AND

************************************************************************************************

LOSP RCIC FAILS

HPCS FAILS

LPCS FAILS

LPCI FAILS

OR

NO POWER 4.16KV

BUS 243

NO POWER 4.16KV

AND

BUS 241Y

12 SINGLES

DG-O SWINGS TO UNIT 1

********************

RCIC ISOLATION SIGNAL

INADVERTANT ADS

293 DOUBLES

153 combinations of
two pressure switch
contacts chattering

119 combinations of
of one pressure switch
contacts chattering

and 1 relay contacts
chattering

21 combinations of
two relay contacts
chattering

NOTES:
1) FAILURE MODES CONSIDERED:
   o relay chatter
   o pressure switch chatter

2) NO OPERATOR RECOVERY ASSUMED

3) MIN CUT SETS -- TOTAL 60,180
   408 MIN CUT SETS OF ORDER 5
   59,772 MIN CUT SETS OF ORDER 6

FIG. 4.16 -- SUMMARY FAULT TREE
LASALLE UNIT 2
SECTION 5
HUMAN RELIABILITY ANALYSIS UNDER HIGH-STRESS CONDITIONS

5.1 Introduction

Human error constitutes a major element in the uncertainties inherent in seismic PRAs. Failure rate data for human operators are usually expressed as the Human Error Probability (HEP) and are obtained from Human Reliability Analysis (HRA).

Although Human Reliability Analysis covers the entire range of operational status of a nuclear power plant, the discussion here will concentrate on high-stress conditions from an external initiating event, such as a large earthquake, flood, hurricane, typhoon or tornado. These events may be life threatening, placing the human operator under considerable stress.

For normal operations, determination of HEPs utilizes techniques such as HRA event trees which include such parameters as the possible failure modes and the number of operators. Normal operating procedures and simulator training are considered in determining HEPs for normal operation.

For off-normal and emergency conditions, "performance shaping factors" are added, to account for the unusual conditions. Also, one must analyze emergency operating procedures, including operator training in their use. The post-earthquake period therefore presents a very different challenge to the HRA analyst.

Due to the high stress condition, the human operator has more possible failure modes. Operators may be injured requiring medical care and reducing the number of operators available to perform the required tasks. Performance shaping factors indicate that the HEPs immediately after such an event may be very high.

The problem for the HEP analyst is severe. First, emergency operating procedures may not be applicable to the situation. Second, it is not possible to simulate the high stress, life threatening situation for simulator training. Third, HRA event trees are not applicable since they are based on task analysis of normal, off normal or anticipated emergency procedures. Most important, the fact that human behavior is unpredictable under life threaten-
ing conditions makes the assignment of appropriate HEPs very difficult.

The determination of very high stress HEPs is seriously hampered by the total lack of actual data. In the U.S. the only data available are derived from military sources and pertain to actions of combat personnel or air crew members under combat conditions. Unfortunately, such data are not thought to be fully applicable to nuclear power plant operators under high stress conditions.

At the start of this study, the literature contained two important previous studies on the subject of HEPs for stress conditions. Swain and Guttmann (Ref. Swain and Guttmann, 1980) referred to a model used in WASH 1400 (Ref. NRC, 1975) which was a linear plot of HEPs for the first 120 minutes after a large LOCA. (This HEP curve is shown graphically in Appendix B-1). Hall et al. (Ref. Hall, 1982) presented a different formulation, in the form of a post-event power function of HEPs vs. time. Although both included the effects of stressful situations on the HEP, neither considered the very high-stress (life-threatening) situation that may exist after a severe earthquake.

5.2 Our Original Approach to the Problem

Initially, we intended to study one specific post-earthquake event condition. The procedure selected was the recovery from loss of all AC power (station blackout) following a very large earthquake. We planned a detailed task analysis of this procedure on the basis of observations by a group of human factors analysts. The task analysis would utilize a group of operators performing the procedure on a nuclear power plant simulator under non-stress conditions.

We then intended to develop a model to apply to the task analysis HEPs for each task of the procedure as a function of time after the earthquake. Finally, we planned to perform sensitivity analyses on the HRA event tree of the procedure, using the high-stress HEPs we had developed. These sensitivity analyses would include comparisons with other data such as those of Swain & Guttmann and of Hall et al.

Unfortunately, we were unable to perform the detailed task analysis at Zion because of inaccessibility to the control room or the simulator. However, in anticipation of the performance of the detailed task analysis on the station blackout recovery procedure, we developed a model to generate the needed high-stress HEPs. It is this model whose features will be the main subject of this section.
5.3 Development of a Model for Generating HEPs for High Stress Conditions

5.3.1 Time Dependence and Stress Factors

The approach of Hall, who used a power function to represent HEP as a function of time after an event, appears to us to be the most plausible model. The linear model as proposed by Swain generates relatively high values for HEP particularly in the first 30 minutes after an event. On the other hand, the Hall model generates relatively low values for HEP for times after 10 minutes. As our own model, we adopted the following power function, where HEP<sub>t</sub> and HEP<sub>1</sub> are the values of the human error probability at time = t and time = 1 minute:

\[ HEP_t = HEP_1 t^{-a} \]

The slope, a, is determined by establishing the values of HEP<sub>1</sub> and HEP<sub>1000</sub> as bounding conditions. The value of HEP<sub>1000</sub> (t = 1000 minutes) for a single-operation task is the HEP assigned to that task on a non-stress basis. HEP<sub>1</sub> is obtained by applying a stress factor to HEP<sub>1000</sub> determined by the level of stress present at time = 1 minute. This stress factor could be very large, with the limitation that HEP<sub>1</sub> cannot exceed one. For the purposes of this study, stress factors were assigned as follows:

<table>
<thead>
<tr>
<th>Stress Level</th>
<th>Stress Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Stress</td>
<td>1</td>
</tr>
<tr>
<td>Medium Stress</td>
<td>5</td>
</tr>
<tr>
<td>High Stress</td>
<td>10</td>
</tr>
</tbody>
</table>

This scale of stress factors appears to be reasonable in that non-stress HEPs in the range of 10<sup>-2</sup> to 10<sup>-1</sup> would be increased to values in the range of 10<sup>-1</sup> to 1. Normal non-stress HEPs with values less than 10<sup>-2</sup> should not necessarily be increased more than HEPs of a few percent. We judge that stress factors like 100, as proposed by Swain, are excessive.

The application of the stress factor is shown in Figure 5-1. The example used is for HEP<sub>1000</sub> = 5 X 10<sup>-2</sup>. (The value is assumed to be the same at this very late time of t = 1000 minutes, whether for non-stress, medium-stress or high-stress conditions. This is explicitly different than the assumption in Swain.)
5.3.2 HEP Model for Several Operators

The HEP for a task performed by a single operator under non-stress conditions must be corrected for the presence of more than one operator. Swain uses the application of "conditional HEPs" for additional operators. For our model, the HEP for one operator is modified as follows:

\[ \text{HEP}_N = (\text{HEP}_1)^B \]

where \( N \) is the number of operators and \( B \) is the assigned exponent. For one operator \( B \) is 1.0 and for four or more operators \( B \) is limited to 2.0. Values for two and three operators have been assigned by curve fitting to a slope of one at \( N = 1 \) and a slope of zero at \( N \geq 4 \).

<table>
<thead>
<tr>
<th>Number of Operators (N)</th>
<th>Exponent (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
</tr>
<tr>
<td>5 or more</td>
<td>2.0</td>
</tr>
</tbody>
</table>

This modification provides values of HEP for three or four operators very close to those obtained using conditional HEPs, but it provides a much greater reduction in the HEP for the presence of the second operator.

The application of the multiple-operator model is shown in Figure 5-2. In the example, we have chosen an HEP_{1000} value for one operator of \( 5 \times 10^{-2} \) with a stress factor of 10 (high stress). Modified HEP plots are shown for the second, third and fourth operators.

5.3.3 Application of the Model

The HEP model described above has been incorporated in a very simple computer program written in the language Basic (MS-DOS) AT. This program facilitates calculating values of the HEP. The application of the model would involve the following steps:

1. Determine the HEP for a specific task performed by one operator under non-stress conditions.

2. Assign a stress factor, ranging from 1 for no stress to 10 for high stress.
3. Determine the number of operators expected to participate in performing the task. Supervisors are to be included in this number.

4. Calculate the value of $\text{HEP}_t$ for times from 1 to 1000 minutes.

If uncertainty ranges were available, our approach could also incorporate an upper bound and a lower bound corresponding to each mean value of $\text{HEP}$ calculated. However, this capability was not utilized here because input data for failure probabilities were limited to mean values.

5.4 Results of Applying the Methodology

As mentioned above, the original intent was to perform a detailed task analysis of the procedure for recovering from loss of all AC power (station blackout). However, because of inaccessibility to either the control room or simulator at Zion, the performance of a detailed task analysis was not feasible. Our alternative has been to demonstrate the model using another procedure.

The procedure selected as a case study for demonstrating our model is establishing feed-and-bleed following a loss of both normal and emergency feedwater to the steam generators in a PWR.

As indicated above, early work on high stress HEPs was presented in Swain & Guttmann (1983). Swain & Guttmann present an example of a HRA using event trees, based on a case study described by Bell and Swain (Ref. Bell, 1983). This case study identifies the major human activities and errors in establishing feed-and-bleed following a loss of feedwater, which is the reason why we have selected the same procedure.

The loss of all feedwater results in inability to maintain cooling of the nuclear reactor core unless the operating crew establishes feed and bleed. The event tree represents the activities of a team of three licensed reactor operators, one of whom is the shift supervisor. (See our Appendix B-2.)

Although this control room task is not necessarily associated with a post-earthquake situation, it could arise after an earthquake, and it provides a relatively uncomplicated procedure with 8 tasks. In the earlier work, joint HEPs for 3 operators are cited with a calculated total failure probability. Therefore, this example provides an excellent vehicle for comparison of different models of high-stress HEP.
The example, as presented by Bell, states that if all HEPs are 0.01 or smaller, the failure equation can be approximated by summing only the primary failure paths. Since many of the HEPs were expected to be greater than 0.01, this approximation was not utilized and the exact success equation for $S_{\text{total}}$, the total success probability, was used instead. The value of $F_{\text{total}}$, the total failure probability, was then calculated by using:

$$F_{\text{total}} = 1 - S_{\text{total}}.$$ 

There are 8 tasks involved in the feed-and-bleed procedure, indicated by letters. For these tasks, the joint HEPs for three operators used in the example are.

<table>
<thead>
<tr>
<th>Task</th>
<th>HEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$8.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>B</td>
<td>$1.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>C</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>D</td>
<td>$1.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>E</td>
<td>$1.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>G</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>H</td>
<td>$1.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>K</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

After a stress factor is assigned for each task, the 8 HEP_{1000} values produced a family of curves, from which one determines the value of each task HEP as a function of time. There are 6 curves (There are 8 Tasks but Tasks D, E, and K have the same HEP.)

Insight can be gained by studying how the HEP values depend on the time available for performing each task, as well as how they depend on the starting time. To provide these insights, three cases were selected for calculation:
Case I (Early)  Procedure starts at 5 minutes with each task performed at 5 minute intervals, so that the procedure is completed at 45 minutes.

Case II (Extended)  Procedure starts at 10 minutes with each task performed at 10 minute intervals, so that the procedure is completed at 90 minutes.

Case III (Deferred)  Procedure starts at 25 minutes with each task performed at 5 minute intervals, so that the procedure is completed at 65 minutes.

Each case was calculated for two stress factors, high stress (SF = 10), and medium stress (SF = 5), with the standard HEPs presented in the example representing the non-stress condition (SF = 1).

To provide comparison with the high stress model as presented by Swain, (Ref. Swain & Guttmann, 1983), each case was also calculated using Swain's values for the stress persisting and for the stress level declining to 0.01 at 120 minutes. Since the values presented in Figure 17-2 of Swain's report are for one operator, the HEPs have been reduced using the same relationship discussed above in Section 5.3. For three operators the relationship is:

$$\text{HEP}_3 = (\text{HEP}_1)^{1.9}.$$ 

In all, 12 calculations have been performed as described above using a spreadsheet format. These are all included in Appendix B-3 to Appendix B-6. In addition, the 6 calculations for this model are presented as log-log plots in Appendix B-7 to Appendix B-12.

To illustrate the comparison of our high-stress HEP model with that of Swain, we present one log-log plot (Figure 5-3). This plot presents the family of 6 curves for Case II (high stress), along with the plot of Swain data modified for three operators. Each task (A through K) is marked on each of the plots.

Results of the 12 calculations are presented in Table 5-1. For each, the value of the total failure probability $F_{\text{total}}$ is shown along with the ratio $F_{\text{total}}/F_{\text{standard}}$ where $F_{\text{standard}}$ is the total failure probability of the standard non-stress example of Bell et al. This ratio represents the amount that the total failure probability for the 8 step procedure will increase from the non-stress condition to the four high-stress models cited. These results
will be discussed in more detail in Section 5.5 below.

The three cases calculated demonstrate the effect on the total failure probability if the 8 step procedure is performed early (in the first 45 minutes), extended (over a 90 minute period) and deferred (starting time deferred from 25 to 65 minutes.)

5.5 Conclusions and Insights

The goal of this part of the project has been to develop a model to generate HEPs for use in a seismic PRA. HEPs generated are, of course, those applicable for high-stress (life-threatening) conditions. The model that has been described and demonstrated here represents a new technique for generating such high-stress HEPs. For the specific feed-and-bleed procedure studied here as an example, a detailed task analysis already developed by Bell et al. (Ref. Bell, 1983) under non-stress conditions has been used. Bell had also already developed the non-stress HEPs for each task involved.

For an actual application to an operator procedure at a specific reactor, the task analysis would need to develop information for each task concerning the time required, as well as the number of operators available. Data developed by the task analysis would provide the input for calculating the HEP for each task. This input consists of the following information:

- the non-stress HEP
- the stress factor
- the number of operators
- the time duration of the task, and
- the time of starting each task.

The output of the analysis consists of a family of plots for each task of HEP vs. time.

High-stress HEPs generated would then provide the input to the HRA event tree developed from the task analysis. These high-stress HEPs would be selected from the plot for each task for the appropriate time in the sequence.

Two parameters in the analysis can be adjusted as appropriate. These are the stress factor and the value of the exponent used to adjust for multiple operators.

Table 5.1 provides the results of our spreadsheet calculation using the high-stress model developed for this project. For comparison, calculations using the Swain & Guttmann high-stress model are also shown. For each case the
value of the total failure probability $F_{\text{total}}$ is shown. For comparison the ratio of the total failure probability to the standard non-stress total failure probability calculated in the Bell example is included. The value of the standard non-stress total failure probability $F_{\text{standard}}$ is:

$$F_{\text{standard}} = 1.78 \times 10^{-3}$$

In summary, the new model developed here produces total failure probabilities ranging from a factor of about 10 to 30 times higher than the standard non-stress total failure probabilities. The Swain & Guttmann model produces increases ranging from about 50 to about 500 times higher than the standard non-stress total failure probabilities.

If the operators perform the procedure early compared with deferring the procedure, our model calculates an increase of approximately 2 in the total failure probability. The Swain & Guttmann model produces increases as high as 10 from the deferred case to the early case.
Table 5-1 Summary Table

<table>
<thead>
<tr>
<th></th>
<th>Case I Early</th>
<th>Case II Extended</th>
<th>Case III Deferred</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F(T)</td>
<td>F(T)/F(S)</td>
<td>F(T)</td>
</tr>
<tr>
<td>Swain &amp; Guttmann Stress Persists</td>
<td>8.65E-01</td>
<td>486.1</td>
<td>6.16E-01</td>
</tr>
<tr>
<td>Swain &amp; Guttmann Stress Declines</td>
<td>8.54E-01</td>
<td>480.0</td>
<td>5.47E-01</td>
</tr>
<tr>
<td>New Methodology High Stress</td>
<td>5.01E-02</td>
<td>28.2</td>
<td>2.77E-02</td>
</tr>
<tr>
<td>New Methodology Medium Stress</td>
<td>3.25E-02</td>
<td>18.3</td>
<td>1.96E-02</td>
</tr>
</tbody>
</table>
Figure 5-1 Effect of Stress Factor

HUMAN ERROR PROBABILITY

STRESS CONDITIONS-ONE OPERATOR

TIME-MINUTES

HIGH STRESS

MEDIUM STRESS

NON STRESS
Figure 5-2 Effect of Multiple Operators

HUMAN ERROR PROBABILITY
HIGH STRESS CONDITIONS

TIME-MINUTES
SECTION 6

SUMMARY OF MAJOR TECHNICAL INSIGHTS

6.1 Introduction

A number of technical insights have resulted from the research reported here. Some of these are quite general, and probably apply broadly to nuclear power reactors as a class. A few of them are very plant-specific, and although they apply to Zion-1 or LaSalle-2, their applicability to any other particular plant is unknown.

The insights will be presented separately for the relay-chatter part of the project* and the human-error-under-high-stress part of the project.

For the part of the project dealing with earthquake-induced chattering of relays and pressure switches, the following questions, posed in laymen’s terms, were introduced in Section 1 as capturing the objectives of the project:

1. Given an earthquake large enough to cause both loss-of-offsite power and chattering of relays and pressure switches, and assuming no operator recovery actions, are there any combinations of relays and switches whose chattering, if they were to occur, could lead to a core-damage accident?

2. If so, what are these combinations of relays and switches, and how many combinations are there?

3. What is the calculated overall core-damage frequency from this type of earthquake-initiated accident, assuming no operator recovery?

4. What is the effect on core-damage frequency of changes in the assumed fragility curves of relay chatter and pressure switch

* In the text that follows, insights about chatter vulnerabilities will be provided first for Zion-1, then for LaSalle-2, and then more generically. The reader should note that there is some repetition in these discussions, which has been written purposely, so that readers interested only in one of the plants but not the other can obtain a full picture of the plant-specific insights.
chatter, such as increasing the median capacity and/or decreasing the standard deviation?

5. What are the types and sizes of the uncertainties in this analysis?

For the part of the project dealing with earthquake-induced high stress for the operators, the following questions, in laymen's terms, capture the objectives of the project:

1. Under very high-stress (life-threatening) situations such as would occur after a major earthquake, what is the probability of human error, and how does it depend on factors such as the number of operators present?

2. What is the probability of error in executing an actual procedure (in our case study, an 8-step procedure to establish feed-and-bleed), and how does it depend on stress level?

6.2 Plant-specific Insights for Zion-1: Vulnerabilities from Relay Chatter

1) Our analysis has identified two different groups of accident sequences at Zion-1, both following earthquake-induced loss of offsite AC power and taking no credit for operator recovery. One accident sequence group involves failure of component cooling water or of service water, either of which produces both a reactor-coolant-pump-seal LOCA and failure of high-pressure-injection pumps. The other accident sequence group comprises various electrically-induced transient sequences involving failure of service water; this leads to overheating of the diesel generators, loss of onsite AC power, and consequent failure of auxiliary feedwater and inability to perform primary heat removal using feed-and-bleed.

2) The electrical distribution problems at Zion-1 leading to both of these sequence groups are similar: earthquake-induced loss of offsite power (LOSP), swing diesel alignment to one or the other of the two units, and state changes in various circuit breakers or load sequencers due to chatter. However, the specific combinations of failures (min cut sets) are extremely plant-specific to Zion-1 in minute detail.

3) The number of relays and pressure switches involved in these sequences is not large: only 94 relays were identified. (No important pressure switch contacts were identified for Zion-1, although for LaSalle-2 some of these
were found to be important). These relays are all in electrical equipment identified in detail in Section 3 of this report. We believe that finding and analyzing them is entirely feasible using the methods that we have developed and applied here.

4) For the pump-seal-LOCA sequence group, the analysis finds over 27,000 min cut sets of order 5 (LOSP, swing diesel alignment to other unit, 3 relay chatters) and over 17,000 of order 6 (LOSP, swing diesel, 4 relay chatters).

5) For the transient group involving failures of service water pumps, over 150,000 min cut sets of order 6 are identified (LOSP, swing diesel, 4 relay chatters).

6) The number of min cut sets is so large that, given an earthquake strong enough to cause LOSP, the probability that at least one of these cut sets will occur is close to 100% assuming that the relays chatter with the fragility function and response behavior we have assumed. This is true for both of the response cases analyzed, the predicted-response case as well as the peak-response case (see Section 3.5). Therefore, in the absence of operator recovery, the value of the computed core-damage frequency, given LOSP and chattering, is approximately equal to the recurrence frequency of the earthquake strong enough to cause LOSP. Thus the calculational problem is reduced approximately to a convolution of the hazard curve and the LOSP fragility curve.

7) Using SSMRP-derived generic fragility values for chattering of relays, and site-specific earthquake hazard information from the SSMRP study of Zion (Ref. SSMRP, 1983), the analysis calculates a best-estimate value (point value) of core-damage frequency from these sequences of about $4 \times 10^{-4}$ per year. For reasons cited next, this number is not to be taken as correct at face value, since several assumptions have been made in this analysis.

8) Our analysis takes no credit for operator recovery. As mentioned, this assumption is pessimistic. In actual fact, manual reset of all circuit breakers at Zion-1 is possible from the individual motor control centers, and many of them can be reset from the control room. Furthermore, a modification that is now in process at Zion for other purposes will further improve recoverability for at least one group of potential sequences by moving certain remotely located controls to the control room. Operator action must be accomplished effectively, of course, for which there may not be assurance immediately after a large earthquake that could induce high stress in the operators.

9) Our fragility curve for relay chatter, taken from the SSMRP data base, is generic, and the great width of the fragility curve (in technical terms, the large "beta" value) is necessary to cover the wide range of individual
fragilities of specific relay types. Also, relays have different fragilities depending on whether or not they are energized, and whether they are open or closed, none of which is captured specifically in the generic fragility curve we use. While we do not have a more appropriate set of fragility curves to use in our analysis, and therefore cannot tell for sure what the "correct" fragility curves would be, our judgment is that the fragility curve used is probably quite conservative. Furthermore, the analysis assumes full independence of the fragilities and full correlation in the responses of the relays in the cut sets. Whether this is correct is not known. Our sensitivity studies reveal that the numerical values of min cut set frequencies are sensitive to the values of the response function width ("beta value").

10) Our sensitivity studies for Zion-1 show that changes in the fragility curve parameters for relay chatter do not have a major effect on the numerical core-damage frequencies calculated. Neither decreasing the "beta" (width) of the curve, nor approximately doubling the "median" fragility value, causes much change. Modifying both parameters together only changes the calculated core-damage frequency by a modest factor (about a factor of 4, which we judge not to be significant in light of other uncertainties).

11) Our analysis assumes that no pipe-break or other LOCA is caused directly by the earthquake. If a pipe break or other LOCA were to be directly caused, its analysis would require a separate detailed study of chatter-caused electrical problems, similar in scope but different in detail from the analysis performed here.

12) We believe that, on balance, the core-damage frequency calculated here is pessimistic (that is, too large). However, it is very difficult to estimate how pessimistic, or how big is the numerical uncertainty, so we will not do so here. The conservatisms arise mainly from the following two sources:

- Operator recovery is pessimistically assumed never to occur (see next comment).
- The fragility values used in this analysis are generic and probably conservative values.
6.3 Plant-specific Insights for LaSalle-2: Vulnerabilities from Relay and Contact Chatter

1) Our analysis has identified accident sequences involving earthquake-induced failures, after loss of offsite power, in the following key systems at LaSalle-2: the electrical power distribution system, the automatic depressurization system (ADS), and the reactor core isolation cooling (RCIC) system. The group of accident sequences identified involves (i) the failure or inadequacy of all coolant makeup systems, due to RCIC steam supply failure or inadvertent opening of ADS safety relief valves causing a medium-sized LOCA; and (ii) failures of both high-pressure and low-pressure heat-removal systems after loss of all AC power.

2) The electrical distribution problems leading to these sequences are similar for all sequences: earthquake-induced loss of offsite power (LOSP); swing diesel alignment to the other unit; and state changes in various breakers and pressure switch contacts due to chatter. However, the specific combinations of failures (min cut sets) are extremely plant-specific to LaSalle-2 in minute detail.

3) Only a small number of relays and pressure switches are involved in these sequences: only 22 relays and 18 pressure switch contacts were identified whose chattering is involved in these vulnerabilities. These relays and switches are all in electrical equipment identified in detail in Section 4 of this report. We believe that finding and analyzing them is entirely feasible using the methods that we have developed and applied here. (Indeed, determining their specific fragility functions should even be feasible.)

4) For the group of sequences identified, the analysis finds about 400 min cut sets of order 5 (LOSP, swing diesel alignment to other unit, 3 relay or pressure switch chatters), and about 60,000 of order 6 (LOSP, swing diesel, 4 chatters of relays and/or pressure switches).

5) The number of min cut sets found at LaSalle-2 is so large that, given an earthquake strong enough to cause LOSP, the probability that at least one of these cut sets will occur is very high. For the peak-response case (see Section 4.5), this probability is essentially 100% assuming that the relays and switches chatter with the fragility functions and response behavior we have assumed. For the predicted-response case, the probability is about 30%, meaning that in the absence of operator recovery, the value of the computed core-damage frequency, given LOSP and chattering, is approximately 1/3 of the recurrence frequency of the earthquake strong enough to cause LOSP.

6) Using SSMRP-derived generic fragility values for chattering of relays and pressure switches, and site-specific earthquake hazard information from the
SSMRP study of LaSalle-2 (Ref. Wells, 1986), the analysis calculates a best-estimate value (point value) of core-damage frequency from these sequences of about $5 \times 10^{-8}$ per year. For reasons cited next, this number is not to be taken as correct at face value, since several assumptions have been made in this analysis.

7) No credit is taken for operator recovery. This assumption is pessimistic. At LaSalle-2, all seal-ins can be recovered by switches in the control room, except diesel lock-out relay seal-ins which must be reset in the diesel room.

If the operators can reset the RCIC breakers first, then several hours are available to get the diesels started; if RCIC is not reset or cannot be reset, the diesels must be available within about 80 minutes to avoid a core-damage accident.

8) Our fragility curves for relay and pressure switch chatter, taken from the SSMRP data base, are generic, and the great widths of the fragility curves (in technical terms, the large "beta" values) are necessary to cover the wide range of individual fragilities of specific relay and switch types. Also, relays have different fragilities depending on whether or not they are energized, and whether they are open or closed, none of which is captured specifically in the generic fragility curve we use. While we do not have a more appropriate set of fragility curves to use in our analysis, and therefore cannot tell for sure what the "correct" fragility curves would be, our judgment is that the fragility curves used are probably quite conservative. Furthermore, the analysis assumes full independence of the fragilities and full correlation in the responses of the relays and switches in the cut sets. Whether this is correct is not known. Our sensitivity studies reveal that the numerical values of min cut set frequencies are sensitive to the values of the response function width ("beta value").

9) Our sensitivity studies for LaSalle-2 show that changes in the fragility curve parameters for relay chatter and pressure-switch chatter can in some cases have a major effect on the numerical core-damage frequencies calculated. Increasing the "median" fragility values, while keeping the widths ("betas") large at 1.5, causes a decrease in core-damage frequency of about two orders of magnitude. Decreasing the "betas" of the fragility curves from 1.5 to 0.4, with medians kept constant, causes a much larger change: core-damage frequency is calculated to decrease by several orders of magnitude.

10) Our analysis assumes that no pipe break or other LOCA is caused directly by the earthquake. If a pipe break or other LOCA were to occur, its analysis would require a separate detailed study of chatter-caused electrical problems, similar in scope but different in detail from the analysis performed here.
11) We believe that, on balance, the core-damage frequency calculated here is pessimistic (that is, too large). However, as is true for the Zion-1 analysis it is very difficult to estimate how pessimistic, or how big is the numerical uncertainty, so we will not do so here. The conservatisms arise mainly from the following two sources, which are identical to those identified for Zion-1:

- Operator recovery is pessimistically assumed never to occur (see next comment).
- The fragility values used in this analysis are generic and probably conservative values derived from the SSMRP.

6.4 Generic Insights: Analyzing Seismic Vulnerabilities from Relay and Contact Chatter

1) Given our several assumptions in this analysis, at both Zion-1 and LaSalle-2, the number of min cut sets identified is very large --- so large that for each reactor the likelihood of having at least one cut set occur, given an earthquake large enough to cause LOSP, is a number close to unity (at Zion-1, about 100% likelihood; at LaSalle-2, about 30% likelihood). This means, if true, that in the absence of operator recovery the frequency of a core-damage accident would be within small factors of the frequency of an earthquake large enough to cause LOSP.

2) The most important methodological insight is that it is feasible to analyze the potential vulnerability of a specific plant to the type of earthquake-induced relay and contact chatter studied in this project. The analysis requires delving into the details of the electrical and control circuitry involved in the AC power distribution system. Major uncertainties in the analysis derive from inadequate information about relay-specific fragility curves for the chatter modes, from ignorance about how independent or correlated are the fragilities and the responses, and from uncertainties about whether or not operator action can effectively recover from any electrical problems that occur. (One example of a specific detail of the kind referred to is given in the next paragraph).

3) Our analysis found distinct differences between the Zion-1 and LaSalle-2 plants, which differences seem not to be related to the fact that Zion is a PWR and LaSalle a BWR --- but rather due to idiosyncracies in the design of
their electrical circuitry. The example of the control circuits to the diesel generators will demonstrate this point. At Zion-1, the device that senses DG-1A differential current, 487DG1A/SA-1 [M-18 on Figure 3.9], is a solid-state device that does not exhibit failure modes due to relay chattering. Thus there are no chatter-related failures that can cause lockout relay 486DG1A to energize. At LaSalle-2, there are numerous interposing relays that could seal in and energize the lockout relay 86DG (for diesel generators DG-0 and DG-2A) and lockout relays K1 and K15 (for diesel DG-2B). Energized lockout relays cause circuit breakers to trip open and also prevent reclosure, unless reset (which is generally accomplished at the local cabinet remote from the control room).

4) Another methodological insight is that this analysis could not have been performed if fault trees generated for an ordinary PRA had been used and modified. We believe that it is necessary to develop specialized fault trees for this type of analysis, which cannot be accomplished without close interaction between analysts and the utility. General event-trees and fault-trees that include all seismic failure modes could be intractable to evaluate either qualitatively and/or quantitatively, because of their large size. Also, we believe that it is important to perform bounding studies before eliminating min cut sets by their probability, because a large number of min cut sets may be risk-significant even if the individual cut-set probabilities are small.

5) If core-damage frequency is the appropriate figure-of-merit, the most important generic safety insight is that plant-specific vulnerabilities may exist at some plants due to earthquake-initiated relay and contact chatter. That is, based on the research reported here, it is not possible to rule out such vulnerabilities with high confidence at either Zion-1 or LaSalle-2.

The rationale for this major insight is based on four points, as follows:

i) First, the analysis identifies very many potential accident sequences (represented by 'cut sets' or Boolean combinations of components) that without operator recovery could lead to core-damage accidents, if the relays and contacts were to chatter following loss of offsite power. Given the assumptions we used, for both Zion-1 and LaSalle-2, many cut sets (literally tens of thousands) involve four different relays or contacts chattering, and at LaSalle-2 a very large number of cut sets involve only three. We believe that there will probably be large numbers of such cut sets at other plants.

ii) Second, there is rather large uncertainty in the actual fragilities of relays and pressure-switch contacts for chatter. We believe that the fragility values we have used are probably
conservative but we are not certain of this at Zion and LaSalle, and of course we have no knowledge about the fragilities of comparable relays and contacts at other plants.

iii) Third, there is uncertainty because we do not know whether correlations in capacity or response are high or low. We have done this analysis using zero correlation for the capacities and full correlation for the responses, but we do not know what is the correct correlation to use.

iv) Fourth, we cannot accept for sure the argument that chatter-caused electrical problems are recoverable by operator action at Zion-1 and LaSalle-2, even though arguments in favor of recovery are plausible. This issue depends in detail on the configurations of the breakers, on the location of reset controls, and on the operators' ability to diagnose the problem, which last issue is aggravated by potentially high stress. A detailed task analysis would be necessary to determine whether recoverability can be accomplished with high assurance.

Based on these four points, in our judgment we cannot say for sure whether the vulnerabilities at either Zion-1 and LaSalle-2 are important. Furthermore, we believe that at this stage generic conclusions about other plants cannot be established.

6) We believe it likely that every U.S. plant will have important idiosyncrasies in its behavior under earthquake-induced relay and contact chatter. This is based on our analysis of Zion-1's and LaSalle-2's electrical and control circuitry for the AC power systems, in which we found that the plant-specific features at the two plants are very different from each other: the designs are characterized by minute design details that affect their behavior under relay and contact chatter.

7) Operator recovery from the chatter sequences we have examined requires resetting circuit breakers either in the control room or at their local cabinets. Our assumption of no operator recovery is surely pessimistic, but we cannot judge what would be a better analytical approach without performing a detailed task analysis for the recovery tasks.
6.5 Generic Insights: Analyzing Human Reliability Under High-Stress Conditions

1) When the model developed here is used to analyze the establishment under post-earthquake high-stress conditions of feed-and-bleed (an eight-step procedure), it produces total operator failure probabilities about 10 to 30 times higher than are found using the standard approach for non-stressful conditions.

2) The widely-used model of Swain and Guttmann calculates even greater increases for high-stress conditions compared to non-stress conditions: increases of factors of about 50 to 500.

3) If the operators perform the feed-and-bleed procedure early after the earthquake compared to deferring the procedure, our model calculates a total failure probability about 2 times higher. The Swain and Guttmann model calculates failure probabilities as large as 10 times higher.

4) Whichever calculation is correct concerning the increases resulting from deferral, there is an obvious benefit to be obtained from delaying complicated control-room procedures after a large earthquake or other high-stress accident initiator. Utilities should be aware of this benefit, so that they can warn and train operators not to act too soon after a major potential external initiator if it is not necessary to do so.

5) This benefit from deferral runs counter to the obvious benefit to be obtained from resetting tripped breakers resulting from relay and contact chatter. It will not be easy to write procedures that can balance the benefits and liabilities of prompt vs. deferred actions after a major earthquake --- and it may be even harder to make a deferral recommendation stick in high-stress post-earthquake conditions.
Based on the insights developed during this project, we believe that additional research is needed in a few areas. Such research would clarify some of the technical issues that have been identified here, and that have been discussed in the "Summary" above (Section 6).

Some of the research that we have identified is related to analyzing the effect of earthquake-caused electrical chattering, and some is related to analyzing operator response under high-stress conditions:

**Area A ---- Research Needs Related to Analyzing Earthquake-Caused Electrical Chattering**

A1. There is a need to develop fragility curves for the chattering mode of specific relays and pressure switches. This includes understanding the different fragilities for relays when energized vs. deenergized, and when open vs. closed. This information is required in order to carry out sequence-specific analysis. Also, information is needed on correlations in the fragilities and the responses of these relays and switches. This analysis would include conducting a detailed FMEA (failure mode and effects analysis) for each relay and pressure switch.

A2. If the analysis conducted in A1 demonstrates that there are relays or other devices with chatter vulnerability, then it would be highly desirable for utilities to conduct a limited-scope PRA analysis similar to that performed here. The abbreviated PRA-type analysis could suggest design changes or operator procedural changes that could ameliorate the effects of chatter, such as resetting circuit breakers or operating reset switches to eliminate seal-in problems.
A3. There is a need to perform a task analysis of the operator tasks involved in recovering from the chattering sequences that we have identified. This task analysis will enable an appropriate human reliability analysis to be performed, using appropriate error rates for the operators. (This research need is related to Area B below.)

A4. Given accomplishment of research in areas A1 and A3, there is the need to develop an integrated analysis that incorporates these two into the analysis approach we have demonstrated in this project.

A5. If earthquake-caused LOCAs are an issue at a given plant (because of a specific piping, valving, or other vulnerability), it would be necessary to do a scoping analysis for them. Such an analysis would be similar in approach but different in detail from the one carried out in this project.

Area B ---- Research Needs Related to Analyzing Operator Performance in Earthquake-Caused High-Stress Situations

B1. Better data are needed on the effects that multiple operators have on the overall error probability in performing complex tasks.

B2. In order to provide more realistic and accurate analysis of multi-step procedures (such as the feed-and-bleed procedure used as a case study in our project), access to a simulator for realistic task analysis is required.

B3. Information is seriously lacking and badly needed on human behavior in high-stress situations analogous to those in a reactor control room during a large earthquake event. While such data are hard to obtain, it should be possible to obtain more data than the meager collection now used as the basis for HRA error probabilities.
SECTION 8

ACKNOWLEDGMENTS

This project was conducted under U.S. Nuclear Regulatory Commission contract number NRC-04-84-138. It has been supported by NRC's Office of Nuclear Regulatory Research as part of NRC's Small Business Innovation Research Program. We wish to thank P.K. Niyogi and Joseph A. Murphy of NRC's Office of Nuclear Regulatory Research, who provided technical support and liaison with other NRC projects and NRC's Division of Contracts.

The work of several individuals who contributed to various technical aspects of this project is gratefully acknowledged:

Gregory Morris and Ellen Scott contributed valuable high-level talent in adapting SEISIM for the project's needs. Paul Budnitz, Thomas Conti, and Stefan Garcia provided computer-programming support. Jack Savage gave the project team advice in its early stages about the systems aspects of electrical and control circuitry. Harold Van Cott and Harold Price of Essex Corporation assisted the team in understanding operator response under high stress.

Two NRC contractors gave crucial assistance to the project: (1) James Wells of Lawrence Livermore National Laboratory supported the project by advising on the SSMRP methodology, and by performing computer-based SEISIM runs. David Lappa and Laurence George of LLNL gave us technical guidance. LLNL also provided access to key engineering drawings for both Zion and LaSalle. (2) Arthur Payne of Sandia National Laboratories, who has played a leading role in the NRC-RMIEP team studying LaSalle-2, provided drawings, systems notebooks, and valuable advice about the systems aspects of LaSalle.

Cooperation from the utility was outstanding: George Crane and Arthur Amoroso of Commonwealth Edison Company provided in-depth technical information and support, assisted by Peter LeBlanc. CECo's engineering colleagues at Sargent & Lundy also provided excellent assistance, information, and advice. The S&L personnel were Ahmed Meligi, Joseph Sinnapan, Ismail Kisisel, Peter Hlepas, Charles Furlow, Mansoor Sanwarwalla, and Angelo Diopoulos. The project could not have been successfully completed without CECo and S&L information, support, and review. Finally, we thank Andrea Grant and Elayne Danks Minor, who provided invaluable secretarial assistance to the project.

We received comments on a draft version of this report issued in February 1987, based on which several modifications were made to the final version, mostly in the treatment of LaSalle-2.
REFERENCES


IPPSS, 1983: Consolidated Edison Company and Power Authority of State of New York, Indian Point Probabilistic Safety Study (1983). The principal contractor was Pickard Lowe & Garrick Inc.

Kassawara, 1986: R. Kassawara, Electric Power Research Institute, private communication with R.J. Budnitz about the SQUG project (1986)


ZPSS, 1982: Commonwealth Edison Company, Zion Probabilistic Safety Study (1982). The principal contractor was Pickard Lowe & Garrick, Inc.
APPENDIX A

Description of the X-Y Circuit Breaker Scheme
For 4-kV Switchgear
APPENDIX A -- DESCRIPTION OF X-Y CIRCUIT BREAKER SCHEME FOR 4KV SWITCHGEAR

A - A standard drawout compartment consists of provision for three breaker positions, namely: Connected, Test and Disconnected.

B - This design is for a four position compartment which includes two test positions without moving the breaker from the normal test position. These two test positions are identified as "Local Test" and "Remote Test".

C - "Local Test" is obtained by the normal movement of the breaker to test position. (See Paragraph E)

D - "Remote Test" is obtained by moving the breaker to test position and pulling the test selector.

E - After the mechanism has been latched for "Remote Test", it may be returned to "Local Test" by depressing the release lever (PC 3). The release from "Remote Test" is automatic if the breaker is moved out of test position.

F - The following tabulation lists the four positions and the condition of associated devices:

<table>
<thead>
<tr>
<th>Device</th>
<th>Condition of Device in each Breaker Position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Connected</td>
</tr>
<tr>
<td>Main Contacts</td>
<td>Connected</td>
</tr>
<tr>
<td>Control Cont.</td>
<td>Connected</td>
</tr>
<tr>
<td>MCC Switches</td>
<td>Operable</td>
</tr>
<tr>
<td>TSC Switches</td>
<td>Not</td>
</tr>
</tbody>
</table>

---

**TSC**

<table>
<thead>
<tr>
<th>CONTACTS</th>
<th>SYMBOL</th>
<th>BREAKER POSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-1-03</td>
<td>LT</td>
<td>OPEN REMOTE TEST</td>
</tr>
<tr>
<td>10-1-03</td>
<td>RTO</td>
<td>LOCAL TEST WITHDRAWN</td>
</tr>
<tr>
<td>20-1-04</td>
<td>LT</td>
<td>X x X</td>
</tr>
<tr>
<td>20-1-06</td>
<td>RTO</td>
<td>X x X</td>
</tr>
</tbody>
</table>

**TCS**

<table>
<thead>
<tr>
<th>CONTACTS</th>
<th>LOCAL SYMBOL</th>
<th>POSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-1-02</td>
<td>C</td>
<td>TRIP</td>
</tr>
<tr>
<td>40-1-03</td>
<td>T</td>
<td>NORMAL CLOSE</td>
</tr>
</tbody>
</table>

LOCAL TEST CONTROL SWITCH
D-C ELECTRICAL OPERATING SEQUENCE

With the circuit breaker open, the closing springs uncharged, and the control power source energized, and motor disconnect switch closed, operation occurs as follows:

1 - Immediately upon the availability of control power, the spring charging motor (motor) is energized, which in turn charges the closing springs. When the closing springs are charged, limit switch contacts "LSb" are opened, and limit switch contact "LSa" is closed.

2 - Operation of the Close Control switch energizes the latch release coil (X) through the circuit breaker auxiliary switch "b" contact, the normally-closed lockout relay contact "Yb", and the limit switch contact "LSa". The latch release coil (X) releases the closing latch. The springs then discharge to close the circuit breaker.

3 - When the springs discharge, limit switch contacts "LSb" close, and limit switch contact "LSa" opens.

4 - When limit switch contact "LSb" in the motor circuit closes, the spring charging motor is energized, which in turn re-charges the closing springs.

5 - When the circuit breaker closes, all auxiliary switch "b" contacts open and all auxiliary switch "a" contacts close.

6 - When limit switch contacts "LSb" close, the lockout relay coil (Y) is energized and opens lockout relay contact "Yb", which de-energizes the latch release coil (X). Lockout relay contact "Ya" closes, which seals-in the lockout relay coil (Y) as long as the "Close" contact is maintained.

The purpose of the lockout relay coil (Y) is to prevent pumping of the closing mechanism when closing against a faulted circuit.

7 - After the breaker has closed and when the "Close" switch is released by the operator, the lockout relay coil (Y) is de-energized. This allows the normally-open lockout relay contact "Ya" to open.

8 - The circuit breaker can be tripped by operation of the Trip Control switch, which energizes the circuit breaker trip coil (TC) through the auxiliary switch "a" contact.

**LEGEND**

a - Auxiliary switch contact closed when breaker is closed
b - Auxiliary switch contact open when breaker is closed
LCb - Latch check switch contact closed when breaker operating mechanism is reset.
LSa - Limit switch contact open when springs are discharged, closed when springs are charged.
LSb - Limit switch contact closed when springs are discharged, open when springs are charged.
X - Closing latch release coil
Y - Control relay lockout coil
Ya - Normally open control relay contact
Yb - Normally closed control relay contact
TC - Trip Coil
APPENDIX B

Human Reliability Analysis Under High-Stress Conditions:
Additional Figures and Tables
Figure 17-2 Estimated human performance after a large LOCA.
Figure 5-3 HRA event tree for loss of steam generator feed.
### Appendix B-3

#### HIGH STRESS HRA

**Case I**

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>5</td>
<td>7.80E-01</td>
<td>2.20E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>10</td>
<td>5.40E-01</td>
<td>4.60E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>15</td>
<td>3.40E-01</td>
<td>6.60E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>20</td>
<td>1.80E-01</td>
<td>8.20E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>25</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>30</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>35</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>40</td>
<td>7.50E-02</td>
<td>1.35E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>8.65E-01</td>
<td></td>
</tr>
</tbody>
</table>

**Case II**

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>10</td>
<td>5.40E-01</td>
<td>4.60E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>20</td>
<td>1.80E-01</td>
<td>8.20E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>30</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>40</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>50</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>60</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>70</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>80</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>6.16E-01</td>
<td></td>
</tr>
</tbody>
</table>

**Case III**

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>25</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>30</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>35</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>40</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>45</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>50</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>55</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>60</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>2.22E-01</td>
<td></td>
</tr>
<tr>
<td>EVENT</td>
<td>STANDARD HEP</td>
<td>TIME Min.</td>
<td>HIGH STRESS HEP</td>
<td>HIGH STRESS HEP</td>
</tr>
<tr>
<td>-------</td>
<td>--------------</td>
<td>-----------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>5</td>
<td>7.80E-01</td>
<td>2.20E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>10</td>
<td>5.40E-01</td>
<td>4.60E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>15</td>
<td>3.40E-01</td>
<td>6.60E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>20</td>
<td>1.80E-01</td>
<td>8.20E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>25</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>35</td>
<td>1.30E-02</td>
<td>9.87E-01</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>40</td>
<td>1.10E-02</td>
<td>9.89E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>40</td>
<td>1.00E-02</td>
<td>9.90E-01</td>
</tr>
<tr>
<td></td>
<td>S(Total)</td>
<td></td>
<td>9.98E-01</td>
<td>1.46E-01</td>
</tr>
<tr>
<td></td>
<td>F(Total)</td>
<td></td>
<td>1.78E-03</td>
<td>8.54E-01</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS HEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>10</td>
<td>5.40E-01</td>
<td>4.60E-01</td>
<td>5.40E-01</td>
<td>4.60E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>20</td>
<td>1.80E-01</td>
<td>8.20E-01</td>
<td>1.80E-01</td>
<td>8.20E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>30</td>
<td>1.30E-02</td>
<td>9.87E-01</td>
<td>1.30E-02</td>
<td>9.87E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>40</td>
<td>1.00E-02</td>
<td>9.90E-01</td>
<td>1.00E-02</td>
<td>9.90E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>50</td>
<td>8.20E-03</td>
<td>9.92E-01</td>
<td>8.20E-03</td>
<td>9.92E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>60</td>
<td>6.40E-03</td>
<td>9.94E-01</td>
<td>6.40E-03</td>
<td>9.94E-01</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>70</td>
<td>4.80E-03</td>
<td>9.95E-01</td>
<td>4.80E-03</td>
<td>9.95E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>80</td>
<td>3.40E-03</td>
<td>9.97E-01</td>
<td>3.40E-03</td>
<td>9.97E-01</td>
</tr>
<tr>
<td></td>
<td>S(Total)</td>
<td></td>
<td>9.98E-01</td>
<td>4.53E-01</td>
<td>9.98E-01</td>
<td>4.53E-01</td>
</tr>
<tr>
<td></td>
<td>F(Total)</td>
<td></td>
<td>1.78E-03</td>
<td>5.47E-01</td>
<td>1.78E-03</td>
<td>5.47E-01</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS HEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>25</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
<td>7.50E-02</td>
<td>9.25E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>30</td>
<td>1.30E-02</td>
<td>9.87E-01</td>
<td>1.30E-02</td>
<td>9.87E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>35</td>
<td>1.10E-02</td>
<td>9.89E-01</td>
<td>1.10E-02</td>
<td>9.89E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>40</td>
<td>1.00E-02</td>
<td>9.90E-01</td>
<td>1.00E-02</td>
<td>9.90E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>45</td>
<td>9.20E-03</td>
<td>9.91E-01</td>
<td>9.20E-03</td>
<td>9.91E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>50</td>
<td>8.20E-03</td>
<td>9.92E-01</td>
<td>8.20E-03</td>
<td>9.92E-01</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>55</td>
<td>7.30E-03</td>
<td>9.93E-01</td>
<td>7.30E-03</td>
<td>9.93E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>60</td>
<td>6.40E-03</td>
<td>9.94E-01</td>
<td>6.40E-03</td>
<td>9.94E-01</td>
</tr>
<tr>
<td></td>
<td>S(Total)</td>
<td></td>
<td>9.98E-01</td>
<td>9.10E-01</td>
<td>9.98E-01</td>
<td>9.10E-01</td>
</tr>
<tr>
<td></td>
<td>F(Total)</td>
<td></td>
<td>1.78E-03</td>
<td>9.04E-02</td>
<td>1.78E-03</td>
<td>9.04E-02</td>
</tr>
</tbody>
</table>
### Appendix B-5

#### HIGH STRESS HRA

**Case I**

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>5</td>
<td>1.40E-02</td>
<td>9.86E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>10</td>
<td>2.00E-01</td>
<td>8.00E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>15</td>
<td>7.70E-03</td>
<td>9.92E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>20</td>
<td>3.30E-02</td>
<td>9.67E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>25</td>
<td>2.80E-02</td>
<td>9.72E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>30</td>
<td>5.20E-04</td>
<td>9.99E-01</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>35</td>
<td>2.10E-02</td>
<td>9.79E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>40</td>
<td>2.20E-03</td>
<td>9.98E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>5.01E-02</td>
<td></td>
</tr>
</tbody>
</table>

**Case II**

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>10</td>
<td>7.30E-03</td>
<td>9.93E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>20</td>
<td>1.30E-01</td>
<td>8.70E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>30</td>
<td>4.00E-03</td>
<td>9.96E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>40</td>
<td>1.90E-02</td>
<td>9.81E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>50</td>
<td>1.60E-02</td>
<td>9.84E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>60</td>
<td>2.40E-04</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>70</td>
<td>1.30E-02</td>
<td>9.87E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>80</td>
<td>1.10E-03</td>
<td>9.99E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>2.77E-02</td>
<td></td>
</tr>
</tbody>
</table>

**Case III**

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>HIGH STRESS HEP</th>
<th>HIGH STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>25</td>
<td>3.00E-03</td>
<td>9.97E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>30</td>
<td>9.70E-02</td>
<td>9.03E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>35</td>
<td>3.60E-03</td>
<td>9.96E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>40</td>
<td>1.90E-02</td>
<td>9.81E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>45</td>
<td>1.80E-02</td>
<td>9.82E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>50</td>
<td>3.00E-04</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>55</td>
<td>1.50E-02</td>
<td>9.85E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>60</td>
<td>1.50E-03</td>
<td>9.99E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>2.38E-02</td>
<td></td>
</tr>
</tbody>
</table>
### HIGH STRESS HRA

#### Case I

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>MEDIUM STRESS HEP</th>
<th>MEDIUM STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>5</td>
<td>8.50E-03</td>
<td>9.92E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>10</td>
<td>1.30E-01</td>
<td>8.70E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>15</td>
<td>5.00E-03</td>
<td>9.95E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>20</td>
<td>2.20E-02</td>
<td>9.78E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>25</td>
<td>1.90E-02</td>
<td>9.81E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>30</td>
<td>3.60E-04</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>35</td>
<td>1.50E-02</td>
<td>9.85E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>40</td>
<td>1.60E-03</td>
<td>9.98E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>3.25E-02</td>
<td></td>
</tr>
</tbody>
</table>

#### Case II

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>MEDIUM STRESS HEP</th>
<th>MEDIUM STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>10</td>
<td>4.60E-03</td>
<td>9.95E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>20</td>
<td>8.60E-02</td>
<td>9.14E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>30</td>
<td>2.80E-03</td>
<td>9.97E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>40</td>
<td>1.40E-02</td>
<td>9.86E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>50</td>
<td>1.20E-02</td>
<td>9.88E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>60</td>
<td>1.80E-04</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>70</td>
<td>9.60E-03</td>
<td>9.90E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>80</td>
<td>8.90E-04</td>
<td>9.99E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>1.96E-02</td>
<td></td>
</tr>
</tbody>
</table>

#### Case III

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STANDARD HEP</th>
<th>TIME Min.</th>
<th>MEDIUM STRESS HEP</th>
<th>MEDIUM STRESS Success Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.00E-05</td>
<td>25</td>
<td>2.10E-03</td>
<td>9.98E-01</td>
</tr>
<tr>
<td>B</td>
<td>1.00E-02</td>
<td>30</td>
<td>6.90E-02</td>
<td>9.31E-01</td>
</tr>
<tr>
<td>C</td>
<td>1.50E-04</td>
<td>35</td>
<td>2.50E-03</td>
<td>9.98E-01</td>
</tr>
<tr>
<td>D</td>
<td>1.60E-03</td>
<td>40</td>
<td>1.40E-02</td>
<td>9.86E-01</td>
</tr>
<tr>
<td>E</td>
<td>1.60E-03</td>
<td>45</td>
<td>1.30E-02</td>
<td>9.87E-01</td>
</tr>
<tr>
<td>G</td>
<td>1.00E-05</td>
<td>50</td>
<td>2.10E-04</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>H</td>
<td>1.60E-03</td>
<td>55</td>
<td>1.10E-02</td>
<td>9.89E-01</td>
</tr>
<tr>
<td>K</td>
<td>1.00E-04</td>
<td>60</td>
<td>1.10E-03</td>
<td>9.99E-01</td>
</tr>
<tr>
<td>S(Total)</td>
<td>9.98E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(Total)</td>
<td>1.78E-03</td>
<td></td>
<td>1.73E-02</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B-9

HUMAN ERROR PROBABILITY
HIGH STRESS CONDITIONS

TIME-MINUTES

1E0 1E1 1E2 1E3

HEP

1E0 1E-1 1E-2 1E-3 1E-4 1E-5

2 3 4 5 6 7 8 9

A B C D E F G H K
Appendix B-10

HUMAN ERROR PROBABILITY
MEDIUM STRESS

TIME-MINUTES

HEP

1E0

1E-1

1E-2

1E-3

1E-4

1E-5

1E0 1E1 1E2 1E3
Appendix B-11

HUMAN ERROR PROBABILITY

MEDIUM STRESS

TIME-MINUTES

HEP

1E0

3

1E-1

1E-2

1E-3

1E-4

1E-5

1E0 1E1 1E2 1E3

1E0 1E1 1E2 1E3
APPENDIX C

Accident Sequence Fault Trees
Zion-1
LOSS OF OFFSITE POWER (LOSP) AND SMALL LOCA CAUSED BY REACTOR COOLANT PUMP SEAL LEAKAGE AND COMPONENT COOLING WATER SYSTEM FAILS TO REMOVE HEAT OR (G-1-1) OR (G-1-9) OR (G-1-10) FAILURE OF COOLANT MAKEUP SYSTEMS OR FAILURE TO REMOVE HEAT (FROM TRANSIENT SEQUENCE SEE SHEET 3) OVER FLOWING WATER SYSTEM MECHANICAL CAUSES (C-1-3) AND SHEET 2 (C-2-1)

LOSS OF SERVICE WATER SYSTEM (G-1-2) 4-OUT-OF-6 (SEE SHEET 3) 2

CCWS PUMP OR FAILS TO START OR RUN OR (G-1-6) OR (G-1-7) OR (G-1-8)

SUPPLY INSUFFICIENT BREAKER POWER ON TRIPS FAILS TO BUS 147 OPEN (SWING)

(CCWS)4 (GS137) (G6147) (C5137) (C6147) (C4CCWS) (C5CCWS) (C6CCWS)
LOSS OF OFFSITE POWER (LOSP) AND FAILURE TO REMOVE HEAT (G-3-1) SHEET 1

FAILURE OF AUXILIARY FEEDWATER SYSTEM TO REMOVE HEAT AND (G-3-2)

AFWS TURBINE DRIVEN PUMP 1A FAILS TO START OR RUN OR (G-3-4) OR (G-3-5)

LOSS OF COOLING SERVICE SYSTEM FAILS (G-3-3) 5-OUT-OF-6

SUPPLY BREAKER TRIPS FAILS ON BUS (G614A) (G5138) (G6149) (G5139)

SW PUMP 1A FAILS TO START OR RUN OR (G-3-6) OR (G-3-7)

UNIT 2 4,160V BUSES

Zion-1, Sheet 3
Transient Sequence

FAILURE OF COOLANT MAKEUP SYSTEMS TO SMALL LOCAL SEQUENCE

AFWS ELECTRIC PUMP 1B Fails TO START OR RUN

AFWS ELECTRIC PUMP 1C Fails TO START OR RUN

FAILURE OF FEED & BLEED TO REMOVE HEAT

FAILURE OF Auxiliary FEEDWATER SYSTEM TO REMOVE HEAT

FAILURE OF COOLANT MAKEUP SYSTEMS TO SMALL LOCAL SEQUENCE
**Zion-1, Sheet 4**

(TOP EVENT)  
SUPPLY BREAKER TRIPS OPEN (ANY ESF LOAD)  
TRIP COIL IS INADVERTANTLY ENERGIZED  
TO SHEETS 1, 2 AND 3  
OR  

<table>
<thead>
<tr>
<th>TOP EVENT NAME</th>
<th>ESF LOAD</th>
<th>427, UNDervoltage RELAY CONTACTS CHATTER</th>
<th>450/451 CO-5 OA, OVERCURRENT CONTACTS, CHATTER</th>
<th>450/451 CO-5 OC, OVERCURRENT CONTACTS, CHATTER</th>
<th>450 G/PJC, OVERCURRENT CONTACTS, CHATTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>G4CCW50E</td>
<td>CCWS OE</td>
<td>QRE27X1C</td>
<td>ARECOOAC</td>
<td>ARECOOCC</td>
<td>AREGJPJC</td>
</tr>
<tr>
<td>G4CCW50D</td>
<td>CCWS OD</td>
<td>RRE27X2C</td>
<td>BREC00AC</td>
<td>BRECOOCC</td>
<td>BREGPJJC</td>
</tr>
<tr>
<td>G4CCW50C</td>
<td>CCWS OC</td>
<td>SRE27X1C</td>
<td>CRECOOAC</td>
<td>CRECOOCC</td>
<td>CREGPJJC</td>
</tr>
<tr>
<td>G4CCW50B</td>
<td>CCWS OB</td>
<td>TRE27X1C</td>
<td>3REC00AC</td>
<td>3REC00CC</td>
<td>3REGPJJC</td>
</tr>
<tr>
<td>G4CCW50A</td>
<td>CCWS OA</td>
<td>VRE27X2C</td>
<td>4REC00AC</td>
<td>4REC00CC</td>
<td>4REGPJJC</td>
</tr>
<tr>
<td>G4CHRG1B</td>
<td>CHARGING 1B</td>
<td>QRE27X2C</td>
<td>DREC00AC</td>
<td>DREC00CC</td>
<td>DREGPJJC</td>
</tr>
<tr>
<td>G4CHRG1A</td>
<td>CHARGING 1A</td>
<td>SRE27X1C</td>
<td>ERC000AC</td>
<td>ERC00CC</td>
<td>ERCGPJJC</td>
</tr>
<tr>
<td>G4S11A</td>
<td>SI 1A</td>
<td>QRE27X2C</td>
<td>FREC00AC</td>
<td>FREC00CC</td>
<td>FREGPJJC</td>
</tr>
<tr>
<td>G4S11B</td>
<td>SI 1B</td>
<td>RRE27X1C</td>
<td>GREC00AC</td>
<td>GREC00CC</td>
<td>GREGPJJC</td>
</tr>
<tr>
<td>G4SW1A</td>
<td>SW 1A</td>
<td>QRE27X2C</td>
<td>HREC00AC</td>
<td>HREC00CC</td>
<td>HREGPJJC</td>
</tr>
<tr>
<td>G4SW1B</td>
<td>SW 1B</td>
<td>RRE27X1C</td>
<td>IreC000C</td>
<td>IreC00CC</td>
<td>IreGPJJC</td>
</tr>
<tr>
<td>G4SW1C</td>
<td>SW 1C</td>
<td>SRE27X2C</td>
<td>JREC00AC</td>
<td>JREC00CC</td>
<td>JREGPJJC</td>
</tr>
<tr>
<td>G4SW2A</td>
<td>SW 2A</td>
<td>TRE27X2C</td>
<td>KREC00AC</td>
<td>KREC00CC</td>
<td>KREGPJJC</td>
</tr>
<tr>
<td>G4SW2B</td>
<td>SW 2B</td>
<td>VRE27X1C</td>
<td>LREC00AC</td>
<td>LREC00CC</td>
<td>LREGPJJC</td>
</tr>
<tr>
<td>G4SW2C</td>
<td>SW 2C</td>
<td>VRE27X2C</td>
<td>MREC00AC</td>
<td>MREC00CC</td>
<td>MREGPJJC</td>
</tr>
<tr>
<td>G4AFWS1B</td>
<td>AFWS 1B</td>
<td>RRE27X2C</td>
<td>OREC00AC</td>
<td>OREC00CC</td>
<td>OREGPJJC</td>
</tr>
<tr>
<td>G4AFWS1C</td>
<td>AFWS 1C</td>
<td>SRE27X1C</td>
<td>PREC00AC</td>
<td>PREC00CC</td>
<td>PREGPJJC</td>
</tr>
</tbody>
</table>
SUPPLY BREAKER \{ FAILS TO CLOSE \} \quad TO SHEETS 1, 2 AND 3

- CLOSING COIL IS NOT ENERGIZED
- CLOSE SIGNAL NOT GENERATED
- LOAD SEQUENCER NOT ENERGIZED
- NO POWER ON 480V BUS 137, 138, 139, 237, 238, 239
- SUPPLY BREAKER TRIPS

TRIP COIL IS INADVERTANTLY ENERGIZED

	| TOP EVENT | 480V BUS | 427, UNDERVOLTAGE RELAY CONTACTS | 450/451 CO-11 OA, OVERCURRENT CONTACTS, CHATTER | 450/451 CO-11 OC, OVERCURRENT CONTACTS, CHATTER | 450 G/PJC, OVERCURRENT CONTACTS, CHATTER |
|------------|---------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| G5137      | 137     | QRE27X1C                         | WRECOOCC                        | WRECOOCC                        | WREGPJCC                        |
| G5138      | 138     | RRE27X1C                         | XRECOOCC                        | XRECOOCC                        | XREGPJCC                        |
| G5139      | 139     | SRE27X2C                         | YRECOOCC                        | YRECOOCC                        | YREGPJCC                        |
| G5237      | 237     | TRE27X1C                         | ZRECOOCC                        | ZRECOOCC                        | ZREGPJCC                        |
| G5238      | 238     | URE27X1C                         | 1RECOOCC                        | 1RECOOCC                        | 1REGPJCC                        |
| G5239      | 239     | VRE27X2C                         | 2RECOOCC                        | 2RECOOCC                        | 2REGPJCC                        |
### TOP EVENT

**NO AC POWER ON 4.16 KV BUS 148, 149, 248, 249**

**OR**

- LOSS OF DIESEL GENERATOR COOLING
- DG SUPPLY BREAKER TRIPS
- TRIP COIL IS INADVERTENTLY ENERGIZED (CAUSES Y RELAY TO SEAL-IN)
- SERVICE WATER SYSTEM FAILS
- (S-3-3)

**OR**

- LOSS OF DIESEL GENERATOR COOLING
- DG SUPPLY BREAKER TRIPS
- TRIP COIL IS INADVERTENTLY ENERGIZED (CAUSES Y RELAY TO SEAL-IN)
- SERVICE WATER SYSTEM FAILS
- (S-3-3)

---

**Zion-1, Sheet 6**

<table>
<thead>
<tr>
<th>TOP EVENT</th>
<th>4.16 KV TO SHEETS 1, 2 AND 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>OR</td>
<td></td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>RELAY</th>
<th>DG CO-6</th>
<th>DG CO-6</th>
<th>DG CO-6</th>
<th>DG CO-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRE4861C</td>
<td>RRE4862C</td>
<td>RRE4861C</td>
<td>RRE4862C</td>
<td>RRE4861C</td>
</tr>
<tr>
<td>SRE4861C</td>
<td>SRE4862C</td>
<td>SRE4861C</td>
<td>SRE4862C</td>
<td>SRE4861C</td>
</tr>
<tr>
<td>URE4861C</td>
<td>URE4862C</td>
<td>URE4861C</td>
<td>URE4862C</td>
<td>URE4861C</td>
</tr>
<tr>
<td>VRE4861C</td>
<td>VRE4862C</td>
<td>VRE4861C</td>
<td>VRE4862C</td>
<td>VRE4861C</td>
</tr>
</tbody>
</table>

---

**Zion-1, Sheet 6**

<table>
<thead>
<tr>
<th>TOP EVENT</th>
<th>4.16 KV NAME BUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OR</td>
<td></td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>RELAY</th>
<th>DG CO-6</th>
<th>DG CO-6</th>
<th>DG CO-6</th>
<th>DG CO-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRE4861C</td>
<td>RRE4862C</td>
<td>RRE4861C</td>
<td>RRE4862C</td>
<td>RRE4861C</td>
</tr>
<tr>
<td>SRE4861C</td>
<td>SRE4862C</td>
<td>SRE4861C</td>
<td>SRE4862C</td>
<td>SRE4861C</td>
</tr>
<tr>
<td>URE4861C</td>
<td>URE4862C</td>
<td>URE4861C</td>
<td>URE4862C</td>
<td>URE4861C</td>
</tr>
<tr>
<td>VRE4861C</td>
<td>VRE4862C</td>
<td>VRE4861C</td>
<td>VRE4862C</td>
<td>VRE4861C</td>
</tr>
</tbody>
</table>
APPENDIX D

Accident Sequence Fault Trees
LaSalle-2
LASALLE UNIT 2

ASSUMPTIONS:
1. NO OPERATOR RECOVERY
2. CONSIDER CHATTER OF RELAY AND PRESSURE SWITCH CONTACTS ONLY

CORE DAMAGE CAUSED BY A SEISMIC EVENT

AND

****************************************************************************************************

LOSS OF OFFSITE POWER

AND

FAILURE TO MAKEUP WITHIN 80 MINUTES

AND

FAILURE OF HIGH PRESSURE MAKEUP SYSTEMS

AND

FAILURE OF LOW PRESSURE MAKEUP SYSTEMS

AND

REACTOR CORE ISOLATION COOLING FAILURE

HIGH PRESSURE CORE SPRAY FAILURE

INSUFFICIENT AC POWER ON BUS 243

LPCS LPCI FAILURE

INSUFFICIENT AC POWER ON BUS 241Y

RHR A PUMP FAILURE

INSUFFICIENT AC POWER ON BUS 241Y

RHR B PUMP FAILURE

INSUFFICIENT AC POWER ON BUS 242Y

RHR C PUMP FAILURE

INSUFFICIENT AC POWER ON BUS 242Y

LaSalle-2, Sheet 1
**Laselle Unit 2**

**Reactor Core Isolation Cooling Failure**

- OR

*------------------------------*

**Steam Supply to RCIC Turbine Unavailable**

- OUTBOARD VALVE
  - FO08 CLOSES
  - RELAY
    - K15 SEALS IN
      - OR
  
*------------------------------*

**Seal in Relay K15 Chatters**

**Seal in Relay K5 Chatters**

---

**REFERENCE DRAWINGS**

- SHEET 1
  - 1E2-4201 AC
  - 1E2-4201 AD
  - 1E2-4201 AE
  - 1E2-4201 AF
  - 1E2-4201 AG
  - 1E2-2-4226AC
  - 1E2-2-4226AD
  - 1E2-2-4226AN

---

**D-2**

<table>
<thead>
<tr>
<th>VALVE</th>
<th>RELAY CONTACTS CHATTER</th>
<th>PRESSURE SWITCH CONTACTS CHATTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>F013A</td>
<td>N/A</td>
<td>N039A</td>
</tr>
<tr>
<td>F013B</td>
<td>N/A</td>
<td>N039B</td>
</tr>
<tr>
<td>(A) F013C</td>
<td>K68A</td>
<td>N039C</td>
</tr>
<tr>
<td>(A) F013D</td>
<td>K66A</td>
<td>N039D</td>
</tr>
<tr>
<td>(A) F013E</td>
<td>K70A</td>
<td>N039E</td>
</tr>
<tr>
<td>F013F</td>
<td>N/A</td>
<td>N039F</td>
</tr>
<tr>
<td>F013G</td>
<td>N/A</td>
<td>N039G</td>
</tr>
<tr>
<td>F013H</td>
<td>N/A</td>
<td>N039H</td>
</tr>
<tr>
<td>F013J</td>
<td>N/A</td>
<td>N039J</td>
</tr>
<tr>
<td>F013K</td>
<td>K71A</td>
<td>N039K</td>
</tr>
<tr>
<td>F013L</td>
<td>N/A</td>
<td>N039L</td>
</tr>
<tr>
<td>F013M</td>
<td>N/A</td>
<td>N039M</td>
</tr>
<tr>
<td>F013N</td>
<td>N/A</td>
<td>N039N</td>
</tr>
<tr>
<td>(A) F013P</td>
<td>K72A</td>
<td>N039P</td>
</tr>
<tr>
<td>(A) F013R</td>
<td>N/A</td>
<td>N039R</td>
</tr>
<tr>
<td>(A) F013S</td>
<td>K65A</td>
<td>N039S</td>
</tr>
<tr>
<td>(A) F013U</td>
<td>K75A</td>
<td>N039U</td>
</tr>
<tr>
<td>(A) F013V</td>
<td>N/A</td>
<td>N039V</td>
</tr>
</tbody>
</table>

A denotes ADS SRV

N/A not applicable
LASALLE UNIT 2

**INSUFFICIENT POWER ON BUS 243-2**

* * *

**BREAKER 2433 FAILS TO CLOSE OR TO REMAIN CLOSED**

* *

**LOCKOUT RELAY SEALS IN, PREVENTS CLOSURE OF HPCS CIRCUIT BREAKER OR TRIPS HPCS CIRCUIT BREAKER**

* *

REFERENCE DRAWING NUMBERS

1E-2-4223 AD (CONTROL CIRCUIT)
1E-2-4223 AG (K1 RELAY)
1E-2-4223 AL (K15 RELAY)

**K1 LOCKOUT RELAY CONTACTS CHATTER**

* *

**K15 LOCKOUT RELAY SEALS IN**

* *

**K10 RELAY CONTACTS CHATTER (HPCS DG OVERSPEED)**

* *

**K9 RELAY CONTACTS CHATTER (HPCS DG UNDERSPEED)**

* *

**K11 RELAY CONTACTS CHATTER (HPCS DG LOW PRESSURE)**

* *

**K12 RELAY CONTACTS CHATTER (HPCS DG HIGH TEMPERATURE)**

* *

**K32 CONTACTS CHATTER (HPCS DG REVERSE POWER)**

* *

**K30A CONTACTS CHATTER (HPCS DG DIFFERENTIAL PHASE A)**

* *

**K30B CONTACTS CHATTER (HPCS DG DIFFERENTIAL PHASE B)**

* *

**K30C CONTACTS CHATTER (HPCS DG DIFFERENTIAL PHASE C)**

* *

**K1 CONTACTS CHATTER (LOSS OF EXCITATION)**

* *

**K35A CONTACTS CHATTER (OVER-CURRENT PHASE A)**

* *

**K35B CONTACTS CHATTER (OVER-CURRENT PHASE B)**

* *

**K35C CONTACTS CHATTER (OVER-CURRENT PHASE C)**

* *
LASALLE UNIT 2

INSUFFICIENT AC POWER ON BUS 241Y
* BREAKER 2413 FAILS TO CLOSE OR REMAINS CLOSED
* DG-O SWINGS TO UNIT 1

(See section 4.2.1 for a discussion of the development of this event.)
LaSalle-2, Sheet 5

REFERENCE DRAWINGS
IE-2-4009 AA
IE-2-4009 AG
IE-2-4009 AH
DG-2A

---

**LaSalle UNIT 2**

**INSUFFICIENT POWER ON**

- BUS 242V
- Sheet 1
- BREAKER 2422 FAILS
  TO CLOSE OR TO REMAIN CLOSED
- LOCKOUT RELAY 86 DC2A
  ENERGIZES
- OR

---

**K9 CONTACTS**
- SEAL-IN
  (LOW ENGINE RPM)
  OR
  SEAL-IN
  (HIGH ENGINE RPM)
  OR
  SEAL IN
  (HIGH ENGINE TEMPERATURE)
  OR
  SEAL IN
  (LOW LUBE OIL PRESSURE)

**K25 CONTACTS**
- CONTACTS
  (DC FIELD RELAY)

**K32 CONTACTS**
- CONTACTS
  (REVERSE POWER)

---

**K9 AUXILIARY CONTACTS**
- CHATTER
  (DIFFERENTIAL CURRENT)

**K39 CONTACTS**
- CHATTER

**K10 CONTACTS**
- CHATTER

**K12 CONTACTS**
- CHATTER
  (UNDER VOLTAGE)

**K11 CONTACTS**
- CHATTER
  (OVER VOLTAGE)

**K10 AUXILIARY CONTACTS**
- CONTACTS
  (DIFFERENTIAL CURRENT)

---

**PHASE A**

**PHASE B**

**PHASE C**
APPENDIX E

Sargent & Lundy Standard STD-ED-115

"Device Function Numbers and Letters as Used on Sargent & Lundy's Electrical Drawings"

Version of 9 January 1981
DEVICE FUNCTION NUMBERS AND LETTERS
AS USED ON SARGENT & LUNDY'S ELECTRICAL DRAWINGS

1. SCOPE
1.1 The device numbers and letters of the following pages of this standard are adopted for use on Sargent & Lundy's Electrical drawings, and are in general agreement with the 1979 revision of the American National Standards Institute publication ANSI/IEEE C37.2, "Electrical Power System Device Function Numbers."

2. PURPOSE
2.1 The purpose of the device number or device letter(s) is to identify the function of each device used in an electrical circuit.

3. GENERAL
3.1 The addition of a prefix and suffix to the basic device number is used on Sargent & Lundy's Electrical drawings to identify and delineate the device application. The complete device number is shown at the proper symbol of each device as it appears on the various diagrams for power and control circuits.

3.2 The device number does not detract from the S&L "Numbering System for Equipment" whose numbers may also appear on Electrical drawings.

4. REFERENCES
4.1 For additional information, see the following standards:
   EC-110 - Graphic Symbols for Power & Control Circuits
   EC-111 - Graphic Symbols for Key Diagrams of Auxiliaries

<table>
<thead>
<tr>
<th>PAGE REVISION STATUS</th>
<th>DEVICE FUNCTION NUMBERS AND LETTERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- 1/9/81</td>
<td>9- 17- 25-</td>
</tr>
<tr>
<td>2- 8/1/75</td>
<td>10- 18- 26-</td>
</tr>
<tr>
<td>3- 8/1/75</td>
<td>11- 19- 27-</td>
</tr>
<tr>
<td>4- 8/1/75</td>
<td>12- 20- 28-</td>
</tr>
<tr>
<td>5- 8/1/75</td>
<td>13- 21- 29-</td>
</tr>
<tr>
<td>6- 8/1/75</td>
<td>14- 22- 30-</td>
</tr>
<tr>
<td>7- 15- 23- 31-</td>
<td>1-9-81 STD-EC-115</td>
</tr>
<tr>
<td>8- 16- 24- 32-</td>
<td></td>
</tr>
</tbody>
</table>

E-1
5. **PREFIX APPLICATIONS**

5.1 Similar applications of the same basic device number are at times separately identified by the use of an additional number prefix which denotes the power voltage level associated with the device. The prefix assignments for each station are normally shown on the single line diagram. Equipment at the generator voltage area may or may not have a prefix.

5.2 Using the AC circuit breaker device number (52) as an example, the device numbers would appear as 152, 252, 352, etc. Some prefix assignments are shown in the following table and differ according to station and client.

<table>
<thead>
<tr>
<th>VOLTAGE AREA</th>
<th>STATION A</th>
<th>STATION B</th>
<th>STATION C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PREFIX</td>
<td>TYPICAL</td>
<td>PREFIX</td>
</tr>
<tr>
<td>745 kV</td>
<td>9</td>
<td>952-1</td>
<td>None</td>
</tr>
<tr>
<td>345 kV</td>
<td>8</td>
<td>852-1</td>
<td>1</td>
</tr>
<tr>
<td>138 kV</td>
<td>7</td>
<td>752-1</td>
<td>2</td>
</tr>
<tr>
<td>Gen. Voltage</td>
<td>6</td>
<td>646G1</td>
<td>No Prefix</td>
</tr>
<tr>
<td>13.8 kV</td>
<td>None</td>
<td>---</td>
<td>3</td>
</tr>
<tr>
<td>6.9 kV</td>
<td>5</td>
<td>552</td>
<td>4</td>
</tr>
<tr>
<td>4.16 kV</td>
<td>4</td>
<td>452</td>
<td>5</td>
</tr>
<tr>
<td>480 V</td>
<td>3</td>
<td>352</td>
<td>6</td>
</tr>
</tbody>
</table>

6. **SUFFIX APPLICATIONS**

6.1 Additional separation is achieved by the use of a suffix number or letter. For example, circuit breakers in the switchyard may be designated 152-1, 152-2, etc., to correspond to the bay in which the breaker is located (see table above). This allows device, cable and drawing numbers on the construction drawings to remain, regardless of changes in the operating name (or number) of the breaker or line.

6.2 Additional functional description is also achieved by the use of a suffix letter or number. For instance, the use of the time overcurrent relay device number (51) with the suffix "G" (51G) would indicate that it is operated by current from a current transformer in a power neutral lead to ground whereas the use of the suffix "N" (51N) would indicate that it is operated by current in the residual circuit of current transformers in the power phase leads. An exception to this is the use of "G" to indicate sensitivity to ground faults on some line relays even though they are operated by current from the current transformers in the power phase leads.
### DEVICE FUNCTION NUMBERS AND LETTERS AS USED ON SARGENT & LUNDY'S ELECTRICAL DRAWINGS

<table>
<thead>
<tr>
<th>Device Description</th>
<th>Device Function Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Master Element</td>
<td>1. 56. Field Application Relay</td>
</tr>
<tr>
<td>2. Time-Delay Starting or Closing Relay</td>
<td>2. 57. Short-Circuiting or Grounding Device</td>
</tr>
<tr>
<td>3. Checking or Interlocking Relay</td>
<td>3. 58. Rectification Failure Relay</td>
</tr>
<tr>
<td>4. Master Contact</td>
<td>4. 59. Overvoltage Relay</td>
</tr>
<tr>
<td>5. Stopping Device</td>
<td>5. 60. Voltage or Current Balance Relay</td>
</tr>
<tr>
<td>6. Starting Circuit Breaker</td>
<td>6. 61. (Reserved for future application)</td>
</tr>
<tr>
<td>7. Anode Circuit Breaker</td>
<td>7. 62. Time-Delay Stopping or Opening Relay</td>
</tr>
<tr>
<td>8. Control Power Disconnecting Device</td>
<td>8. 63. Liquid or Gas Pressure or Vacuum Relay</td>
</tr>
<tr>
<td>9. Reversing Device</td>
<td>9. 64. Ground Protective Relay</td>
</tr>
<tr>
<td>10. Unit Sequence Switch</td>
<td>10. 65. Governor</td>
</tr>
<tr>
<td>11. (Reserved for future application)</td>
<td>11. 66. Notching or Jogging Device</td>
</tr>
<tr>
<td>12. Over-Speed Device</td>
<td>12. 67. AC Directional Overcurrent Relay</td>
</tr>
<tr>
<td>13. Synchronous-Speed Device</td>
<td>13. 68. Blocking Relay</td>
</tr>
<tr>
<td>15. Speed or Freq. Matching Device</td>
<td>15. 70. Rheostat</td>
</tr>
<tr>
<td>16. (Reserved for future application)</td>
<td>16. 71. Liquid or Gas-Level Relay</td>
</tr>
<tr>
<td>17. Shunting or Discharge Switch</td>
<td>17. 72. DC Circuit Breaker</td>
</tr>
<tr>
<td>18. Accelerating or Decelerating Device</td>
<td>18. 73. Load-Resistor Contactor</td>
</tr>
<tr>
<td>20. Valve</td>
<td>20. 75. Position Changing Mechanism</td>
</tr>
<tr>
<td>21. Distance Relay</td>
<td>21. 76. DC Overcurrent Relay</td>
</tr>
<tr>
<td>22. Equalizer Circuit Breaker</td>
<td>22. 77. Pulse Transmitter</td>
</tr>
<tr>
<td>23. Temperature Control Device</td>
<td>23. 78. Phase-Angle Measuring or Out-of-Step Protective Relay</td>
</tr>
<tr>
<td>24. (Reserved for future application)</td>
<td>24.</td>
</tr>
<tr>
<td>25. Synchronizing or Sync-Check Device</td>
<td>25.</td>
</tr>
<tr>
<td>27. Undervoltage Relay</td>
<td>27.</td>
</tr>
<tr>
<td>29. Isolating Contactor</td>
<td>29.</td>
</tr>
<tr>
<td>32. Directional Power Relay</td>
<td>32.</td>
</tr>
<tr>
<td>33. Position Switch</td>
<td>33.</td>
</tr>
<tr>
<td>34. Master Sequence Device</td>
<td>34.</td>
</tr>
<tr>
<td>35. Brush-Operated or Slip-Ring Short Circuiting</td>
<td>35.</td>
</tr>
<tr>
<td>36. Polarity or Polarizing Voltage Device</td>
<td>36.</td>
</tr>
<tr>
<td>37. Undercurrent or Underpower Relay</td>
<td>37.</td>
</tr>
<tr>
<td>38. Bearing Protective Device</td>
<td>38.</td>
</tr>
<tr>
<td>40. Field Relay</td>
<td>40.</td>
</tr>
<tr>
<td>41. Field Circuit Breaker</td>
<td>41.</td>
</tr>
<tr>
<td>42. Running Circuit Breaker</td>
<td>42.</td>
</tr>
<tr>
<td>43. Manual Transfer or Selector Device</td>
<td>43.</td>
</tr>
<tr>
<td>44. Unit Sequence Starting Relay</td>
<td>44.</td>
</tr>
<tr>
<td>45. Atmospheric Condition Monitor</td>
<td>45.</td>
</tr>
<tr>
<td>46. Reverse-Phase or Phase-Balance Current Relay</td>
<td>46.</td>
</tr>
<tr>
<td>47. Phase-Sequence Voltage Relay</td>
<td>47.</td>
</tr>
<tr>
<td>49. Machine or Transformer Thermal Relay</td>
<td>49.</td>
</tr>
<tr>
<td>50. Instant. Overcurrent or Rate-of-Rise Relay</td>
<td>50.</td>
</tr>
<tr>
<td>51. AC Time Overcurrent Relay</td>
<td>51.</td>
</tr>
<tr>
<td>52. AC Circuit Breaker</td>
<td>52.</td>
</tr>
<tr>
<td>53. Exciter or DC Generator Relay</td>
<td>53.</td>
</tr>
<tr>
<td>54. (Reserved for future application)</td>
<td>54.</td>
</tr>
<tr>
<td>55. Power Factor Relay</td>
<td>55.</td>
</tr>
<tr>
<td>56. Field Application Relay</td>
<td>56.</td>
</tr>
<tr>
<td>57. Short-Circuiting or Grounding Device</td>
<td>57.</td>
</tr>
<tr>
<td>58. Rectification Failure Relay</td>
<td>58.</td>
</tr>
<tr>
<td>59. Overvoltage Relay</td>
<td>59.</td>
</tr>
<tr>
<td>60. Voltage or Current Balance Relay</td>
<td>60.</td>
</tr>
<tr>
<td>61. (Reserved for future application)</td>
<td>61.</td>
</tr>
<tr>
<td>62. Time-Delay Stopping or Opening Relay</td>
<td>62.</td>
</tr>
<tr>
<td>63. Liquid or Gas Pressure or Vacuum Relay</td>
<td>63.</td>
</tr>
<tr>
<td>64. Ground Protective Relay</td>
<td>64.</td>
</tr>
<tr>
<td>65. Governor</td>
<td>65.</td>
</tr>
<tr>
<td>66. Notching or Jogging Device</td>
<td>66.</td>
</tr>
<tr>
<td>67. AC Directional Overcurrent Relay</td>
<td>67.</td>
</tr>
<tr>
<td>68. Blocking Relay</td>
<td>68.</td>
</tr>
<tr>
<td>69. Permissive Control Device</td>
<td>69.</td>
</tr>
<tr>
<td>70. Rheostat</td>
<td>70.</td>
</tr>
<tr>
<td>71. Liquid or Gas-Level Relay</td>
<td>71.</td>
</tr>
<tr>
<td>72. DC Circuit Breaker</td>
<td>72.</td>
</tr>
<tr>
<td>73. Load-Resistor Contactor</td>
<td>73.</td>
</tr>
<tr>
<td>74. Alarm Relay</td>
<td>74.</td>
</tr>
<tr>
<td>75. Position Changing Mechanism</td>
<td>75.</td>
</tr>
<tr>
<td>76. DC Overcurrent Relay</td>
<td>76.</td>
</tr>
<tr>
<td>77. Pulse Transmitter</td>
<td>77.</td>
</tr>
<tr>
<td>78. Phase-Angle Measuring or Out-of-Step Protective Relay</td>
<td>78.</td>
</tr>
<tr>
<td>79. AC Reclosing Relay</td>
<td>79.</td>
</tr>
<tr>
<td>80. Liquid or Gas Flow Relay</td>
<td>80.</td>
</tr>
<tr>
<td>81. Frequency Relay</td>
<td>81.</td>
</tr>
<tr>
<td>82. DC Reclosing Relay</td>
<td>82.</td>
</tr>
<tr>
<td>83. Auto.Selective Cont. or Transfer Relay</td>
<td>83.</td>
</tr>
<tr>
<td>84. Operating Mechanism</td>
<td>84.</td>
</tr>
<tr>
<td>85. Carrier or Pilot-Wire Receiver Relay</td>
<td>85.</td>
</tr>
<tr>
<td>86. Locking-Out Relay</td>
<td>86.</td>
</tr>
<tr>
<td>88. Auxiliary Motor or Motor Generator</td>
<td>88.</td>
</tr>
<tr>
<td>89. Line Switch</td>
<td>89.</td>
</tr>
<tr>
<td>90. Regulating Device</td>
<td>90.</td>
</tr>
<tr>
<td>91. Voltage Directional Relay</td>
<td>91.</td>
</tr>
<tr>
<td>93. Field-Changing Contactor</td>
<td>93.</td>
</tr>
<tr>
<td>94. Tripping or Trip-Free Relay</td>
<td>94.</td>
</tr>
<tr>
<td>95. Used only for specific applications where none of the assigned numbered functions are suitable.</td>
<td>95.</td>
</tr>
</tbody>
</table>

**Notes:**
- The table lists various device functions and their corresponding numbers and letters as used on Sargent & Lundy's electrical drawings.
- The device functions are classified into categories such as starting, closing, protection, control, and more.
- The numbers and letters are used to identify and specify the functions in their drawings.

**Approval:**
- Approved by E. Zamora
- Date: 4-18-49

**Revision:**
- Revisions from 2-7-64
- Standard: STD-EC-115

**Page:**
- Page 3 of the document.
8. DEVICE LETTERS

8.1 Device letters are used to designate function in cases where the device number does not apply.

8.2 For letters identifying the function of indicating or integrating instruments, thermal converters, and transducers, see Standard EC-110.

8.3 The device letter can be either a single letter or a combination of letters.

9. DEVICE LETTER (Single) & WORD ASSOCIATIONS

A - Auxiliary, amperes, automatic, air, Phase A
B - Bus, Blocking, Back-up, Brake, Breaker, Bushing, Phase B
C - Control, Current, Coil, Close, Check, Circuit, Phase C
D - Down, Delay
E - Excitation, Energized, Emergency
F - Forward, Field, Fast, Fault, Flow
G - Generator, Ground, Gas Application of Device
H - High, Hour, Heater
I - Intermediate
K - Kilo
L - Low, Lower, Limit, Level, Local, Latch, Indicating Light
M - Main, Manual, Maturing, Starter Coil
N - Normally, Neutral, Neutron, in Residual Current Circuit
O - Open, Operated
P - Potential, Pressure
Q - Oil Application of Device
R - Reverse, Raise, Remote, Relay, Reserve
S - Slow, Switch, Solenoid
T - Transformer, Trip, Test, Time, Temperature
U - Up, Upper, Unit
V - Voltage, Volts, Vibration
W - Watts, Water Application of Device
X -
Y - Auxiliary Relays
Z -
10. **DEVICE LETTER (MULTIPLE) & WORD ASSOCIATION**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>Alarm</td>
</tr>
<tr>
<td>AS</td>
<td>Ammeter Switch</td>
</tr>
<tr>
<td>BPD</td>
<td>Bushing Potential Device</td>
</tr>
<tr>
<td>BT</td>
<td>Bus Tie</td>
</tr>
<tr>
<td>CCPD</td>
<td>Coupling Capacitor Potential Device</td>
</tr>
<tr>
<td>CC</td>
<td>Closing Coil</td>
</tr>
<tr>
<td>CS</td>
<td>Control Switch</td>
</tr>
<tr>
<td>CT</td>
<td>Current Transformer</td>
</tr>
<tr>
<td>DE</td>
<td>De-Energized</td>
</tr>
<tr>
<td>DG</td>
<td>Diesel Generator</td>
</tr>
<tr>
<td>FB</td>
<td>Fault Bus</td>
</tr>
<tr>
<td>FF</td>
<td>Fast Forward</td>
</tr>
<tr>
<td>FR</td>
<td>Fast Reverse</td>
</tr>
<tr>
<td>FS</td>
<td>Flow Switch</td>
</tr>
<tr>
<td>LS</td>
<td>Limit (or level) Switch</td>
</tr>
<tr>
<td>OP</td>
<td>Operate Coil (*)</td>
</tr>
<tr>
<td>PB</td>
<td>Pushbutton</td>
</tr>
<tr>
<td>PS</td>
<td>Pressure (or vacuum) Switch</td>
</tr>
<tr>
<td>PT</td>
<td>Potential Transformer</td>
</tr>
<tr>
<td>RE</td>
<td>Reset Coil (*)</td>
</tr>
<tr>
<td>SS</td>
<td>Synchronizing Switch</td>
</tr>
<tr>
<td>ST</td>
<td>Shunt Trip Attachment</td>
</tr>
<tr>
<td>SV</td>
<td>Solenoid Valve (**)</td>
</tr>
<tr>
<td>TB</td>
<td>Terminal Block</td>
</tr>
<tr>
<td>TC</td>
<td>Trip Coil</td>
</tr>
<tr>
<td>TS</td>
<td>Test Switch</td>
</tr>
<tr>
<td>VS</td>
<td>Voltmeter Switch</td>
</tr>
<tr>
<td>WRS</td>
<td>Watt-Voltmeter Switch</td>
</tr>
</tbody>
</table>

* Indicates application to an electrically reaet latching relay.

** Indicates application to controlling another item (damper, valve, etc.), device number "205" would be used for a solenoid valve controlling a liquid or gas process.

11. **ADDITIONAL COMBINATIONS**

11.1 Combinations of the letters may also be used to separately identify similar equipment function, for instance the following:

- AT - Auxiliary Transformer
- MT - Main Transformer
- RAT - Reserve Aux. Transformer
- SAT - System Aux. Transformer
- UAT - Unit Aux. Transformer
- ACT - Auxiliary Current Transformer
- APT - Auxiliary Potential Transformer
- CS - Control Switch (in Main Control Room)
- RCS - Remote Control Switch (at aux. panel remote from Main Control Room)
- LCS - Local Control Switch (at control station or cabinet near the controlled equipment)
DEVELOPMENT NUMBERS AND LETTERS
AS USED ON SARGENT & LUNDY'S ELECTRICAL DRAWINGS

11. ADDITIONAL COMBINATIONS (Cont'd.)
11.2 Control is always by Control Switch (CS) or Pushbutton (PB) regardless of catalogue nomenclature. Interposing manual permissive devices can be "SS"-Synchronising Switch, "43"-Transfer Switch, "69"-Cut-off Switch, etc. Instrument Switches "AS" & "VS" are used to select the proper phase for the instrument.

12. OPERATIONAL FEATURES
12.1 Further functional delineation of the graphic symbol, on schematics, is achieved by the addition of the "Operational Feature". This feature denotes type-of-function or a particular component within the equipment and is indicated by device letters adjacent to the symbol and below a line drawn under the device number.

12.2 For instance, indicates a control switch contact which is closed when the switch handle is turned to the "close" position indicated on the switch escutcheon or nameplate. The operational feature is used on schematics to furnish rapid comprehension of contact function.

12.3 Example 1:

```
device number

152-1

operational feature

345 kV

Bay 1

AC Circuit Breaker
```

12.4 In Example 1 above, the symbol is a normally open contact. The operational feature, lower case "a", indicates that this is an auxiliary contact (not for power service) which pilotes the position of the breaker power contacts. It is open when the breaker is open and closed when the breaker is closed.

12.5 Example 2:

```

152-1

operational feature

345 kV

Bay 1

AC Circuit Breaker
```

12.6 In Example 2 above, the symbol is a normally closed contact. The operational feature, lower case "b", indicates that this is an auxiliary contact whose closure is opposite to that of the breaker: closed when the breaker is open, open when the breaker is closed.

12.7 Lower case "sa" and "bb" have similar features except that they are used to indicate a more precisely calibrated contact in mechanism control.

12.8 See EC-110 for additional examples.
The report addresses methodological weaknesses in the PRA systems analysis used for studying post-earthquake relay chatter and for quantifying human response under high stress. An improved PRA methodology for relay-chatter analysis is developed, and its use is demonstrated through analysis of the Zion-1 and LaSalle-2 reactors as case studies. This demonstration analysis is intended to show that the methodology can be applied in actual cases. The analysis relies on SSMRP-based methodologies and data bases. For both Zion-1 and LaSalle-2, it is assumed that loss of offsite power (LOSP) occurs after a large earthquake and that there are no operator recovery actions. The report also presents an improved PRA methodology for quantifying operator error under high-stress conditions such as after a large earthquake. Single-operator error rates are developed, and a case study involving an 8-step procedure (establishing feed-and-bleed in a PWR after an earthquake-initiated accident) is used to demonstrate the methodology.