SEISMIC SAFETY MARGINS RESEARCH PROGRAM*

(PHASE I)

Project VII - Systems Analysis

Specification of Computational Approach

February 1979

Prepared by

Nuclear Services Corporation
Campbell, California

P.O.# 3074909

Ian B. Wall
Maharaj K. Kaul
Richard I. Post
Sam W. Tagart, Jr.
Thomas J. Vinson

MASTER

Prepared for

Nuclear Test Engineering Division
Mechanical Engineering Department
Lawrence Livermore Laboratory
Livermore, California

NRC

Program Manager
J. E. Richardson
Project Manager
M. A. Taylor/J. Burns

LLL

Program Leader
F. J. Tokarz
Program Manager
P. D. Smith
Project Manager
G. E. Cummings

*This report was prepared as an account of work sponsored by the U.S. Nuclear Regulatory Commission under the auspices of the U.S. Department of Energy, Contract No. W-7405-ENG-48.

LLL FOREWORD

The work reported in this document was performed under subcontract to the Lawrence Livermore Laboratory as part of the Seismic Safety Margins Research Program (SSMRP) sponsored by the U.S. Nuclear Regulatory Commission. Two subcontractors were asked to develop specifications for a computational approach to be used to help accomplish the objectives of the SSMRP. This document represents the specifications developed by one of the subcontractors. The work was performed in close coordination with LLL but represents the approach suggested by the subcontractor. What the actual computational approach will be has yet to be determined and information developed in this subcontract will be used to help determine that approach.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS RESTRICTED

eb

TABLE OF CONTENTS

	<u>PAGE</u>
1.0 SUMMARY AND CONCLUSIONS	1
2.0 BACKGROUND	2
3.0 REVIEW OF PREVIOUS SEISMIC RISK ASSESSMENT	7
3.1 FAST	7
3.2 PG&E Amendment 52	11
3.3 Acres Study	16
3.4 "Conditioned" vs. "Incremental" Seismic Risk	17
4.0 OVERALL APPROACH	19
4.1 Data Flow Diagram	19
4.2 Calculational Approach	19
5.0 DESCRIPTIONS OF THE CALCULATIONAL MODULES	24
5.1 Seismic Input	24
5.2 Soil-Structure Interaction	26
5.3 Transfer Functions	29
5.4 Operating and Induced Loads	33
5.5 Load Combination	34
5.6 Fragility Curves	36
5.7 System Model	37
6.0 STATISTICAL METHODS	48
6.1 Sampling Techniques	48
6.2 Weighting Methods	52
6.3 Rank and Uncertainty Band Methods	55
6.4 Sensitivity Studies	57
7.0 COMPUTATIONAL APPROACH AND RESOURCES	59
7.1 Computational Approach	59
7.2 Computational Resources	71
8.0 RECOMMENDATIONS	83
9.0 REFERENCES	85
APPENDIX A - DEFINITIONS	88
APPENDIX B - DETAILED DESCRIPTION OF CALCULATIONAL MODULES	93
APPENDIX C - FOURIER SPECTRUM AND TRANSFER FUNCTIONS	151

TABLE OF CONTENTS

FIGURES

	<u>PAGE</u>
2.1 ILLUSTRATION OF RANDOM AND MODELING UNCERTAINTY	5
3.1 EXAMPLES OF FRAGILITIES FROM FAST METHODOLOGY	9
3.2 CONDITIONAL FRAGILITY POINT GIVEN SEISMIC ACCELERATION OF 0.4g AND TRANSIENT LOADING FOR COMPONENT A	13
3.3 CONDITIONAL FRAGILITY POINT GIVEN SEISMIC ACCELERATION OF 0.4g PLUS TRANSIENT LOADING PLUS LOCA, FOR COMPONENT A	14
4.1 DATA FLOW DIAGRAM FOR SSMRP MODEL	20
4.2 OVERALL CALCULATION STRATEGY FOR SSMRP MODEL	22
5.1 SCHEMATIC FOR SEISMIC INPUT MODULE	25
5.2 SCHEMATIC FOR SSI MODULE	28
5.3 SCHEMATIC FOR TRANSFER FUNCTIONS	30
5.4 REPRESENTATION OF TRANSFER FUNCTION MODELING UNCERTAINTY	32
5.5 FAILURE PROBABILITY CALCULATION LOOP	35
5.6 TYPICAL FRAGILITY CURVE	37
5.7 SCHEMATIC FOR SYSTEM MODEL	39
5.8 HISTOGRAM OF PWR RADIOACTIVE RELEASE PROBABILITIES	45
7.1 STAGE I CALCULATION - PREPARE INPUT DATA SET	61
7.2 STAGE II CALCULATION (OPTION 1) - CALCULATE CONDITIONAL PROBABILITY OF COMPONENT FAILURE	62
7.3 STAGE III CALCULATION (OPTION 1) - CALCULATE PROBABILITY HISTOGRAM OF RELEASE WITH ITS UNCERTAINTY BANDS	63
7.4 STAGE II CALCULATION (OPTION 2) - CALCULATE CONDITIONAL LOADS ON COMPONENTS	69
7.5 STAGE III CALCULATION (OPTION 2) - CALCULATE PROBABILITY HISTOGRAM OF RELEASE WITH ITS UNCERTAINTY BANDS	70

TABLE OF CONTENTS

TABLES

	<u>PAGE</u>
3.1 METHODOLOGY COMPARISON: FAST-SSMRP	10
3.2 PG&E AMENDMENT 52 METHODOLOGIES	12
3.3 ACRES SEISMIC RISK STUDY	18

1.0 SUMMARY AND CONCLUSIONS

The work reported herein is an initial specification of a computation approach for a probabilistic risk assessment model for use in the Seismic Safety Margin Research Program. This model encompasses the whole seismic calculational chain from seismic input through soil-structure interaction, transfer functions to the probability of component failure, integration of these failures into a system model and thereby estimate the probability of a release of radioactive material to the environment. It is intended that the primary use of this model will be in sensitivity studies to assess the potential conservatism of different modeling elements in the chain and to provide guidance on priorities for research in seismic design of nuclear power plants.

This report describes such a model including suggested approximations for each element. A powerful approach to sensitivity studies based upon sophisticated sampling procedures is described. This approach allows sensitivity studies to be made at very modest cost. The required computational resources and programming effort are estimated. It is concluded, that while the computational approach described herein is feasible, a careful review of the proposed approximations would be prudent prior to proceeding with implementation. Some recommendations on further work are submitted.

2.0 BACKGROUND

Probabilistic risk assessment is concerned with placing technical issues into perspective and thereby providing guidance on the allocation of resources. For example, the Reactor Safety Study⁽¹⁾ concluded from its analysis of two reactors that the accidents which dominate public risk were not those initiated by large LOCAs but rather those initiated by transients and small LOCAs. Such types of information can be used to guide the development of regulatory criteria, the value of additional engineered safety features and the priorities for reactor safety research. The emphasis in probabilistic risk assessment is on an examination of a whole problem in a systematic way. The Seismic Safety Margin Research Program (SSMRP) is examining seismic design of nuclear power plants from this viewpoint.

Concerns have been expressed that current seismic design methodologies for nuclear power plants may be overly conservative.⁽²⁾ However, there is no consensus on the principal sources of such conservatism. In general, conservatism in design is roughly proportional to the degree of uncertainty in the assumed models. The main objective of SSMRP is to address this concern by identifying all sources of conservatism or uncertainty and by ranking their contribution in terms of a common yardstick. This objective requires the development of an overall model for the seismic calculational chain. The proposed yardstick is the probability of radioactive release since it is directly proportional to public risk. From this reasoning, the stated overall objective⁽³⁾ of SSMRP is to estimate the conservatisms in the Standard Review Plan seismic safety requirements and to develop improved requirements. In Phase I, mathematical models are to be developed that realistically predict the probability of radioactive releases from seismically induced events in nuclear plants. These models will be used for sensitivity studies which will assess the impact of modeling uncertainty in an individual model upon the uncertainty in the probability of release. Such sensitivity studies should provide rough guidance on the more fruitful subjects for research funds during Phase II in order to reduce overall uncertainty and hence conservatism.

The seismic calculational chain requires the modeling of many complex physical phenomena each of which involves several parameters. The predictions of such a calculation will have uncertainties reflecting uncertainties in the models and the parameters. In this report, we have distinguished between modeling and random uncertainties. These terms are defined in Appendix A.

A modeling uncertainty reflects the assumptions inherent in any model and is a measure of its imperfect representation of reality. For example, a three-dimensional non-linear model might be the most accurate representation of soil-structure interaction but, in practice, one- and two-dimensional models assuming linear or quasi-linear behavior are used. These latter models would have greater modeling uncertainty than the first. Modeling uncertainty can only be eliminated by benchmarking the "best" model by physical measurements. For complex phenomena, these experiments hardly ever bracket the total range of potential conditions so a model is always being required to extrapolate and some modeling uncertainty will always be present. It must be recognized that the use of modeling uncertainties has certain limitations in that although they may reflect the best information currently available, they still may not be close to the "true" state of nature. For example, a recent Venus probe found that the argon concentration in the planet's atmosphere far exceeded any previous estimates. Such surprises cannot be incorporated into modeling uncertainty.

A random uncertainty is usually associated with a physical parameter or the timing of a future event. For example, soil properties (e.g., shear modulus) vary from point to point and the occurrence of an earthquake of specified magnitude within the plant life is uncertain. If one views probability as an encoding of one's state of knowledge, this distinction between modeling and random uncertainty becomes somewhat arbitrary. For example, one could envisage a future seismological model which would predict the magnitude and timing of earthquakes. The more pragmatic distinction is that near-term research would reduce modeling uncertainties, but long-term research would be required to reduce random ones at possibly exorbitant cost.

Modeling uncertainties can be expressed in several ways. Let us consider a fragility curve as an example. The central estimate of an idealized fragility curve might be a cumulative distribution function on applied load as shown by the solid line in Figure 2.1. As the applied load is increased, the probability of the component's failure increases to unity. This failure probability is viewed as a random uncertainty since, for any specific load, it reflects the fraction of a large number of like components which fail when all are subjected to that load. Since experimental data are limited, one's estimate of that fraction is uncertain so upper and lower bounds can be estimated as suggested by the dotted lines in Figure 2.1. Conceptually, one can view these bounds either as uncertainty in the failure probability at a given load or as uncertainty in the load which would cause a certain fraction (e.g., 50%) of the components to fail. Estimates of fragility curves and their uncertainty bands are often the result of engineering judgement by a group of experts and are sometimes supported by only limited data. In reaching their judgement, these engineers may find it easier to view the modeling uncertainty in terms of load as suggested by the horizontal line in Figure 2.1a. For the calculational approach proposed in this report, modeling uncertainty is always applied to the probability as suggested by the vertical line in Figure 2.1b. The two statements of uncertainty should be equivalent.

An overall systems model, as proposed in this report, requires the integration of many disciplines including seismology, geotechnical, structural, and mechanical engineering, systems and statistics. Seismic analysis has customarily been focused on the calculations of stresses in a component. The probabilistic model requires that normal engineering safety factors be translated into failure probabilities and that interaction of these components then be integrated into a system model. This integration has proved a major challenge. Recognizing that this report is likely to be read by many specialists who may have equal difficulty with other disciplines, we have endeavored to facilitate communication by describing each element for the non-specialist.

a. MODELING UNCERTAINTY ON LOAD

b. MODELING UNCERTAINTY ON PROBABILITY

FIGURE 2.1 ILLUSTRATION OF RANDOM AND MODELING UNCERTAINTY

Finally, we view this work as a first iteration of a large complex problem. There is room for large improvements which should come from review by the technical community and the seasoning of time. We would welcome constructive comments from any party.

3.0 REVIEW OF PREVIOUS SEISMIC RISK ASSESSMENT

There have been three previous risk assessment methodologies which have been reviewed as part of the NSC work plan; namely FAST, (4, 5) PG&E Amendment 52 for Diablo Canyon, (6) and Acres. (7) The highlights of these three approaches are discussed in this section along with key assumptions and limitations as they relate to the SSMRP program. The Reactor Safety Study simplified seismic risk model was a starting point for both the PG&E Amendment 52 study and the Acres study. There are numerous other related studies and methodologies which also appear in the open literature such as references 8 and 9; however, these three were considered representative of previous work toward a solution to the SSMRP type problem.

3.1 FAST

The FAST computer program has been in various stages of development since 1968. Its main purpose has been to analyze the failure of systems and components of strategic defensive weapons systems against nuclear weapons blast effects. The similarity between the FAST problem and the SSMRP problem is evident in that both problems involve destructive type wave energy propagation through the earth, transfer of this earth wave motion into dynamic response for structures and components, evaluation of structural and component failure, and prediction of system performance. Each of these methodologies also involve uncertainty at various stages and the objective of FAST as well as the proposed SSMRP risk model is to propagate the numerous input uncertainties to output uncertainty on system performance. FAST has numerous features which account for physical phenomena of weapons effects which are of no direct interest to the SSMRP program such as air blast waves, debris effects as well as the ability to adapt the methodology to radiation or thermal environments in addition to mechanical effects. FAST has been designed to encode two types of uncertainty, random and systematic, and the SSMRP program has been similarly structured to keep track of two types of uncertainty. It is important to note, however, that the reasons for defining and

separating random and systematic uncertainty features of FAST are not identical with the reasons for providing two types of uncertainty in the SSMRP methodology. In FAST methodology, the reasons apparently stem mainly from a desire to separate uncertainties which involve one facility from those which involve a population of facilities. In SSMRP methodology, the reasons involve a desire to separate modeling uncertainties for any single facility which could be reduced with future seismic research, from random uncertainty which could not be reduced through seismic research. The definition of these uncertainty terms used in FAST documentation (references 4, 5, and 10) is vague and the following words are quoted directly from reference 4.

"Two categories of variations are recognized by the FAST code, namely random and systematic variations. The fundamental difference between them is that a systematic variation represents potential errors of a system model and extends uniformly over a population of facilities; whereas random variations extend non-uniformly from one facility to another. Random variations tend to average out over a large population, whereas systematic variations do not. It is noted that systematic variations may usually be reduced by test or analysis programs which improve models of the methodology and system behavior. The effects of random variations may also be reduced under some conditions."

The difficulty with the FAST definitions is that they are discussed in terms of how they differ from each other without defining them individually. The last sentence of the quoted definition even raises some doubt as to how the two FAST terms differ. For these reasons the terms random and modeling uncertainty are defined in Appendix A and used for the proposed SSMRP model.

The FAST treatment of random and systematic uncertainty is illustrated through examining fragility curves. Figure 2.3 of reference 5 is reproduced here as Figure 3.1 to show the intent. It is seen that random variation

A. FRAGILITY WITH NEITHER
RANDOM NOR SYSTEMATIC VARIATION

B. FRAGILITY WITH RANDOM VARIATION
BUT NO SYSTEMATIC VARIATION

C. FRAGILITY WITH BOTH RANDOM
AND SYSTEMATIC VARIATION

D. FRAGILITY COMPOSED OF
LINEAR SEGMENTS
(UP TO 5 SEGMENTS PERMITTED)

FIGURE 3.1 EXAMPLES OF FRAGILITIES FROM FAST METHODOLOGY

involves a single solid line fragility curve of Figure 3.1 B., C., and D expressed as a cumulative distribution function (cdf) which represents the "best estimate" of component failure probability as a function of component response. The dotted curves of Figure 3.1 C., and D illustrate systematic uncertainty and are alternate cumulative distribution functions representing different model assumptions for the random uncertainty. The FAST methodology provides for probabilistic weighting of the alternate cdfs by assigning another probability function (Beta) parallel to the component response axis. While valid mathematically, this procedure is not necessarily well suited for the SSMRP methodology because it requires a detailed probability fit where little or no user information will be available to perform that fit. Further, the best estimate and bounding curves are assumed to be parallel which may not be realistic. FAST introduces systematic and random uncertainties for three of the four methodologies involved in the weapon system performance prediction, 1) environments, 2) transfer functions, and 3) fragilities. The fourth methodology is the system model and is assumed to be a deterministic processor to relate component failures to system or subsystem failures.

The original version of FAST involved a Monte Carlo scheme wherein the systematic uncertainty was computed in an outer loop and random variation was computed in an inner loop. There were statistical stopping procedures built in to determine convergence of the Monte Carlo processes. In this way the two types of uncertainty could be displayed as an output which in turn became inputs for various weapon systems decisions.

The following table summarizes the mathematical methodologies of FAST and the required methodologies for SSMRP.

<u>FAST</u>	<u>SSMRP</u>
1. Blast Environment	1. Seismic Input
2. Transfer Functions	2. Soil Structure Interaction
3. Fragility Curves	3. Transfer Functions
4. System Model	4. Load Combinations
	5. Fragility Curves
	6. System Model

Table 3.1 Methodology Comparison; FAST-SSMRP

As shown in Table 3.1, four of the six methodologies are roughly similar to those in FAST; however, both the computation algorithms and the detailed structure for handling the weapons methodology of FAST are sufficiently different from those needed for the SSMRP program that NSC recommends the development of an independent program.

3.2 PG&E Diablo Canyon Amendment 52

The PG&E Amendment 52 was a computational effort to provide a conservative estimate of seismic risk for the Diablo Canyon Units 1 and 2. Its purpose was to demonstrate that the combined effects of the new Hosgri Fault information together with plant modifications would not produce an undue public risk. Several existing computer programs were used together with hand calculations to assemble the seismic risk results and conclusions. All of the basic methodologies of interest to the SSMRP program were addressed, and Table 3.2 illustrates a few summary comments on the level of treatment in each methodology.

The approach taken in PG&E Amendment 52 to evaluate seismic risk was to condition the fault trees at the different seismic levels so that dependencies or common cause seismic effects would be properly evaluated. This approach was executed by plotting each fragility curve as a function of the effective peak acceleration level.

The fragility curves were established from three sources. 1) Estimates based on discussions with system engineers, 2) data resulting from analysis, and 3) other failure data.

Fragility curves developed as a function of effective peak acceleration are conditional and dependent on a particular load combination (seismic plus operating plus seismic dependent transients). A problem arises when the question comes up as to what the probability of failure for a particular component will be when a LOCA event is present with the seismic loading as compared with the case where only a transient event occurs with the seismic event.

SSMRP Terminology

Amendment 52 Approach

Seismic Input

Utilizes probabilistic effective ground acceleration for site without modeling uncertainty

Soil Structure Interaction

Utilizes results from conservative design calculations (no random or modeling uncertainty)

Transfer Functions

Utilizes results from conservative design calculations plus implifying assumptions (no random or modeling uncertainty)

Load Combinations

Utilizes conditional seismic event with initiating events involving transients, LOCA and reactor vessel rupture following the procedure of the Reactor Safety Study (no random or modeling uncertainty)

Fragilities

Assigned random uncertainties conservatively based on tests and design calculations (no modeling uncertainty)

System Model

Utilizes system model development from Reactor Safety Study

Table 3.2. PG&E Amendment 52 Methodologies

To be more specific, suppose we ask the system engineer to estimate the component A fragility (point O of Figure 3.2) at an effective acceleration level of 0.4g.

Figure 3.2. Conditional Fragility Point Given Seismic Acceleration of 0.4g and Transient Loading for Component A

Let his estimate be P_{f1} for that condition. Now suppose we ask him to estimate the component A fragility point at the same acceleration level of 0.4g, but now assume that a LOCA event occurs in addition to the seismic event and transient events. Suppose also that component A receives a large additional loading as a result of the LOCA event so that the combined loading is significantly higher than in Figure 3.2. This second case is illustrated in Figure 3.3 as point n.

Figure 3.3. Conditional Fragility Point Given Seismic Acceleration of 0.4g plus Transient Loading plus LOCA, for Component A

It is expected that the point P_{f2} will be a higher probability of failure than P_{f1} . It is also expected that the conditional event probabilities associated with Figures 3.2 and 3.3 are different and that therefore a different fragility curve should be used for the two different conditions. However, in the PG&E Amendment 52 study, only one set of fragility curves were discussed while event trees and fault trees were developed for both types of conditions represented in Figures 3.2 and 3.3. This means that the PG&E Amendment 52 treatment of the load combination problem may have introduced technical inconsistencies with the fault tree analysis. The situation could be accounted for by developing different conditional fragility curves for the different load combination curve. However, even if multiple fragility curves were developed, there is another problem in the integration of the load combination methodology with the systems methodology which is evident in the Amendment 52 study. By conditioning all fault tree events on the seismic event, the Amendment 52 study apparently avoids having to deal with the release risk associated with nonseismic conditions. Section 3.4 of this report briefly discusses this other problem.

While all areas of interest to SSMRP have been addressed to some degree, emphasis has been on presenting a conservative risk evaluation and showing various comparisons of risk with and without certain plant modifications. An unsuccessful attempt was made to determine whether the seismic-caused accidents would be as significant as all other possible causes. Consequently, this effort was inconclusive because of the differences in methods and data upon which comparisons were based.

Several observations concerning the PG&E Amendment 52 effort appear pertinent:

1. It did not attempt to present a realistic seismic risk but a conservative evaluation
2. It did not address modeling type uncertainties of interest to the SSMRP program
3. Its treatment of load combinations following the Reactor Safety Study approach produces a risk result which may include more or less than the incremental seismic loading risk. Any nonconservative aspects of this assumption are probably more than offset by the other conservative assumptions made. (see Section 3.4 of this report for a further explanation of this point.)
4. The PG&E Amendment 52 study addressed methodologies considerably beyond the scope of the SSMRP program such as radiation dose and health effects, human population distribution and actions, and risk benefit considerations.

Because PG&E Amendment 52 attempted to cover so many difficult methodologies, the seismic risk results cannot be considered more than a conservative estimate. The results are not particularly useful in showing the relative importance of various methodologies of interest to the SSMRP program.

3.3 Acres Study

Acres is a consulting firm which performed a seismic risk analysis of a generic type Canadian reactor site.⁽⁷⁾ The Acres study began with the simplified type seismic analysis performed in the Reactor Safety Study⁽¹⁾ and had an objective of determining whether Canadian type reactors had a similar type seismic risk. In addition, the Acres study performed sensitivity studies to determine which of the seismic methodologies would have the greatest influence on the seismic risk.

The Acres study was performed on a very simplified system consisting of three typical components in parallel (the report said series, but the analysis indicated parallel). The three components were: 1) a main steam line, 2) an emergency core cooling system, and 3) a containment structure. These "components" were assigned basic fragility curves where failure was assumed to have a 10% probability if the design acceleration was reached, and a 90% failure probability if 4 times the yield stress was reached under seismic loading. Then, using a model for seismic input developed in reference 11, the component and system failure probabilities were studied under various conditions. No firm conclusions were reached on comparative seismic risk values with the range 10^{-6} to 10^{-8} per year of reference 1, however, qualitatively it was suggested that a range of 10^{-5} to 10^{-6} per year was an achievable safety level.

Examples were given to illustrate why treatment of common cause failure was important in seismic risk analysis. The major insights available in the study are associated with the various sensitivity studies performed. It should be noted that the entire analysis is done with manual type calculations, and some interesting sensitivity conclusions were drawn. For example, the sensitivity studies showed that accurately defining the probability of large magnitude earthquakes and accurately defining the fragility curves were the two most sensitive items of input.

As a specific design example, it was shown that system failure as a function of maximum possible ground accelerations of 0.5g and 2.0g are predicted to be 3.1×10^{-6} and 1.3×10^{-4} per year respectively.

Due to the great number of simplifying assumptions required to reduce the analysis to a tractable form for hand calculation, it is unlikely that the sensitivity conclusions would be unchanged by different system models or different fragility assignments.

To summarize, the Acres study addresses in elementary form the following methodologies of interest in SSMRP shown in Table 3.3.

3.4 "Conditioned" versus "Incremental" Seismic Risk

The load combination aspect of seismic risk introduced an apparent inconsistency as discussed in Section 3.2. This inconsistency raises a question of how the seismic related risk should be separated from that risk due to other loads or load combinations.

Both the PG&E and Acres studies compute seismic risk by first calculating the probability of system failure conditional upon the seismic event and then multiplying by the seismic probability. For convenience, we denote this approach as estimating the "conditioned" seismic risk. Within this calculation, the conditional loading on a component includes operating loads plus direct seismic loads plus any induced loads from seismically-initiated transients or seismically-initiation LOCAs. Alternatively, the "incremental" seismic risk could also be calculated. This risk would be the difference between the total risk from all loadings (i.e., seismic plus non-seismic) minus the non-seismic risk, the loading on a component would include operating loads plus any induced loads from the non-seismic transients or LOCAs. In this latter calculation it would be assumed that there is zero probability of any seismic loading.

It can be shown that the two seismic risks discussed (i.e., "conditioned" and "incremental") will not in general be equal because of the nature of the load combination problem. In addition, if the "conditioned" or "incremental" risks are computed to each of the contributing load combination effects, the

summed risk with either approach will generally not be equal to the total loading risk. This is because some loadings may contribute to different risk increments more than one time. This difficulty can be solved through the use of some type of normalizing scheme with either the "conditioned" or the "incremental" risk if desired. The main point of this discussion is that different quantities can be defined as the seismic risk as a result of the load combination problem. In this report, the unnormalized "conditioned" seismic risk is calculated as will be discussed further in Section 5.7.1.

<u>SSMRP Terminology</u>	<u>Acres Approach</u>
Seismic Input	Uses probabilistic ground acceleration for site with some consideration of modeling uncertainty
Soil Structure Interaction	Avoids specific analysis
Transfer Functions	Uses response spectrum analysis with some consideration of modeling uncertainty
Load Combinations	Not treated
Fragilities	Assigns random uncertainties using judgment relative to code allowable stresses. Provides for modeling uncertainty
System Model	Uses very simple 3-component system

Table 3.3. Acres Seismic Risk Study

4.0 OVERALL APPROACH

4.1 Data Flow Diagram

The principal elements of the proposed SSMRP risk assessment model are shown in Figure 4.1. The calculation starts with seismic input and flows from left to right to the system model. The probabilities of initiating events are calculated before failure probabilities for engineered safety features (ESFs) since the latter are conditional upon the former. The boxes in Figure 4.1 are reasonably self-explanatory and consistent with the terminology in the SSMRP Program Plan⁽³⁾ with the exception of "induced loads." These loads are additional loads imposed upon a structure or component as the result of the failure of another component or of transients. The six major calculational modules-- seismic input, soil-structure interaction, transfer functions, load combinations, fragility curves, system model--are described in detail in Section 5.0. The output of the model is a probability histogram for release magnitude which is discussed in Section 5.7 and illustrated in Figure 5.7. This probability histogram is intended to be used as a yardstick for sensitivity studies. The underlying approach to these sensitivity studies is described in Section 6.4.

4.2 Calculational Approach

In establishing an overall calculational approach, our objective is to specify a computer program which is user-oriented for sensitivity studies. We wanted a program with the following characteristics:

- a) Sensitivity studies should be economic so that the user may readily explore the interactions of different modules;
- b) Different models for selected modules (e.g., transfer function) may be individually evaluated without redoing the whole calculation.
- c) A minimum of constraints should exist in the representation of modeling uncertainty (e.g., asymmetry, nonparametric distributions).

- * INCLUDES CONTAINMENT
- ** FUNCTION OF INITIATING EVENTS

FIGURE 4.1 DATA FLOW DIAGRAM FOR SSMP MODEL

These goals require a fast and flexible program for the sensitivity studies which could incorporate the output of more sophisticated models.

The calculational chain from seismic input to probability histogram of release involves many complex phenomena which are customarily modeled by several large time-consuming computer programs. In order to achieve the above goals, we envisage that these computer programs would be Auxiliary Programs which would provide input data to a Master Probabilistic System (MPS) program. The MPS program would incorporate approximations to the more complex models and would encode their modeling uncertainties in a simple way and thereby achieve a feasible running time.

A three stage calculation is envisaged as illustrated in Figure 4.2. In Stage I of the calculation, the Auxiliary Programs would be used to calculate an input data set for the MPS program to be run in Stages II and III. For example, a seismological model would be used to calculate the potential free field seismic motions at the Zion site. For the purpose of the MPS program, these free field seismic motions would be characterized by a set of Fourier amplitude spectra. The recommended Auxiliary Programs and the proposed encoding of their results for the MPS program are described in Section 5.0 for each major module. The calculations are summarized in Section 7.1.1.1.

In Stage II, these input data are utilized in a set of parametric calculations in which the conditional probabilities of initiating events and structure/component failure are computed as a function of the selected values of the major models spanning the potential range of their modeling uncertainty. The Stage II calculation would represent a major investment in computation, but, if the parametric values are carefully chosen, should not have to be revised very frequently.

In Stage III, the parametric values calculated in Stage II are weighted according to the assigned modeling uncertainties in order to calculate the probability histogram of release with its uncertainty

STAGE

I

PREPARE INPUT
DATA SET

USE OF AUXILIARY PROGRAMS TO
GENERATE INPUT DATA FOR MASTER
PROBABILISTIC SYSTEM

II

CALCULATE PROBABILITIES OF
INITIATING EVENTS AND
STRUCTURES/COMPONENTS
FAILURE CONDITIONAL UPON
SEISMIC EVENT

SET OF PARAMETRIC STUDIES AS
A FUNCTION OF INPUT PARAMETERS
HAVING MAJOR MODELING
UNCERTAINTIES

III

CALCULATE PROBABILITY
HISTOGRAM OF RELEASE
AND MODELING
UNCERTAINTY BAND

COMPARE

PERFORM
SENSITIVITY
STUDIES

ASSIGN PROBABILITIES/WEIGHTING
TO MODELING UNCERTAINTIES

FIGURE 4.2 OVERALL CALCULATION STRATEGY FOR SSMRP MODEL

()
bands. Sensitivity studies would be performed by repeating this calculation with different weighting factors. The Stage III calculation would be relatively inexpensive thereby permitting numerous sensitivity studies.

The demarcation between the Stage II and III calculations is a trade-off between the computational investment in Stage II and the cost of sensitivity studies. The demarcation shown in Figure 4.2 is effectively at the calculation of component failure probabilities. This choice should result in economic sensitivity studies but would slightly overestimate the overall uncertainty band and would not allow sensitivity studies on individual fragility curves. These limitations, which are discussed in more detail in Section 7.1.2, can be avoided by moving the demarcation back to the calculation of combined load on a component but at the cost of increasing the cost of sensitivity studies. These two calculational options are described in more detail in Section 7.1.

5.0 DESCRIPTIONS OF THE CALCULATIONAL MODULES

This section contains brief descriptions of the seven major calculational modules--seismic input, soil-structure interaction, transfer functions, operating and induced loads, load combinations, fragility curves, system model. The emphasis is upon the input data required for the Auxiliary Programs used in Stage I and the form of the data presumed available to the MPS program in Stages II and III. A more detailed discussion of each module is presented in Appendix B. The use of Fourier analysis is recommended for representing dynamic loads. It should be noted that the use of power spectral density analysis could be substituted with little modification to the overall algorithms.

5.1 Seismic Input

5.1.1 Objective

The objective of this module is to appropriately characterize the free-field seismic input and quantify it from a combination of historical data available for the Zion site and a knowledge of the local geology.

5.1.2 Discussion

This module integrates the different seismological data to determine the site ground motion intensity in a quantitative manner. The site ground motion intensity is defined by the quantity Z_f which measures the earthquake energy in all the three components of motion. Prior to determining Z_f , the site-specific Fourier amplitude spectra (FAS) in the three directions of motion are obtained in a probabilistic manner. These then lead to a definition of Z_f . The details of this procedure are given in Appendix B.1, however, Figure 5.1 provides a conceptual scheme of the module.

RANDOM UNCERTAINTY: m, r, Z_f

MODELING UNCERTAINTY: m, r, Z_f

FIGURE 5.1 SCHEMATIC FOR SEISMIC INPUT MODULE

5.1.3 Inputs

The inputs to the module are in the form of seismological relations, e.g., magnitude-exceedance relationship, attenuation laws, whose parameters are site dependent. These relations are probabilistic in nature and thus provide a source of random uncertainty. However, the variation in the parameters of these relations account for modeling uncertainties. In addition to these inputs, the module requires that the site-source geometry be described by a probabilistic statement on the epicentral distance and a set of earthquake records applicable to the site with estimates of the locations of their sources be provided. The PDF on the epicentral distance r is a source of both random and modeling uncertainties.

5.1.4 Outputs

The aforementioned inputs are processed by the seismic input calculation module to result in the probability description of the FAS of three ground motion components. From these a CCDF of the random variable Z_f is directly obtained.

Analyses are repeated for a new set of parameters that contribute to the modeling uncertainty in Z_f and as before a new CCDF for Z_f is obtained. All possible combinations of parameters are thus investigated to result in the extremes of CCDF's for Z_f which thus describe its modeling uncertainty bands. However, the FAS are retained only for the base case with the assumption that distortion in their shapes for the same probability of exceedance will be small.

5.2 Soil-Structure Interaction

5.2.1 Objective

The objective of the soil-structure interaction (SSI) module is to translate the free-field motion into base mat motion. For each magnitude

of free-field motion defined by the variable Z_f , the random variable(s) Z_b defining the six components of base-mat motion (3 rigid body translations and 3 rotations) will be generated. This variable(s) will then completely define the inputs to be used for building and component response analysis.

A schematic diagram illustrating the SSI module is shown in Figure 5.2.

5.2.2 Discussion

The discussion of the SSI module will be limited to two-dimensional analysis. Details for a three-dimensional analysis can be found in Appendix B.2.

The SSI analysis will be performed by using a two-dimensional model for each of the 5 to 10 levels of Z_f . For a given Z_f , the FAS for three components of motion will be transformed to free-field time histories (see Appendix B.2 for details). SSI analysis will then result in 5 components of base mat motion. The analysis will be repeated for the same value of Z_f by treating the soil properties as random variables. An ensemble of base mat motions thus obtained are then analyzed to yield probability statements on the FAS of the 5 components of motion. This leads to a CCDF of the random variable Z_b defined as the energy in a manner similar to Z_f .

The modeling uncertainty results from the three-dimensional and non-linear effects which are quantified by performing simplified comparative analyses to determine variation expected in Z_b .

The preceding procedure is then repeated for other values of Z_f . Thus, if 5 values of Z_f are considered, 5 sets of CCDF's for Z_b are obtained along with 5 sets of FAS, each set consisting of FAS's for 5 components of base mat motion.

RANDOM UNCERTAINTY: Z_f , soil data, (θ, v for 3-D)

MODELING UNCERTAINTY: Z_f, Z_b

FIGURE 5.2 SCHEMATIC FOR SSI MODULE

5.2.3 Inputs

The inputs to this module are the three FAS for each value of Z_f considered in the analysis. Other inputs include soil properties, soil layering, depth of structure foundation embedment which are treated as random variables.

The quantification of modeling uncertainties requires that the SSI module be exercised on two simplified and comparable models - one for two-dimensional analysis and one for three-dimensional analysis and possibly one for non-linear analysis. This also constitutes part of the input.

5.2.4 Outputs

The outputs are in the form of CCDF's of Z_b with their modeling uncertainty bands for each magnitude of Z_f . For each CCDF, exclusive of the uncertainty bands, FAS curves are obtained for the 5 components of base mat motion.

5.3 Transfer Functions

5.3.1 Objective

The objective of this module is to develop two sets of transfer functions: namely, those relating the building response to five (or six) components of base mat motions and secondly, those relating the component response to the building response. These transfer functions are described by frequency dependent functions which scale the Fourier amplitude spectra of the input motions to result in the Fourier amplitude spectra of the response. Figure 5.3 illustrates the calculation scheme.

5.3.2 Discussion

The transfer functions for structures or components (S/C) will be generated from a time history analysis of the S/C, in which the time

TRANSFER FUNCTIONS (≈ 50)
 + SCALE FACTORS FOR BUILDING RESPONSE QUANTITIES (≈ 200)

RANDOM UNCERTAINTIES:

None

MODELING UNCERTAINTIES:

Damping, nonlinearities, transfer functions

FIGURE 5.3 SCHEMATIC FOR TRANSFER FUNCTIONS

history of excitation is selected so as to encompass all frequencies of interest. The transfer function is then obtained by dividing the Fourier spectrum of the response by the Fourier spectrum of the input time history. The random uncertainties, resulting primarily from material properties, may be incorporated into the analysis in an approximate way by the procedure outlined in Appendix B.3.

The modeling uncertainties in the transfer functions are derived from non-linearities in the material behavior which results not only in frequency shifts in the response, but also in the amplitude attenuation due to hysteretic damping in the structure. It is proposed that the transfer function modeling uncertainties be quantified by two independent random variables K_w and K_a , the former of which accounts for frequency shifts and the latter for amplitude variation. The ranges of K_w and K_a will be determined from a comparison of the results from a simplified analyses on the linear and the non-linear models of a S/C. The use of K_w and K_a is illustrated in Figure 5.4 and is explained in Appendix B.3.

It should be pointed out here, that whereas, the building response is relatively easy to analyze, the component response evaluation may not be possible for the Zion plant because of the large effort and cost incurred in such an evaluation. It is proposed here that the component responses be obtained in an approximate way from the existing design calculations for the Zion plant and large modeling uncertainty be incorporated to account for the inaccuracy of results. This can be obtained from a refined analyses of a representative sample of components in the plant and subsequent comparison with the approximate analysis.

5.3.3 Inputs

The inputs required to determine transfer functions for the building response are essentially a wide band time history and a linear model of

FIGURE 5.4 REPRESENTATION OF TRANSFER
FUNCTION MODELING UNCERTAINTY

the building(s). Simplified linear and non-linear models are required to quantify modeling uncertainty.

For the analysis of components, the inputs required are essentially the existing design calculations when they can be properly reduced to a form whereby transfer functions may be obtained. Quantification of modeling uncertainty requires models similar to those for building but for only a small sample of components.

5.3.4 Output

The outputs from this module are transfer functions relating a building response quantity to each of the 5 (or 6) base mat motions. The transfer functions describe only the amplification (or attenuation) of the Fourier amplitude spectra of the base-mat motions and not the phase angle shifts.

Transfer functions relating component response to an appropriate building response quantity will also be developed.

5.4 Operating and Induced Loads

5.4.1 Objective

The purpose of this module is to develop operating, induced static and induced dynamic loads for structures or components (S/C). These loads are then combined with direct seismic loads to obtain the resultant response of S/C.

5.4.2 Discussion

The operating loads are essentially static loads even though some of these, such as steady state vibration, are dynamic in nature. For each S/C, the operating load will be defined as a random variable with an appropriate probability distribution.

The induced dynamic loads are those arising from LOCA and transients caused by a seismic event. These loads are generally available as deterministic time histories, however uncertainties do exist in these loads which may be quantified by a scale factor on the amplitudes of the time history and another one that shortens or stretches the time scale to account for frequency variation. Associated with the induced dynamic loads are static loads, e.g., containment pressurization, which also will have random characteristics and will thus be defined by probability distributions.

These loads will be supplied to the MPS externally for all structures and components or groups thereof that will be considered in the analysis. The loads will be completely defined by probability distributions and base time histories.

5.5 Load Combination

5.5.1 Objective

This section describes procedures for combining seismic and operating loads and, if appropriate, induced loads on structures and components (S/C). The load combination procedure proposed adds the loads in a Monte Carlo scheme to yield a probability distribution of the failure governing stress. The location of this module in the MPS calculation chain is identified in Figure 5.5.

5.5.2 Discussion

The load combination procedure should take into account the randomness associated with all the loads, i.e., their amplitudes and the randomness in their relative time phasing. The proposed method samples the probability distribution for each load and adds the sampled loads at every time step to result in a combined load time history. The peak value in this history then determines the failure governing "stress." The sampling process is repeated in a Monte Carlo loop whence the "stress"

FIGURE 5.5 FAILURE PROBABILITY CALCULATION LOOP
(See Section 7 for details)

probability distribution is obtained for comparison with fragility. The number of Monte Carlo trials to obtain convergence may be large depending upon the nature of the individual loads, and, since these Monte Carlo runs are repeated for each S/C and for all combinations of Z_f , Z_b and other variables, the cost of the analysis rapidly grows with the number of such trials. It is proposed therefore that a parametric distribution of peak load be assumed and a few Monte Carlo trials be made to estimate the distribution parameters.

5.5.3 Inputs and Outputs

The inputs required in this calculation module are the Fourier amplitude spectra of seismic loads generated within the program, the phase spectra supplied externally to MPS and the information on the operating and induced loads also supplied externally.

The loads are processed to finally yield a probability density function of the peak load consistent with the S/C fragility curve.

5.6 Fragility Curves

Fragility curves are cumulative distribution functions which plot component or structure failure probability as a function of some convenient random variable. The random variables used in the proposed SSMRP model are expected to be somewhat different for the 50 to 150 different classes of components anticipated, however they will all have these features in common. The random variables will represent the combined maximum or minimum summed primary type response on the component regardless of the source, such as operating, seismic, or induced loads. The addition or subtraction of individual co-linear responses to obtain combined response, will be assumed to be a valid procedure consistent with a linear theory of the phase 1 SSMRP effort. Since many fragility curves associated with dynamic phenomena are highly non-linear, this will introduce large modeling uncertainty into the methodology. The quantification of this modeling uncertainty for specific classes of fragility curves should be evaluated through selected non-linear deterministic analysis in the absence of test data.

A typical fragility curve is illustrated in Figure 5.6. The solid line is the central estimate and the outer dashed lines represent the uncertainty bands. Within the MPS program, the modeling uncertainty on fragility curves will be represented by a set of 3 to 5 curves including the central estimate. These curves will be assigned different weightings to reflect alternate assumptions in the modeling uncertainty. Appendix B contains a more detailed discussion of fragility curves including an example of a piping component fragility.

Figure 5.6. Typical Fragility Curve

5.7 System Model

5.7.1 Objective of Module

The objective of the system model is to appropriately combine the probabilities of component and structural failures, human errors and

test/maintenance outages in order to determine the probabilities of an initiating event followed by system failure and hence a large release of radioactive material to the atmosphere and/or geosphere. System failure is defined by a sequence of events whose joint occurrence would lead to core melting.

The inputs and outputs for the system model are summarized in Figure 5.7. The calculation may be summarized by considering a typical accident sequence, AB- δ . Event A represents some initiating event. Event B represents the unavailability of some engineered safety feature and event δ represents a containment failure mode. The probability of a radioactive release via this accident sequence due to a seismic event is given by:

$$P(E) P(A|E) P(B|E, A) P(\delta|E, A, B)$$

where $P(E)$ is probability of the seismic event. The objective of the system model is to estimate the conditional probabilities $P(A|E)$, $P(B|E, A)$ and $P(\delta|E, A, B)$.

5.7.2 Input Parameters

The following input parameters would be generated in Stage I externally from the MPS program: magnitude of radioactive releases, descriptions of accident sequences including initiating events and subsystems, and seismically-independent failure rates (defined in Appendix A). The component failure probability would be calculated within Stage II or III of the MPS program.

As described in Appendix B.7, of the nine Release Categories used by the Reactor Safety Study, only the three largest ones, PWR-1, PWR-2 and PWR-3, need be considered in the SSMRP model. Hence, only the accident sequences assigned to one of these Release Categories will need

RANDOM UNCERTAINTIES: STRUCTURE/COMPONENT FAILURE PROBABILITIES,
SEISMICALLY-INDEPENDENT FAILURE RATES

MODELING UNCERTAINTIES: STRUCTURE/COMPONENT FAILURE PROBABILITIES,
SEISMICALLY-INDEPENDENT FAILURE RATES, EVENT/
FAULT TREE REPRESENTATION

FIGURE 5.7 SCHEMATIC FOR SYSTEM MODEL

to be analyzed. The magnitude, composition, and timing of radioactive releases would be calculated independently of the MPS program.

The potential accident sequences would be generated by event trees which would be prepared in Stage I of the calculation external from the MPS program. The system model within the MPS model would basically be an encoding of each accident sequence in terms of its Release Category, initiating event, engineered safety features (ESFs) involved and containment failure mode. An example is shown in Appendix 8.7. In order to correctly calculate the occurrence probability of each Release Category, the assigned accident sequences need to be added with the correct Boolean logic. Thus, the system model will consist of three arithmetic expressions involving the conditional probabilities of initiating events, failure of ESFs and containment failure mode. With small and conservative numerical error, many higher order terms can probably be omitted. For the Surry reactor, the RSS identified 5 initiating events, 11 major ESFs and 5 containment failure modes. Comparable numbers of items can be expected for the Zion plant.

It is envisaged that initiating events at the Zion reactor will be subdivided into 5 to 10 categories. For convenience, this discussion will be oriented around the 5 categories used by the RSS for the Surry reactor. It is assumed that only earthquakes of sufficient magnitude to cause at least a transient will be of interest in SSMRP. Thus, in the event of an earthquake, one of the following initiating events is assumed to occur.

<u>Symbol</u>	<u>Event</u>
T	Transient requiring successful cooldown of primary system
S ₂	Small-small LOCA (1/2 to 2" dia reactor coolant system (RCS) piping)

- S_1 Small LOCA (2 to 6" dia RCS piping)
- A Large LOCA (>6" dia RCS piping)
- R Reactor pressure vessel (RPV) rupture or collapse of
 its support

The conditional probability of each event given an earthquake will be denoted by $P(T|E)$, etc. It should be noted that the definition of event R is slightly different from that in RSS. Collapse of the RPV support is assumed to sever all RCS piping which would be equivalent to a RPV rupture. The above initiating events are assumed to be mutually exclusive and their combined conditional probability is unity. In other words, one but not more than one event is assumed to occur in the event of an earthquake.

For Phase I of the SSMRP, a relatively simple model for calculating the probabilities of initiating events is recommended. Its potential deficiencies are discussed in Appendix B.7. It has the following steps:

1. Review each of the primary coolant loops to identify the piping segments between supports (Stage I).
2. Considering a potential severance in each segment, identify all possible combinations of segments whose severance would result in break areas equivalent to events S_2 , S_1 and A defined above. For example, event S_1 could result from the severance of one 5"-dia segment, three 2"-dia segments or five 1"-dia segments. Conceptually, one prepares a fault tree for events S_2 , S_1 and A (Stage I).

3. Within the MPS program, for each seismic input, compare the combined operating and seismic loads on each segment to its fragility curve in order to estimate its conditional failure probability. The probabilities of all possible combinations are summed to determine $P^*(A|E)$, $P^*(S_1|E)$ and $P^*(S_2|E)$.

4. The calculated values of $P^*(A|E)$, $P^*(S_1|E)$ and $P^*(S_2|E)$ are normalized as follows:

$$P(A|E) = P^*(A|E) [1 - P(R|E)]$$

$$P(S_1|E) = P^*(S_1|E) [1 - P(R|E)] [1 - P(A|E)]$$

$$P(S_2|E) = P^*(S_2|E) [1 - P(R|E)] [1 - P(A|E)] [1 - P(S_1|E)]$$

$$P(T|E) = 1 - [P(R|E) + P(A|E) + P(S_1|E) + P(S_2|E)]$$

It is envisaged that the unavailability of the engineered safety features (ESFs) at Zion will be analyzed with fault trees or an equivalent method. These analyses will determine the minimal cut sets which will identify those components or events whose joint occurrence would result in the failure of the ESF to operate. If a particular ESF is associated with more than one initiating event, then separate fault trees and minimal cut sets may be needed for each such initiating event. It is also envisaged that, for each initiating event, a spectrum of induced loads will be precalculated in Stage I for each component involved in the ESFs. It is intended that these induced loads span the potential range both with respect to amplitude and phase angle with the direct seismic load. These sets of induced loads would be treated as a random variable and would be combined with the random operating load and the direct seismic loads as described in Section 5.5. The probabilities of components failing would generally be a function of the seismic input. The unavailability of an ESF will also be a function of other events whose probability is independent of the seismic event. Their failure rates would be input data and are discussed below.

It is necessary to calculate the probability of each ESF failing to operate conditional upon the initiating event and upon the seismic input. Again a relatively simple model is recommended for Phase I of SSMRP; its potential deficiencies are discussed in Appendix B.7. The steps in the calculation for each seismic input are as follows.

1. As part of input data, each component is identified by (a) its location in the plant which determines the magnitude and character of the seismic load and (b) the initiating events for which it is supposed to operate (Stage I).
2. For each initiating event, the conditional probability of each associated component failing is calculated by comparing the combined operating, seismic and induced loads to its fragility curve. The random variation in operating and induced loads are incorporated in this calculation as described in Sections 5.4 and 5.5.
3. For each initiating event, the conditional probability of each associated ESF failing to operate is calculated by combining the component failure probabilities in the appropriate Boolean expression. Some ESFs may appear for more than one initiating event.

As noted above, the fault trees for the ESFs will include some events whose probabilities are independent of the seismic input. Examples of such events include prior operator error (e.g., a manual valve not re-opened after an earlier surveillance test) and test/maintenance outages for a component or subsystem. The probabilities of these events would presumably be taken from the Reactor Safety Study or an equivalent source. They have significant modeling uncertainties which should be incorporated into the overall modeling uncertainty for the SSMRP model. It is judged that there will be 10 to 100 seismically-independent failure rates appearing in the models for ESFs.

The final input parameter to the system model is the component failure probabilities which are calculated within the MPS program (Stage II or III). The number of components whose failure probabilities significantly contribute to the system model is somewhat speculative until some event/fault trees are prepared for Zion and some scoping calculations are performed. In studies of other nuclear plants, Nuclear Services Corporation has found a total of about 25,000 components excluding piping segments of which 30% (7500) are safety-related. Our colleagues who are experienced with piping calculations estimate there may be about 3000 separate piping segments. We judge that it is neither necessary nor practical to account for this number of components and segments in the SSMRP model. Conceivably, the system model could be approximated by 100 or so components with increased modeling uncertainty. For the purpose of estimating the size and running time of the computer program, we have assumed 1000 components.

There are random and modeling uncertainties associated with the system model. Random uncertainties are inherent in the component failure rates and seismically-independent failure rates. With respect to the former, this randomness stems from the seismic input, soil properties and fragility curves. There are also modeling uncertainties for both the above failure rates which stem from modeling uncertainties in the same underlying parameters. The final modeling uncertainty is associated with the use of event/fault trees to model a structural system. This is discussed in Appendix B.7. For Phase I, this modeling uncertainty has been neglected.

5.7.3 Output Parameters

The endpoint of the calculation is a probability histogram for the radioactive release to the atmosphere with some uncertainty bands to reflect the modeling uncertainty. An example is shown in Figure 5.8. As stated earlier, the probability of release for each Release Category

FIGURE 5-8 HISTOGRAM OF PWR RADIOACTIVE RELEASE PROBABILITIES

is calculated by adding the probabilities of the accident sequences assigned to it by using the appropriate Boolean algebra. The central estimate and uncertainty bands would be calculated by taking 200 to 750 random samples from the underlying modeling uncertainties and ranking the resultant release probabilities. The magnitude of the uncertainty bands would be determined by considering the order statistics. The desirable number of samples and the use of order statistics will be discussed in Section 6.4.

The probability histogram for release is an integral output and provides only limited insight into the critical factors of the seismic risk. Important engineering insights could be gained by identifying in the output which accident sequences dominate the probability of each Release Category. For non-seismic accidents at the Surry plant, this information can be culled from Table B.4. In our opinion, this output should be required from the SSMRP model.

Another very desirable output would be the identification of critical ESFs and components from a seismic design viewpoint. For example, safety-related components are currently classified as Seismic Category I or II. Components assigned to the former category have more stringent design criteria and hence, for the same function, are more expensive than those assigned to the latter category. On the basis of public risk, are all the critical components assigned to a Seismic Category I or are some overlooked? Conversely, are some non-critical components overclassified and could be down-graded for a cost saving? The above information can be obtained either by reviewing the dominant accident sequences or by performing sensitivity studies for components whose classification appears questionable. The latter method would involve assigning a different fragility curve to the component in question. We favor the former, more heuristic approach since we are skeptical that the probability of release will be a sufficiently sensitive yardstick for such a study. For a similar reason, we recommend

that the failure probabilities of individual components be retained in the MPS calculation with the option to use these parameters directly in sensitivity studies.

The MPS program is intended for use in sensitivity studies. As explained in Sections 4.2, 6.4 and 7.1, sensitivity studies would be performed by reassigning the probability distributions for the various modeling uncertainties and thereby reweighting different parameters. Each sensitivity study would produce a new probability histogram for release and its uncertainty bands which can be compared to a previous one. As mentioned above, an alternate yardstick for sensitivity could be the component failure probabilities.

5.7.4 Auxiliary Programs

Two Auxiliary Programs are envisaged for the system model. The first is for the analysis of fault trees or the equivalent model for Engineered Safety Features. The following computer programs are a few of the many available: FTAP⁽¹²⁾, SETS⁽¹³⁾, PLMOD-1⁽¹⁴⁾. The CAT⁽¹⁵⁾ program is available to aid in the preparation of the fault trees. An equivalent method with some advantages/disadvantages is the GO⁽¹⁶⁾ program. The selection from these available computer programs would be guided by the unique characteristics of the problem and the familiarity of the analyst. We would merely note a potential need to obtain higher-order minimal cut sets than usual; one program may have an advantage in this respect. The second program is for the calculation of the radioactive release magnitudes. The BOIL and CORRAL programs, initially developed for the Reactor Safety Study, would be used.

6.0 STATISTICAL METHODS

Statistics plays a major role in all three stages of the calculational model. In the first two stages, where the input data set is prepared and the conditional structure and component failure rate are calculated, the techniques of sampling are extremely important. The sampling concepts used are discussed in Section 6.1. In calculating the probabilities of release in Stage III, the various sample combinations are weighted based on the probabilities assigned to their components. The weighting method is discussed and illustrated in Section 6.2. The method of ranking the probabilities obtained in Stage III about a central value is discussed in Section 6.3. Stage III of the calculational approach also involves the sensitivity studies. Section 6.4 examines the types of assumptions and alternatives that might be considered in the sensitivity studies as well as the methods to be employed.

6.1 Sampling Techniques

When a computer program is used to model a real phenomena it is often difficult to determine the values of the variables to be used as inputs. This difficulty can arise from within the physical process itself when system parameters are not constant, but vary in some manner about nominal values. It can also arise from the uncertainty in the approximations used in some parts of the code.

If the input variables take on a finite number of values, then an exhaustive enumeration might be conducted. Thus, all possible value of the output can be associated with values of the inputs. However, in this case, because of the form of the input variables and the complexity of the calculation, it is not feasible to run at all values of the inputs. Therefore, only certain combinations of values of the inputs are used to make runs. That is, the value of the inputs are sampled.

Three types of sampling schemes are presented:

- 1) Random sampling,
- 2) Fractional factorial sampling, and
- 3) Latin Hypercube sampling.

6.1.1 Random Sampling

Assume that there are K input variables and N samples are desired. In this technique, each of the K variables is assumed to be associated with a probability distribution and is sampled on the basis of this distribution. A vector of the K sampled values represents a random sample of the inputs and by repeating this procedure N times, the N samples are generated. If N is large enough, the K -dimensional space is represented proportionately by the N samples.

6.1.2 Fractional Factorial Sampling

This technique arises from the classical factorial and fractional factorial experimental design.⁽¹⁷⁾ In this approach, each input variable X_i , is considered at only l_i levels or values. If $l_i = 3$, these values might be a nominal value, a high value, and a low value. If all combinations of levels and variables are considered, then $\prod_{i=1}^K l_i = M$ samples would be required. For example, if there are 5 input variables and each variable is considered at 3 levels, then $3^5 = 243$ samples would be required. This method is a form of stratified sampling since all areas of the input variables are represented.

There are several variations of this factorial technique. One approach obtains the l_i values of the input variable X_i by using the probability distribution of the input variable and dividing the range of the variable into l_i parts having equal probability content. Each of these intervals are then sampled at random to determine the l_i values for each of the variables. The $M = \prod_{i=1}^K l_i$ samples are then obtained as before.

Another variation of this method utilizes either of the above methods for forming the samples but only generates a subset of all the points. Hence, a fractional factorial sample is formed. For example, a one-ninth fraction of the 3^5 samples or 27 samples might be utilized. Many of the Box designs used in response surface work on experimental design use this approach.⁽¹⁸⁾

6.1.3 Latin Hypercube Sampling

The Latin Hypercube Sampling (LHS) technique is an extension of the idea of Latin Squares in experimental design.⁽¹⁹⁾ As in the random sampling description, assume there are K input variables and N sample vectors required. The range of each variable is divided into N mutually exclusive and exhaustive intervals on some basis such as equal length or equal probability increments. The sample K -tuples are then formed by selecting an interval at random for each of the variables and then selecting a value at random from the chosen interval for each of the variables. The sampling of the intervals are done without replacement so that for each of the components of the N vectors, each interval is selected exactly once.

The three techniques may be illustrated by the following example. Suppose it is desired to select 4 input vectors from two variables X_1 and X_2 . For the sake of simplicity, assume X_1 and X_2 are uniformly distributed over the interval from 0 to 1. Using the method of random sampling, 4 pairs of numbers are selected at random between 0 and 1. Let these 4 pairs be as follows:

(.07, .31), (.12, .23), (.55, .85), and (.56, .09).

(These pairs were selected from a table of random digits.) Using the fractional factorial method, a one-fourth replicate or fraction of the $4^2 = 16$ combinations is used. These points are generally in the

corners of the space. Selecting values at random appropriately from the corners results in the following 4 pairs:

(.23, .19), (.80, .76), (.20, .90), and (.81, .21).

Finally, using the LHS technique, the interval from 0 to 1 is divided into four equal parts (0, .25), (.25, .50), (.50, .75) and (.75, 1.00) and a value is selected at random from each interval for each variable:

x_1 - .14, .27, .68, .96

x_2 - .21, .31, .65, .76

The 4 points are now obtained by selecting a value for each variable at random and without replacement. Hence,

(.27, .65), (.68, .21), (.14, .76), and (.96, .31)

represent the points selected. In the following diagram, the circles represent the points selected by random sampling, the squares by fractional factorial sampling, and the asterisks by LHS.

Note that if the asterisks are mapped onto the x_1 and x_2 axes, then it is clear the LHS has forced each of four intervals to be represented

at least once. That is the entire range of both X_1 and X_2 has been covered. On the other hand, the random sampling method resulted in not covering the high interval of X_1 and one of the middle intervals of X_2 . Also, the fractional factorial technique does not adequately represent the middle of the range for either X_1 or X_2 . This illustrates a real advantage of the LHS technique, the space of the input variables is fully represented. This fact is utilized in Section 6.2 where sample weighting is discussed and in the sensitivity studies of Section 6.4.

6.2 Weighting Methods

In calculating the probabilities of release in Stage III, the various sample combinations are weighted based on the probabilities assigned to their components. This weighting will now be addressed.

Recall that in Stage I, during the preparation of the input data set, 3-5 scaling factors on frequency and on amplitude were established for each transfer function used in the MPS system. In addition, 5 levels of each fragility curve were generated. From the 45-125 potential combinations of transfer functions (TF) and fragility curves (FC), a subset of 15-25 samples are selected by Latin Hypercube Sampling (LHS). That is, 15-25 triples of the form

$$(K_w, K_a, FC)$$

are selected.

As an example, let there be 5 levels of K_a and K_w denoted simply 1, 2, 3, 4 and 5. Let the five levels of the fragility curves be denoted by A, B, C, D, and E. Then the 25 samples might be represented in the following Latin Square.

K_w

		1	2	3	4	5	
							FC = A
	1	A	C	E	B	D	B
	2	C	E	B	D	A	C
K_a	3	B	D	A	C	E	D
	4	D	A	C	E	B	E
	5	E	B	D	A	C	

or as triples:

(1, 1, A), (1, 2, C), (1, 3, E), (1, 4, B), (1, 5, D)

(5, 1, E), (5, 2, B), (5, 3, D), (5, 4, A), (5, 5, C).

It can be observed that the entire space has been sampled and that every pair of levels appears exactly once in the 25 samples.

Let P_{a_i} ($i = 1, 2, 3, 4, 5$) denote the probability associated with the level i of the scaling factor on amplitude and similarly let P_{w_i} denote the probability associated with the frequency scaling factor. Furthermore let P_j ($j = A, B, C, D, E$) denote the probability associated with level j of the fragility curve. Since the levels of K_a , K_w , and FC are selected independently, a probability matrix may be calculated for any Latin Square sample in the following manner:

$$\text{Prob}[K_w = 2, K_a = i, FC = j] = P_{w_2} P_{a_i} P_j.$$

However, since not all 125 combinations are used, the total probability in the matrix is less than unity. Let P_T denote the total probability. Then, if each element of the matrix is divided by P_T , the resulting set of probabilities now sum to unity. These adjusted or normalized probabilities represent the weightings assigned to each sample triple. The triples are selected according to their weights during the Monte Carlo portion of the program. Utilizing the samples represented previously and assigning the following probabilities to the various levels of K_a , K_w , and FC:

$$P_{a_i} = .1, .2, .4, .2, .1 \quad \text{for } i = 1, 2, 3, 4, 5$$

$$P_{w_i} = .2, .2, .2, .2, .2 \quad \text{for } i = 1, 2, 3, 4, 5$$

and

$$P_j = .1, .1, .5, .2, .1 \quad \text{for } j = A, B, C, D, E,$$

the unadjusted probability matrix associated with the previous Latin Square is:

.002	.010	.002	.002	.004
.020	.004	.004	.008	.004
.008	.016	.008	.040	.008
.008	.004	.020	.004	.004
.002	.002	.004	.002	.010

Thus, $\text{Prob}[K_w = 2, FC = D, K_a = 3] = P_{w_2} P_{a_3} P_4 = (.2)(.4)(.2) = .016$.

Also $P_T = 0.200$,

So that the adjusted or normalized matrix is:

.01	.05	.01	.01	.02
.10	.02	.02	.04	.02
.04	.08	.04	.20	.04
.04	.02	.10	.02	.02
.01	.01	.02	.01	.05

Hence, the probability of selecting the triple (2, 3, D) is 0.08.

The weights assigned to the samples may be modified by simply modifying the probabilities assigned to the various levels of K_a , K_w , and FC. This concept will be discussed further in Section 6.4.

6.3 Rank and Uncertainty Band Methods

A method of ranking the probabilities or responses obtained in Stage III about a "central" value will be discussed in this section. Although it is doubtful that the distribution of the output variable or response will be known, it will be possible to make some statements concerning the output with only some modest assumptions. If it is known or assumed that the distribution of the output is continuous, then non-parametric methods utilizing the order statistics can be applied. (20)

Let Y_i and Y_j be the i th and j th order statistics from a sample of size N . Then (y_i, y_j) is a 100% confidence interval for the quantile of order $1-\alpha$ (e.g., the median is the quantile of order 0.5). The relation between i , j , γ , and α is expressed in the equation

$$\gamma = \sum_{x=i}^{j-1} \binom{n}{x} (1-\alpha)^x (\alpha)^{n-x}$$

Letting $i=1$, $j=n=10$ and $1-\alpha=0.5$, it is seen that the interval (min R, max R) is a 99.8% confidence interval for the median response in a sample of

size 10. By increasing the sample size the confidence is increased for the above interval or an interval involving values greater than the minimum and less than the maximum may be obtained for similar confidence levels.

It is also possible to obtain one-sided tolerance limits, i.e., to obtain 100% confidence that at least 100(1- α)% of the distribution lies below Y_j . Setting $i=0$ in the above equation

$$\gamma = \sum_{x=0}^{j-1} \binom{n}{x} (1-\alpha)^x (\alpha)^{n-x}$$

If $j=n$, that is the maximum R is used, the following sample sizes are required for the given γ and $1-\alpha$.

	γ			
$1-\alpha$	.90	.95	.99	.995
.999	2302	2995	4603	5296
.995	459	598	919	1379
.99	230	299	459	688
.95	45	59	90	135
.90	22	29	44	66

In the event that one or more of the values obtained far exceeds the remainder of the data, (hence, a potential outlier) one may wish to use an order statistic other than the largest or nth order statistic. If this is done, the required values of n increase. The following table gives the required sample size for the Kth order statistic to be an upper 90 percent confidence limit for the 95th percentile:

K	45	76	103	129	154
n	45	77	105	132	158

Thus, for a sample of size 158, the 154th largest value of the response exceeds at least 95% of the distribution of responses with 90 percent confidence. This would allow for as many as four possible outliers. Two-sided tolerance statements may be obtained in a similar fashion.

6.4 Sensitivity Studies

During the course of running the calculational model many assumptions are made regarding the probability distributions of the various parameters. In Stage III, a complementary cumulative distribution function (ccdf) and its uncertainty bands are assigned to Z_f . At the same time, uncertainty bands are applied to the ccdf of the Z_b . Additionally, weights are calculated for the (K_w , K_a , FC) triples as discussed in Section 6.2 of this chapter. An obvious question that must be considered and studied is related to the relative importance on the output of the various input assumptions. This is the general purpose of the sensitivity studies.⁽²¹⁾ The remainder of this section is divided into two parts - what is studied and how it is studied.

6.4.1 Subject of Sensitivity Studies

The choice of the ccdf and its uncertainty bands on Z_f will be used as an example to discuss some alternatives. Perhaps an assumption that the ccdf is related to the lognormal is initially considered. How crucial that assumption is to the response distribution may be measured by repeating the calculations using a Weibull or Gamma ccdf assumption, for example. It is also possible to use any empirical distribution that one chooses. Changes in the assumed distributions that are possible study areas are:

- A. Underlying distribution,
- B. Changes in the parameters of the assumed distribution by some amount (e.g., $\pm 10\%$),

- C. Changes in nominal values holding variance measure constant,
- D. Changes in variation with nominal value held constant,
- E. Any other that user may feel is important.

The above studies may be of interest on the distribution of the uncertainty bands placed on Z_f and Z_b . Additionally, the probabilities on K_w , K_a , and FC may be modified to determine the relative importance of these assumptions on the response.

6.4.2 Sensitivity Studies Method

The conditional structure and component failure probabilities are determined in Stage II for each of the 5 levels of Z_f and 5 levels of Z_b in combination with the 15-25 (K_w , K_a , FC) triples or a total of 375-625 points. Therefore, the sensitivity of the response variable may be measured by comparing the outputs of the program for various assignments of probabilities on Z_f , Z_b , K_a , K_w , and FC. By using the weighting methods described in Section 6.2, the weights on the (K_w , K_a , FC) are easily modified. At the same time (at the start of Stage III) the ccdf and uncertainty bands on Z_f and Z_b may also be modified. An advantage of this method is that all alternatives are being compared with respect to the same base case or set of points.

7.0 COMPUTATIONAL APPROACH AND RESOURCES

7.1 Computational Approach

This section integrates the overall approach described in Section 4.0 and the module descriptions of Section 5.0 and the statistical concepts described in Section 6.0, into the recommended computational algorithms. As described in Section 4.2 and illustrated in Figure 4.2, a three-stage calculation is envisaged. In Stage I, the Auxiliary Programs would be used to generate input data specific to the Zion plant and site for the Master Probabilistic System. In Stage II, a parametric study would generate component failure probabilities as a function of those parameters which represent major modeling uncertainties. In Stage III, the modeling uncertainties would be introduced by probability weighting the parametric output of Stage II and thereby calculate a probability histogram of release. Sensitivity studies would be performed by using different probability weighting in the Stage III calculation. The above calculations are described in Section 7.1.1. As stated in Section 4.2, the demarcation between Stages II and III can be altered to provide a more accurate and flexible calculation but at higher cost for sensitivity studies. This alternative is presented as an option in Section 7.1.2.

For clarity, the major parameters having random and modeling uncertainty are summarized below:

Z_f - measure of total free-field earthquake energy. Variation in magnitude of Z_f represents random uncertainty of earthquakes. Variation in probability of specific magnitude of Z_f reflects modeling uncertainty in seismic input.

Z_b - measure of basemat motions. Five or six components of Z_b represent directions of basemat motion. A set of Z_b is generated for each magnitude of Z_f . Variation in magnitude

of Z_b represents random uncertainty of soil properties. Variation in conditional probability of specific magnitude of Z_b represents modeling uncertainty in soil-structure interaction. If 3-D SSI model is used instead of a 2-D one, the number of parameters are doubled.

K_w, K_a scalar parameters applied to each base-line transfer function (TF) to represent modeling uncertainty.

FC - Fragility curve. For each group of components, a set of fragility curves is postulated to represent modeling uncertainty. Each FC represents random uncertainty in component failure.

SIFR - Seismically-independent failure rates. The individual values represent random uncertainty in the occurrence of the event. An uncertainty band about each probability represents modeling uncertainty.

7.1.1 Computational Approach - Option 1

The overall data flow diagrams for Stage I, II & III calculations are shown in Figures 7.1, 7.2 and 7.3, respectively. As noted above, sensitivity studies are merely a repeat of Stage III (Figure 7.3) with new weighting factors. A more detailed data flow diagram for the combining of loads in Stage II (Figure 7.2) is shown in Figure 5.5. Let us review the calculations depicted in Figures 7.1, 7.2 and 7.3.

FIGURE 7.1 STAGE I CALCULATION - PREPARE INPUT DATA SET

FIGURE 7.2 STAGE II CALCULATION (OPTION 1) - CALCULATE CONDITIONAL PROBABILITY OF COMPONENT FAILURE

FIGURE 7.3 STAGE III CALCULATION (OPTION 1) - CALCULATE PROBABILITY HISTOGRAM OF RELEASE WITH ITS UNCERTAINTY BANDS

7.1.1.1 Stage I

As described in Section 5.1, it is envisaged that the free-field seismic motion will be represented by a set of Fourier amplitude spectra each of which is characterized by a parameter Z_f , which is a measure of the earthquake energy. A minimum of 5 amplitudes of earthquake are judged necessary to adequately represent the potential range of earthquakes from below SSE to several times SSE. For each amplitude and its associated Fourier spectra, the Fourier amplitude spectra for each of 5 components of basemat motion will be calculated assuming the use of a 2-D soil model. Each set of basemat motions will be measured by a parameter Z_b . The range of Z_b will represent the random uncertainty of soil properties and a minimum of 5 amplitudes is judged necessary. A probability distribution for each magnitude of Z_b will represent modeling uncertainty in soil-structure interaction. Thus, 25 Fourier spectra for each of 5 components of basemat motions will be generated for use in Stage II calculation. If a 3-D soil model is used, the basemat motion should be represented by a pair of variables, Z_x and Z_y and a 6th component of basemat motion is justified. If, in addition, 10 magnitudes each of Z_f , Z_x and Z_y are used, a total of 1000 Fourier spectra in each of 6 directions would be generated for use in Stage II.

As described in Section 5.3, transfer functions would be generated between the basemat to structural compartments and groups of components. It is estimated that an average of 3 motions will be needed for each structure/compartment in order to calculate its seismic load. For 200 structure/components, there would be a total of $5 \times 200 \times 3$ or 3000 transfer functions. As described in Section 5.3., it is proposed to approximate each transfer function by a rational polynomial approximation requiring 6 to 15 coefficients. The total storage required would be 18000 to 45000 locations. Modeling uncertainty would be represented for each transfer function by scaling factors on frequency and amplitude. If 3 factors (e.g., 0.8, 1.0, 1.1) are used for each, there would be 9 transfer functions; 5 factors would result in 25 transfer functions.

The induced dynamic loads would be represented by time histories; their randomness will be incorporated via scale factors on amplitude and time. The operating and induced static loads will be constant with time and appropriate PDF's are specified to account for their randomness.

For each group of structures/components, a set of fragility curves would be generated as described in Section 5.5. It is judged that 50 to 150 groups will be needed to adequately represent the range of structures/components present in the plant. For each group, it is envisaged that a minimum of 5 fragility curves would be needed to adequately represent the potential modeling uncertainties.

Combining 5 fragility curves with 9 to 25 transfer functions would result in 45 to 125 potential combinations. It is proposed to reduce the amount of computation by only calculating component failure probabilities (conditional upon basemat motion) for 15 to 25 of them. These 15 to 25 combinations would be selected from the complete set of 45 to 125 by Latin Hypercube Sampling as described in Section 6.1.

The system model is formed by generating accident sequences and minimal cut sets as described in Section 5.6. The Reactor Safety Study assumed that the modeling uncertainty for the seismically-independent failure rates was log-normally distributed.

7.1.1.2 Stage II

The Stage II calculation, which is shown in Figure 7.2, represents the major computational investment. For all of the designated magnitudes of Z_f and Z_b and the (K_w , K_a , FC) combinations, the probabilities of initiating events and of structure/component failure conditioned upon the occurrence of the earthquake are calculated. For the minimum 5 magnitudes each of Z_f and Z_b and 15 combinations of (K_w , K_a , FC), there would be

375 calculations of each conditional probability. At the other extreme of 10 magnitudes of each Z_f , Z_x and Z_y (for a 3-D SSI model) and 25 combinations of (K_w , K_a , FC), there would be 25,000 calculations. As shown in Section 7.2, the computational costs of the latter appear prohibitively high. If it is necessary to consider 1000 components in the system model, the storage from Stage II would be 375,000 to 25 million locations.

7.1.1.3 Stage III

The Stage III calculation, which is shown in Figure 7.3, would be used both for the initial benchmark for the probability histogram of release and for subsequent sensitivity studies. It is unnecessary to repeat Stage II calculations for the latter. Indeed, if the original ranges for Z_f , Z_b , K_w , K_a and fragility curves (FC) were sufficiently large, Stage II calculations might not have to be repeated even if a new model was proposed for one of the Auxiliary Programs in Stage I; one would merely change the weightings in Stage III.

To this point in the calculation, no probabilities have been assigned to Z_f , Z_b , K_w , K_a and FC. Let us consider the earthquake magnitude, Z_f . The input variables shown in Figure 5.1 can be translated into a complementary cumulative distribution function (ccdf) for Z_f plus uncertainty bands. Effectively, one estimates a set of ccdf's for Z_f which one can associate with different percentiles of the modeling uncertainty distribution. A random sample from this latter distribution selects a ccdf for Z_f over which one integrates to incorporate the random uncertainty Z_f . From the viewpoint of this model, one has flexibility in postulating the central estimate for Z_f and its uncertainty bands and there are no constraints on the bands being symmetrical or constant as a function of Z_f . The modeling uncertainty distribution can be parametric (e.g., log-normal) or non-parametric. In practice, consideration of physical phenomena constrains one's selections. The assignment of probability

and modeling uncertainty to Z_b is similarly flexible. The estimate of the ccdf on Z_b does reflect the random uncertainty in the soil properties so its choice is fairly constrained. Similar considerations apply to the weighting of the (K_w , K_a , FC) combinations and to the selection of the seismically-independent failure rates and their uncertainties.

In order to determine the median probability of release plus tolerance limits (such as an upper 90 percent confidence limit for the 95th percentile) described in Section 6.3, a sample of size 200 should be adequate. This size would allow for as many as five outliers without substantially biasing the results.

7.1.2 Calculational Approach - Option 2

The Option 1 calculational approach has limitation as the price of its relatively inexpensive sensitivity calculations. Although each group of structures/components is assigned an individual set of fragility curves, only one modeling uncertainty parameter is used. In other words, if the 90th percentile fragility curve is sampled, the respective 90th percentile fragility curve is used for each group of structures/components. Effectively, the modeling uncertainties on all the fragility curves being used are assumed to be correlated. It is not feasible to examine the sensitivity of the probability histogram of release to an individual fragility curve. The Option 2 calculational approach avoids this limitation at the price of more costly sensitivity studies.

7.1.2.1 Stage I

The only change in the Stage I calculations is that only (K_w , K_a) combinations are considered instead of (K_w , K_a , FC) ones. For 3 levels each for K_w and K_a , a full factorial design would have 9 combinations; for 5 levels, there would be 25 combinations. Fractional factorial designs might have 5 or 15 samples respectively. It may not be worthwhile to use less than a full factorial design for the 3 by 3 array.

7.1.2.2 Stage II

The Stage II calculations are slightly modified for Option 2 as shown in Figure 7.4. Since one now wishes to consider 10 to 100 fragility curves (FC) individually with respect to their modeling uncertainty, it does not appear feasible to precalculate probabilities as a function of all these variables so combined loads on structures/components are stored as output from Stage II. If it is necessary to consider 1000 components in the system model, the storage from Stage II would be 125,000 to 25 million locations.

7.1.2.3 Stage III

The Stage III calculations, shown in Figure 7.5, now include the calculation of structure/component failure probabilities within the main Monte Carlo sampling loop. Since the number of random variables has been increased by 10 to 100 to account for individual modeling uncertainties in fragility curves, it is estimated that the number of samples required to obtain desirable statistics on output will increase from 200 to 750.

FIGURE 7.4 STAGE II CALCULATION (OPTION 2) - CALCULATE CONDITIONAL LOADS ON COMPONENTS

FIGURE 7.5 STAGE III CALCULATION (OPTION 2) - CALCULATE PROBABILITY HISTOGRAM OF RELEASE WITH ITS UNCERTAINTY BANDS

7.2 Computational Resources

The structure of a computer program is governed by its functional requirements and the system on which it will be operated. Previous sections have provided functional requirements in terms of input definition, module description, flow diagrams, and output. The computational approach thus defined is influenced only to a minor degree by the characteristics of the CDC 7600 operating system vis-a-vis other computers and operating systems; it is, however, generated with due regard to minimization of storage and mathematical operations. This section provides an estimate of analysis, programming, and computer resources based, for the given computational approach, on the following additional factors: a program management procedure, the characteristics of the CDC 7600 operating system, the volume of data to be processed, and a proposed mode of user operation. Section 7.2.1 describes the characteristics of the proposed MPS-AP program. A modular definition of each analysis stage is supplied in Section 7.2.2, with related resource requirements and costs in Sections 7.2.3 and 7.2.4. A program management procedure is presented in Section 7.2.5.

7.2.1 Program Characteristics

The MPS-AP program is an integrated interdisciplinary tool whose purpose is to generate probability histograms as a function of seismic input parameters, plant structural characteristics and engineered safety features. The nature of the problem implies a large volume of data transfer and manipulation, multiple users, and the need for convenient source code and data base revision. In more specific terms, the following program features are necessary.

1. A high degree of program modularity. Each module or functional unit within the program system must have a specific task with well-defined input and output. Communication between modules will be controlled by interface programs.

2. Multiple entry points for selective/repetitious use of program links in an interactive operating mode.
3. A flexible data base, with provisions for controlled growth, adequate file security, and efficient access.
4. Graphical display of data base contents and output.
5. An internal computer resources estimate for user-requested operating sequences.
6. Minimization of storage through use of (for example):
 - a. Curve fitting of data,
 - b. Selective recomputation of variables,
 - c. Convenient editing/interrogation of data base,
 - d. Use of efficient I/O processors to facilitate data transfer between mass storage, LCM, and SCM,
 - e. Integer packing, and
 - f. Dynamic core allocation.
7. Portability, ensured through avoidance of machine-dependent features (e.g., assembly language programming), use of a standard operating system (SCOPE 2.1), extensive documentation, and use of generalized data transfer interfaces.
8. Comprehensive operating instructions.

The importance of quality documentation and its impact on cost must not be underestimated. As a rough rule, two hours of FORTRAN coding requires about an hour of documentation.

Modularity is the key to successful programming. A "module" as used herein, is a single program (or subprogram) that provides a functional relationship between a domain of input values and a range of output parameters. The execution of such modules may have the effect of expanding or contracting the data base. The MPS-AP program, viewed as a single module, has as input seismic, soil, and nuclear plant description; it has as output radioactive release histograms; it provides a functional relationship between the input and output thus defined. "Top-down" structured programming implies successive reduction of over-all modules into smaller modules according to function. This reduction is accomplished while observing simple flow of control rules. In this fashion, each part of the system maintains its modular nature, with concomitant blessings of ease of modification or substitution, concurrent documentation, minimization of error generation and verification effort, and reduced necessity for coordination between individual programmers.

7.2.2 Modular Definition of Analysis Stages

This specification has described the analysis functions in three stages. In general terms, Stage I uses seismic events, soil, structure, and component properties as input and produces, in effect, functional relationships between the input and structure/component response. In addition, an auxiliary program or fault tree analysis will use as input primary coolant piping and engineered safety features to provide minimal cut sets. These functional relationships, along with structure/component fragility curves, non-seismic loads, and minimal cut-sets, constitute a data base for Stages II and III. In Stage II, the data base of Stage I is processed to output conditional probability of failure of structures and components (including engineered safety features). Stage III employs a system model relating component performance (failure) to system performance to produce histograms of radioactive release. Analysis, programming and computer resources requirements are enumerated below, referenced to the three stages of analysis. It will be shown that development associated with each of the stages need not be conducted sequentially, although, in practice, there are advantages to sequential development.

7.2.3 Resource Requirements

Resources required to generate a functional MPS-AP program may be estimated with moderate accuracy at this preliminary stage. The cost associated with programming, verification, documentation, coordination, planning and computer facilities usage will become more firm when module definitions are complete, the necessary software development has been determined and a program management procedure and schedule have been agreed upon. The estimates at the end of this section reflect for Option 1 a "best guess" based on comparison of the complexity of this system development task with others of similar magnitude undertaken at Quadrex. The Option 2 approach results in a sixfold increase in the computing costs of the inexpensive Stage III analysis segment.

7.2.3.1 Stage I (Use of AP to produce input for MPS)

Input: Seismic acceleration time histories, soil, structure, component properties, configurations of primary coolant piping and engineered safety features.

Software: Two- and three-dimensional SSI programs (existing).

General three-dimensional structural analysis program (existing).

Fourier Amplitude Spectrum generator. Data base management program (entry, interrogation, editing). Curve fitting routines.

Fault tree analysis program (existing).

Output: Functional relationship between

1. Seismic event and base mat response,
2. base mat motion and compartment response, and
3. compartment motion and component response.
4. Minimal cut sets for engineered safety features.

Storage (base 10 single precision words)

Soil-Structure interaction results	60,000
------------------------------------	--------

Transfer Functions	400,000
Operating and Induced Load	160,000
Phase Spectra	200,000
Fragility Curves	<u>30,000</u>
TOTAL	850,000

Project Tasks for Stage I

- o Reduce seismic ground motion histories to Fourier Amplitude Spectra.
- o Perform 2-D and 3-D SSI analysis for base mat response.
- o Perform seismic analysis of containment and auxiliary structures for compartment response.
- o Establish component loads for floor motion and non-seismic loads.
- o Develop fragility curves for structures and components.
- o Generate data base management system and store data.
- o Analyze fault trees for minimal cut sets.

Comments: Current state of non-seismic loads and quality of component characterization is unknown. Pre- and post-processors for 2-D/3-D SSI model generation and data reduction will be necessary. Anticipate some difficulty in converting existing component analysis into fragility curves.

7.2.3.2 Stage II (Processing plant/seismic data for conditional failure probabilities)

Input: Free field acceleration levels; base mat spectra; transfer functions; frequency amplitude scaling factors; fragility curves; induced and operating loads; phase spectra.

Software: Control program for cycling over random variables to produce structure/component failure probabilities. Random selection subprogram. Procedure for generating time history from FAS for random phase angles.

Output: Conditional probability of structure/component failure (P_f).

Storage: $P_f(300)$ added to data base.

7.2.3.3 Stage III (Processing failure probabilities for probability histogram of release)

Input: Conditional failure probability (P_f) for structures and components, accident sequences, minimal cut sets, seismically-independent failure rates, ccdf's for Z_f and Z_b and their uncertainty bands.

Software: Control program for cycling over random variables to produce probability histograms. Random selection subprogram.

Output: Probability histograms of radioactive release and their uncertainty bands.

Storage: Minimal.

7.2.4 Cost

The cost figures included herein are based on several factors, some of which might be subject to dispute. In light of this, an explanation of these judgemental factors seems in order.

1. The cost of auxiliary program execution assumes 40 runs with 2-D models at two man-days of data preparation per run, and 5 runs with 3-D models at ten man-days per run. Computer charges at commercial rates would be \$40,000 at low priority with a 25% increase for error correction. Compartment transfer functions, if not available, would add to the cost of Stage I.

2. Computer cost at LLL is about one-fifth of commercial rates.
3. The MPS program is characterized by heavy numerical calculation over a moderate data base. On this basis, total charge time is calculated assuming I/O and memory charges are approximately one-half of charges for numerical operations.
4. LCM is full.
5. The data base is approximately three times the size of LCM.
6. MPS will contain around 4000 source statements.
7. Maximum area for source code in SCM will be 20000_{10} words
8. The cost of a "calculation" (3 seeks + average numerical operation) is 37 clock-cycles.
9. One clock-cycle is 27.5×10^{-9} central processor seconds.
10. A competent programmer generates about 10 lines of debugged source code per day.
11. Documentation, verification, and coordination, taken together, are equivalent to programming time.

Using these factors, the cost associated with each analysis stage is estimated in the following subsections.

7.2.4.1 Stage I Cost

Stage I is characterized by moderate software development, heavy use of existing programs, and considerable effort expended at manual

digestion of seismic input/response data. The major programming task is generating a data base management system. Other tasks involve repetitive use of standard structural analysis and fault tree tools and encoding of output into the data base. Specific tasks and associated costs (assuming commercial computer rates) are as follows:

- Task I.1 Reduction of seismic free-field data: 2 man-months, \$2000 computer
- Task I.2 SSI models, data reduction: 5 man-months, \$40000 computer
- Task I.3 Generate transfer functions: 4 man-months, \$20000 computer
- Task I.4 Encode and/or develop fragility curves and non-seismic loads: 4 man-months, \$4000 computer
- Task I.5 Encode and analyze fault tree for 10 to 15 systems
 ___ man-months, \$ ___ computer
- Task I.6 Program data base management system 5 man-months, \$10000 computer

Total: _____ man-months, \$ _____ computer

7.2.4.2 Stage II Cost

Stage II is characterized by heavy numerical processing, moderate I/O and moderate program development. It is highly likely that the LLL or LBL computing system would be used for development work and program execution, since commercial computer costs would be prohibitive. This conclusion is based on the prodigious number of calculations required, determined as follows:

$$C_I = N_f * N_b * (K_w, K_a) * N_c * N_m * N_I$$

$$C_S = N_f * N_b * (K_w, K_a) * (IE, N_c) * N_m * N_S$$

where

C_I = Number of calculations associated with Initiating Events

C_S = Number of calculations associated with Engineered Safety Features

N_f = Number of Earthquake Magnitudes

N_b = Number of base mat motion magnitudes

(K_w, K_a) = selected pairs of frequency-amplitude scaling factors

N_c = number of components

N_m = number of Monte Carlo trials

(IE, N_c) = number of component-initiating event combinations

N_I = number of computations in one Monte Carlo Loop without induced loads (Figure B.8)

N_S = number of computations in one Monte Carlo Loop with induced loads (Figure B.8)

PARAMETER VALUES

	N_R	N_b	(K_w, K_a)	N_c	N_m	(IE, N_c)	N_I	N_S	NUMBER CALCULATIONS
C_I	5	5	25	20	10	--	25000	--	0.3×10^{10}
C_S	5	5	25	--	10	200	--	30000	3.75×10^{10}

For perspective, this number of calculations is approximately 600 times the number required for the reduction of a moderately large (2000 degrees of freedom with 180 semi-bandwidth) structural stiffness matrix.

Using the judgemental factors enumerated in the introduction to 7.2.4, generation of the probability factors for output to Stage III would result in charge time of (for the NMFECC charging algorithm)

$$\begin{aligned} \text{CHARGE TIME} &= 4 \times 10^{10} \text{ CALC} \times \frac{37 \text{ CYCLES}}{\text{CALC}} \times \frac{27.5 \times 10^{-9} \text{ CPSEC}}{\text{CYCLE}} \times \frac{1.5 \text{ total chge}}{\text{CPSEC CHGE}} \times \frac{1 \text{ CPHR}}{3600 \text{ CPSEC}} \\ &= 17 \text{ CP hours} \end{aligned}$$

Even though the Stage II calculation may be carried out in segments, this computation charge is only marginally tractable with a severely limited set of parameters.

Programming, verification and documentation of the Stage II program would require about 30 man-months of effort. This would include time for periodic reviews and setting up of user operating and program control procedures.

7.2.4.3 Stage III Cost

Stage III involves repeated calculations using a limited data set. With 200 accident sequences, 4 ESF per sequence, 20 cut-sets per ESF, three components per cut set, and use of Boolean arithmetic, approximately 24000 mathematical operations are required for each combination of Z_f and Z_b . This calculation loop would be repeated about 200 times for a total of 80×10^6 calculations. I/O would be minimal. If a factor of two is used to account for increased cost of logical operations, and 1.5 for total charge to CP charge, the equivalent charge time is 230 sec. Establishing the system model and associated programming requires about four man-months.

7.2.4.4 Effect of Parameter/Option Selection on Cost

The cost associated with Stages II and III reflects option 1 with a set of adequate parameter values. Option 2 shifts a small part of

the computational burden from Stage II to Stage III. The effect of this on Stage III, and the effect of other selected parameters are shown in the tables below.

	STAGE II (CPHR)	STAGE III (CPHR)
Option 1 (375 cycles)	17	.06
Option 2	17	.4
Option 1 (25000 cycles)	1000	--
Reduce number of components 1000-100	1.7	--

7.2.5 Program Management

The MPS-AP program, generated by observing the precepts of structured programming, will grow as a set of individual modules, each of which may be subject to review upon completion. A program management procedure is necessary to ensure that the individual modules satisfy the needs of the system as a whole, to coordinate program interfaces for the final assembly of modules, and to identify completion schedule difficulties. In addition, the methodology to be employed with each module should be reviewed by LLL before programming begins.

The disciplines involved in the MPS-AP program are seismic, structural, mathematical and systems analysis. A project team should be established representing a balance of expertise in these areas. The rather extensive use of machine facilities implies that a computer scientist should participate in the project in order to minimize change time and provide an efficient, flexible data base management system. A four or five man team thus constituted could pursue development of all three analysis stages simultaneously, with project completion in one year. A smaller group would both dilute expertise and lengthen the project; a larger group would increase coordination requirements.

The interdisciplinary nature of the MPS-AP program and the significant effort that will be required to produce a viable analysis system of uniform quality suggests that a rather close client-vendor relationship should be maintained. A comprehensive discussion of methodology is in order when all modules are firmly defined; programming should not begin until a high degree of confidence has been established that meaningful results can be obtained at reasonable cost. Once programming has begun, individual modules may be released upon completion to LLL for review and execution. The review cycles will continue for each major link in the program analysis chain, and, finally, for the entire system. This irregular review procedure would be supplemented by monthly progress reports, bi-monthly project team - LLL meetings, a midpoint project review and final presentation of program documentation and system demonstration. A close review cycle thus conducted serves not only to gauge the quality of completed modules, but as a means of influencing the direction of subsequent effort.

Previous comments in this section relate to the procedure by which the MPS-AP program is produced. A more difficult task is control of the baseline program with respect to alterations in methodology. It should be permissible to have many versions of the baseline program for individual contributors to experiment with, but the integrity of the system must be maintained. This is usually managed by preserving images of the data base and baseline system chronologically, by a review procedure for proposed program alterations, and by invoking mandatory self-documentation procedures for candidate system entries. In this fashion, each set of results derived from system operation would be accompanied by sufficient information to identify the program configuration and data base contents used to obtain the output.

1

8.0 RECOMMENDATIONS

At the conclusion of this project, we continue to believe that a systematic overview of the whole seismic design methodology is a very worthwhile endeavor. We especially believe that integration of the seismic calculation into an overall model of the reactor safety system in the sense of the Reactor Safety Study will provide very valuable engineering insights. However, despite our introducing some significant approximations, the potential running time of the computer program appears formidable. We submit the following recommendations for further work:

1. Delay decision on overall computation task until additional scoping work is performed and/or other contractual tasks for individual methodologies are completed, such as seismic input, SSI, transfer functions, load combinations, fragility curves, system model.
2. Distribute reports from NSC and J.H. Wiggins to selected contractors and LLL consultants and request written comments which address specific questions such as: a) is the degree of technical depth properly balanced in the individual methodologies, b) are the individual approximations technically sound, c) is the integration of the modules technically sound, d) would results of computations from the proposed computer program be understood and accepted by the seismic community, e) would the results be useful in guiding research priorities, f) should a smaller computation scheme be developed which strikes a balance between the simple hand calculations performed by Acres⁽⁷⁾ and the complex NSC approach by making further approximations?
3. Scoping work should be done for the proposed computation scheme by performing simplified calculations for each of the six methodologies separately, i.e., without connecting them together. This should

lead to better understanding and evaluation of the individual methodologies and also provide a reference case for possible verification of the proposed complete interconnected computation scheme. Examination of specific characteristics of the Zion plant may reveal potential parameter reductions.

4. The potential for further simplifications in the methodologies should be examined in order to develop an overall computation scheme which is somewhere between the simplicity of the Acres study and the complexity of the NSC proposal. Since even the complex NSC approach requires assumptions which make the results questionable, a simpler scheme may be more useful and have a significantly lower cost to develop and use.
5. Stage II should be exercised over a small number of component groups, selected according to engineering judgement. Resulting probabilities may provide justification for elimination of other component groups.

9.0 REFERENCES

1. Reactor Safety Study, "An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants." U.S. Nuclear Regulatory Commission, WASH-1400, NUREG-75/014 (1975).
2. Newmark, N. M., "Probability of Predicted Seismic Damage in Relation to Nuclear Reactor Facility Design," Consulting Engineering Services, September 1975.
3. Smith, P. D., et al., "Seismic Safety Margin Research Program. Program Plan, Revision II," UCID-17824 Rev. II (1978). (Amended January 25, 1979).
4. W. H. Rowen, "Recent Advances in Failure Analysis by Statistical Techniques (FAST)" The Shock and Vibration Bulletin Part 2, September 1977.
5. "Failure Analysis by Statistical Techniques (FAST) Vol. 1, User's Manual," DNA 3336F-1, TRW Systems Group, prepared for Defense Nuclear Agency, October 31, 1974.
6. "Seismic Evaluation for Postulated 7.5M Hosgri Earthquake," Units 1 and 2, Diablo Canyon Site, PG&E, Amendment 52, USNRC Docket Nos. 50-275 and 50-323.
7. D. L. Anderson, R. G. Charlwood, and L. B. Chapman, "On Seismic Risk Analysis of Nuclear Plants Safety Systems," Canadian Journal of Engineering, 2, 558 (1975).
8. T. M. Hsieh and D. Okrent, "Some Probabilistic Aspects of the Seismic Risk of Nuclear Reactors," UCLA-ENG-76113, UCLA School of Engineering, Los Angeles, December 1976.

9. R. V. Whitman, J. M. Biggs, J. E. Brennan III, C. A. Cornell, R. L. De Neufville, and E. H. Vanmarke. "Seismic Design Decision Analysis." *Journal of the Structural Division, ASCE*, 1975.
10. J. D. Collins, "Hardened System Vulnerability Analysis," *The Shock and Vibration Bulletin*, Part 1, September 1977.
11. EMR Earthquake Probability Analysis, Seismology Division, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 1969.
12. Willie, R. R., "Computer-Aided Fault Tree Analysis," Operations Research Center Report 78-14, University of California; Berkeley (1978).
13. Worrell, R. B., "Using the Set Equation Transformation System in Fault Tree Analysis," SAND 74-0240 (1974).
14. Olmos, J. and L. Wolf, "A Modular Approach to Fault Tree and Responsibility Analysis," MITNE-209 (1977).
15. Apostolakis, G. E., et al, "CAT: A Computer Code for the Automated Construction of Fault Trees," EPRI Report NP-705 (1978).
16. Gately, W. Y. and R. L. Williams, "GO Methodology - System Reliability Assessment and Computer Code Manual," EPRI Report NP-766 (1978).
17. Kempthorne, O. The Design and Analysis of Experiments. New York: John Wiley and Sons, Inc. (1952).

18. Box, G. E. P., and J. S. Hunter, Multifactor Experimental Designs for Exploring Response Surfaces. Annals of Mathematical Statistics, 28. (1957).
19. McKay, M. D., W. J. Conover, and R. J. Beckman, A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. To appear in Technometrics. (1979).
20. Hogg, R. V., and Craig, A. T. Introduction to Mathematical Statistics, Fourth Edition. New York: The MacMillan Company. (1978).
21. Iman, R. L., J. C. Helton, and J. E. Campbell. "Risk Methodology for Geologic Disposal of Radioactive Waste: Sensitivity Analysis Techniques," SAND 78-0912. (1978).

APPENDIX A

Definitions

1. Random Variation, Model Uncertainty, and Probability Uncertainty Bands

Consider a system in which there are k independent variables, $X_1, X_2, \dots, X_k$, and a single dependent variable, Z . Further assume that Z is a known function, f , of the k variables, i.e.,

$$Z = f(X_1, X_2, \dots, X_k).$$

Thus, for a given vector $(x_1, x_2, \dots, x_k)$, there is unique Z .

Suppose that the values of the x_i 's of the vector are each selected from a probability density function, $g_i(x_i)$. The variation in the dependent variable due to the influence of the independent densities, is called random variation. (Note that X_1 might be pressure loading, $g_1(x_1)$ might determine the probability of a given pressure loading, and z might be a structural response).

If the density functions, $g_i(x_i)$ are not known, then there might be several alternative sets of probability density functions, say, $h_i(x_i)$, $m_i(x_i)$, etc., used to select the x_i 's. The resulting band of probabilities on the dependent variable, z , is called the probability uncertainty band (PUB). For example, $g_1(x_1)$ might be a normal distribution and $h_1(x_1)$ might be a gamma distribution or uniform distribution.

Finally, assume that the function, f , is also subject to some uncertainty. Other functions such as F , G , and H might be used to generate the dependent variable, Z . The variation in the dependent variable due to the different functions is called the model uncertainty or model variation.

2. Random Variable

Consider an experiment in which the set of all possible outcomes may be described prior to the performance of the experiment, such as the rolling of a die. Experiments of this type, which may be repeated under the same conditions, are called random experiments; and the set A of all outcomes is called the experimental or sample space. A real-valued function X defined on the sample space of the random experiment is called a random variable.

3. Failure A (Crack in Steel)

Monolithic steel components used in nuclear plants such as piping elbows or pressure vessel nozzles can be said to incur a special type of failure when a defect or crack is present which exceeds an acceptable size. The acceptable size differs for different components and for the purposes of the SSMRP study, the acceptable size will be considered that size for which the intent of ASME Section XI is deemed acceptable. This implies that the component is fully capable of performing its primary stress (primary stress per ASME III) structural function if no defect is present greater than the acceptable size.

4. Failure B (Detectable Leak)

Parts of the reactor coolant pressure boundary can be said to incur a special type of failure when a leak of detectable size is present. The detectable size depends upon the plant leak detection system to discriminate between normal background leakage due to packings and seals and a leaking crack in the coolant pressure boundary. The presence of a leaking type failure implies that the structural component involved may have an uncertain lifetime before a Failure C (rupture) may occur and therefore the presence of a Failure B (Detectable Leak) requires plant shut down and repair of the failure.

5. Failure C (Rupture)

Any component which experiences failure due to fracture of a load carrying member is said to be a Failure C. The LOCA event used in plant design is an example of Failure C in a piping component.

6. Failure D (Crack in Concrete)

Reinforced concrete structural components are designed as a composite element so that the concrete is utilized mainly in compression stress while the reinforcing steel is utilized mainly in tension. A preliminary failure stage wherein the concrete material cracks but the reinforcing steel has not grossly yielded is said to be a Failure D. A Failure D does not imply Failure E (collapse).

7. Failure E (Collapse)

Any component (steel or reinforced concrete) is said to collapse when excessive distortion occurs which destroys its primary stress structural capability. This term is used in SSMRP to imply a complete failure of the component as opposed to an insipient Failure A, B, D, or at the plastic limit load. It may be used to indicate incremental type collapse associated with repeated dynamic loads or single loading collapse.

8. Failure F (Induced)

Any component or structure of a nuclear plant can experience, rupture, collapse, loss of functionality due to failure of other components or structures. For example, if the reactor vessel support were to experience rupture or collapse at some seismic loading level, then all piping system components which are connected to the reactor vessel may experience conditions which are likely

to induce their failure. Similarly if a valve support component were to fail, the valve itself may be considered to have failed and this constitutes an indirect failure mode for the valve where this loading condition would not normally be included.

All failures which result in Failure C, Failure E, loss of operability or loss of functionality due to indirect conditions are called Failure F.

9. Plastic Limit Load

This term is an ideal mathematical expression to define the point where a structure made of rigid perfectly plastic material loses its ability to carry additional primary load. The plastic limit load always occurs at a loading which is less than the single loading collapse, Failure E.

10. Operability

Active components such as valves, motors, diesels, electronic equipment, etc. are components which must perform a mechanical or electrical function as part of the nuclear safety system. They can experience a failure mode where the active operation becomes impaired. Such components are said to experience operability failure. Such failure modes are best determined by actual test or a shaker table, but often it is necessary to use analysis and test results to predict such failures.

11. Functional Failure

Passive structural components have some system related functional requirements which may be impaired by excessive deformation of the component. For example, the pipe loop deformations become so large that flow capability for the pipe loop would be impaired,

the piping system would be said to experience functional failure. This term has been defined by NRC licensing requirements and is a failure mode different from Induced in that no other component failure is necessarily involved.

Functional failure can also occur when a system operates but does not perform its intended function due to some unexpected phenomena (e.g., excessive core bypass flow). The Reactor Safety Study acknowledged this possibility for ECCS by including a probability for such non-functioning in its large LOCA event trees.

12. Fragility

Fragility as used in SSMRP means a probabilistic distribution function or set of functions to quantitatively describe the uncertainty concerning loading parameters on structures or components at which any of the following five types of failure may occur, 1) Failure C, 2) Failure E, 3) Loss of operability, 4) loss of functionality, and 5) Failure F. Fragility here implies the summation of failure probability due to all five of these exhaustive failure modes.

13. Simultaneous Loading

Simultaneous loading means that static or slowly varying loads occur at the same time on a component or structure and that dynamic loadings (rapidly varying) are occurring with a finite and possibly uncertain degree of time phasing overlap.

14. Seismically-independent Failure Rates

Seismically-independent failure rates apply to events whose probabilities are independent of the seismic input. Examples include prior operator error (e.g., a manual valve not re-opened after an earlier surveillance test) and test/maintenance outages.

APPENDIX B

Detailed Description of Computational Modules

B.1 SEISMIC INPUT

B.1.1 Discussion

The seismic hazard at a site may be defined in terms of the peak accelerations, site dependent uniform risk response or Fourier spectrum⁽¹⁾ or by a stochastic process. The choice of peak acceleration as the measure of seismic hazard at a site implies the use of a constant shape site-independent response spectrum. It is well known, however, that response spectra for different sites differ widely in shape and therefore peak acceleration alone cannot be a satisfactory determinant of the ground motion. The use of a site-dependent uniform risk response spectrum eliminates this deficiency; however, the subsequent generation and use of a spectrum-consistent time history introduces uncertainties for which a proper accounting is difficult. This difficulty is overcome by the use of a uniform risk Fourier amplitude spectrum.

The site ground motions may be alternatively defined as a stochastic process. Considerable work has been done in the seismic structural area on the assumption that seismic disturbance can be modeled as a stationary process (power spectral density approach). This assumption may be adequate for structures which respond in modes of relatively higher frequencies but, for soil-structure interaction analysis, the assumption is certainly in error. Furthermore, the assumption of stationarity suffers from another drawback in that the peak response of a highly damped structure becomes unrealistically large unless corrections for finiteness of duration are introduced. On the other hand, a non-stationary stochastic model of the ground motion could eliminate the difficulties encountered in processing stationary inputs, however, the complexities in developing and using such a model render it useless except for very simple systems.

Because of the aforementioned reasons, the use of a Fourier amplitude spectrum to model ground motion will be proposed here. This does not, however, preclude the use of a stationary stochastic model for ground motion in the proposed computational scheme.

It should be noted here that the ground motion is not completely specified by a Fourier amplitude spectrum but has to be supplemented by the phase spectrum. For reasons described in detail in Appendix C, it is proposed that the phase spectrum of any quantity (ground motion or any response quantity) be independently developed only when it is required to invert the Fourier spectrum to obtain a time history. This procedure is also outlined in Appendix C.

B.1.2 Seismic Input Generation

The essential components in the quantification of seismic hazard defined by the Fourier amplitude spectrum are:

- 1) Magnitude-exceedance relation
- 2) Spatial distribution of epicenters and site-source geometry
- 3) Attenuation law

The procedure suggested here is similar to the one described by Cornell⁽²⁾, however, considerable sophistication can be built in to account for modeling and random uncertainties in the procedure. A schematic diagram illustrating the procedure is shown in Figure 5.1.

B.1.2.1 Magnitude-exceedance Relation

The relationship between magnitude and the number of earthquakes exceeding it generally follows the Richter relationship⁽³⁾, namely

$$\ln N_m = a - bm \quad m_0 < m < m_c \quad (1)$$

in which N_m is the number of earthquakes exceeding magnitude m per unit time (e.g., a year); a and b are source-dependent parameters that determine the frequency and distribution of different magnitude earthquakes; m_c is the largest possible magnitude and m_0 is the smallest magnitude of significance from the viewpoint of seismic hazard evaluation. Relationship between N_m and m is shown graphically in Figure B.1.

The relationship (1) not only defines the total number of earthquake events (v) between magnitudes m_0 and m_c occurring per unit time but also the distribution of magnitude, which are obtained as

$$v = \{ \exp(-bm_0) - \exp(-bm_c) \} \exp(a) \quad (2)$$

$$p(m) = \frac{be^{-bm}}{e^{-bm_0} - e^{-bm_c}} \quad (3)$$

in which $p(m)$ is the probability density function of magnitudes; equation (3) is illustrated in Figure B.2. Thus the randomness associated with earthquake events at the source is built into the relationships (2) and (3). The modeling uncertainties are, however, determined by the degree of confidence in the values of the parameter b for which upper and lower limit values may be appropriately specified. Parameter a affects the frequency of earthquakes at the site as is evident from equation (2).

It may be noted here that even though magnitude is not a good source parameter from the viewpoint of quantifying seismic hazard, the use of alternate source parameters such as stress drop, rupture length, dislocation, etc. (which may be more appropriate from a seismological viewpoint) increases the complexities of the analysis by introducing additional uncertainties, the net effect of which may not be any real increase in accuracy.

FIGURE B.1 EARTHQUAKE FREQUENCY VS. MAGNITUDE

FIGURE B.2 PROBABILITY DESCRIPTION OF EARTHQUAKE MAGNITUDES

B.1.2.2 Spatial Distribution of Epicenters

The seismic hazard will not only depend on the frequency and magnitude of the causative events, but also the manner in which these events are distributed in the vicinity of the site. If the earthquakes can be associated with a well-defined fault structure, these may be assumed to be distributed on the fault in accordance with an appropriate distribution that can be estimated from the fault geology⁽⁴⁾ or from an observed pattern of fault activity. In the absence of any useful data, the spatial distribution may be assumed to be uniform.

For the situations where no well-defined fault structures exist, the seismic events may be randomly distributed over an area in which these events are expected to occur. Together with the description of the site-source geometry, this will then result in the probability density function $p(r)$ of the distance r of the source from the site.

A typical density function $p(r)$ for earthquakes originating from a fault is shown in Figure B.3. The discontinuity in $p(r)$ occurs when r equals the distance of the site to the end of the fault closest to it.

B.1.2.3 Attenuation Law

For a given magnitude earthquake that is postulated to occur at a specified location, the seismic hazard at the site is generally obtained from an attenuation law of the type⁽⁵⁾

$$\ln Z = A + Bm + C \ln (r + r_0) \quad (4)$$

in which Z is the quantity defining seismic hazard, A , B , C , r_0 are parameters that account for the effect of geometric spreading of the waves and the energy dissipation in the intervening soil medium.

Alternatively an attenuation law of the type used in Ref. 1 may be employed. In the current application, Z is the Fourier amplitude at a given frequency and is obtained from actual earthquake records. Constants A , B , C and r_0 are obtained from fitting equation (4) to the observed

FIGURE B.3 PROBABILITY DISTRIBUTION OF EPICENTRAL DISTANCE

data. For a given value of m and r , the observed data generally show a wide scatter around the value of Z computed from equation (4) as shown in Figure B.4. Therefore, the value of Z in equation (4) is identified by Z_c to distinguish it from the observed value of Z which can only be defined in a probabilistic sense by assigning to it a probability distribution with Z_c as one of its parameters. For example, Z might be assumed to be lognormally distributed around Z_c as follows

$$p(Z|m,r) = \frac{1}{\sigma Z \sqrt{2\pi}} \exp \left\{ -1/2 \left(\frac{\ln Z/Z_c}{\sigma} \right)^2 \right\} \quad (5)$$

where it is assumed that $\ln Z_c$ is the expected value of $\ln Z$ and σ is the standard deviation of $\ln Z$. This is illustrated in Figure B.5. The modeling uncertainty is again defined by the variation of parameters A , B , C , r_0 and σ in equations (4) and (5). The parameters A , B , C , and r_0 in equation (4) are dependent on the frequency ω of the ground motion and so are the values of σ , Z_c and the site response Z .

Combining equation (5) with equation (4) and the probability density function for r , the unconditional density for Z may be obtained from

$$p(Z) = \int_{r_0}^{r_c} \int_{m_0}^{m_c} p(Z|m,r) p(m) p(r) dm dr \quad (6)$$

here r_0 and r_c denote the lower and upper bounds on r . Equation (6) then defines the seismic hazard in terms of the ground motion spectrum at the site. A cumulative non-exceedance probability for Z (for each frequency ω may be obtained from

$$q(Z) = \int_0^Z p(u) du \quad (7)$$

This procedure is repeated for each frequency. A uniform risk spectrum is then defined as that Fourier amplitude spectrum for which the ordinates $Z(\omega)$ will have the same probability of exceedance (or non-exceedance). With each spectrum thus obtained is associated only one random variable. This, however, is not strictly correct, since each

FIGURE 8.4 ATTENUATION RELATIONSHIP

FIGURE B.5 CONDITION PROBABILITY OF ACCELERATION
FOURIER AMPLITUDES

ordinate of the Fourier amplitude spectrum is a random variable. Thus, if the spectrum is defined by 50 ordinates, the correct characterization of the spectrum requires that a joint probability density for 50 random variables be defined which would render the computation chain for the SSMRP impractical. However, by assuming that the Fourier amplitude spectrum does not significantly vary in shape for similar earthquake events, the 50-random variable may be assumed to be fully dependent and can be represented by one random variable.

The one random variable which completely characterizes the ground motion may be selected in a variety of ways; however, the one proposed here will measure the total earthquake energy and will be denoted by Z_f . Mathematically Z_f is expressed as follows

$$Z_f = \int_0^{\infty} (Z_{H_1}^2 + Z_{H_2}^2 + Z_V^2) d\omega \quad (8)$$

in which Z_{H_1} , Z_{H_2} , Z_V are the frequency-dependent Fourier amplitudes at one exceedance (or non-exceedance) level. The same exceedance (or non-exceedance) level is then associated with Z_f . A cumulative exceedance probability plot for Z_f is shown in Figure 8.6.

The definition of the two horizontal directions for the purpose of this analysis will depend on the type of soil-structure interaction (SSI) analysis performed. For a two-dimensional SSI analysis, it is recommended that the two horizontal earthquake components be treated as identical; thus an analysis of the Fourier spectrum will treat both the recorded and derived orthogonal components of motion as belonging to one set and there will be no discrimination between two earthquakes originating from two different azimuthal angles with respect to the site.

For a three-dimensional SSI it is important to preserve the information on the azimuth angle and therefore the distinction between two horizontal components of ground motion. For this purpose, the two horizontal directions will be defined as the one along the line connecting source

FIGURE B.6 EXCEEDANCE PROBABILITY OF
FREE-FIELD ACCELERATION

to the site and the one orthogonal to it. These two directions are not fixed but will vary with the location of the earthquake epicenter. In this case, therefore, three independent spectra will be specified to define the ground motion.

B.1.3 Random and Modeling Uncertainty

The random uncertainties in the seismic input are incorporated in the analysis by the procedure already described. These uncertainties are included in the magnitude-exceedance relationship (eq. (1), (2) and (3)), in the spatial distribution of epicenters described by the probability density functions $p(r)$ of the site-source distance, $p(\theta)$ of the azimuth angle, $p(v)$ of apparent wave speed v and, lastly, by the conditional PDF $p(Z|m, r)$ (eq. (5)) of the Fourier amplitude of the site motion.

The modeling uncertainty is specified only for Z_f which is the only variable characterizing the intensity of site ground motion. The modeling uncertainty in Z_f results from the uncertainty in the parameters identified earlier, i.e., a , b , A , B , C , r_0 , σ and possibly other parameters describing PDF's of θ and r .

The modeling uncertainty bands on Z_f are obtained by repeating the preceding analysis for new sets of values of these parameters and determining thereby the variation in Z_f for a given level of exceedance (or non-exceedance) probability. The extremes of these variations then represents the modeling uncertainty band of Z_f . These are shown by dotted lines in Figure B.6.

B.1.5 Summary

The random variable defining the seismic input is characterized by Z_f which is a measure of the energy and is defined in equation (8). Modeling uncertainty bands on Z_f are obtained by reprocessing the inputs for different values of parameters identified earlier. For each value of Z_f , Fourier amplitude spectra of the different components of ground acceleration are available for later use.

B.2 SOIL-STRUCTURE INTERACTION

B.2.1 Discussion

The finite element procedures currently in use for soil-structure interaction analyses employ two-dimensional quasi-linear models to account for the non-linear soil behavior. Furthermore, the current SSI methodology is based on the assumption that the seismic disturbance can be represented by vertically propagating waves, an assumption which is more often than not dictated primarily by convenience rather than by an accurate representation of the phenomenon. A three-dimensional non-linear analysis taking account of the direction and speed of the seismic wave is certainly superior to any two- or three-dimensional quasi-linear analysis but is beyond the state-of-the-art. A three-dimensional quasi-linear analysis can, however, be implemented, but the cost may be an inhibiting factor. The modeling uncertainties in such an analysis result primarily from the approximation of a non-linear behavior by a quasi-linear one.

The chief advantage of a two-dimensional quasi-linear analysis is its economy of computation and, for symmetric structures, the loss of accuracy may not be significant. However, the three-dimensional effects, the effects of azimuth angle and wave speed will generally be lost.

B.2.2 SSI Analysis

The SSI analysis will be performed for each level of the free-field variable Z_f . Given a value of Z_f , the Fourier amplitude spectra of the three components of ground motion are selected and inverted to obtain three input acceleration time-histories. The random variables (e.g., soil properties) are now sampled and an SSI analysis is performed and the Fourier amplitude spectra of the six base mat acceleration histories are obtained. When a sufficient number of Monte Carlo trials have been processed, an ensemble of Fourier amplitude spectra for each component

of the base mat motion are obtained. This ensemble is then processed to determine the probability levels for the base mat motions. The base-mat motions will be obtained along a fixed set of axes decided by the plant geometry.

The phase angle spectra for the input motion to be used in the SSI analysis can be arbitrary since in a quasi-linear SSI analysis, the soil properties for a given level of excitation are based on the root-mean-square value, which is not at all affected by the choice of the phase angle spectrum⁽⁶⁾. Thus, to obtain the Fourier amplitude spectrum of the base mat motions, it is not necessary to know the phase angle spectrum.

B.2.2.1 Two-dimensional Analysis

For a two-dimensional SSI analysis, only 5 base mat motions will be generated, since rotation about the vertical axis cannot be included in a two-dimensional model. Also, for a two-dimensional analysis, three vertical motions will be obtained for a single causative earthquake however, since the predominant vertical base mat motion results from the vertical earthquake, the three vertical motions may be combined by square-root-of-the-sum-of-the-squares without significant error. In summary, a two-dimensional SSI analysis will result in 5 components of base mat motion, the sixth being zero.

The base mat motions will be characterized by a single random variable Z_b in a manner similar to the characterization of the free-field motion. For each value of Z_f , this random variable will have a different distribution; in other words Z_f and Z_b are jointly distributed. Focussing attention on one value of Z_f , the two-dimensional SSI analysis will lead to 5 sets of Fourier amplitude spectra for 5 base mat motions. Each set will be analyzed for each frequency independently and the probability distribution for each Fourier amplitude ordinate will be obtained. A Fourier amplitude spectrum corresponding to a given probability level will then be obtained such that, at each frequency, the

ordinate of the curve has the same associated probability. For example, a Fourier amplitude spectrum that has an exceedance probability of 0.5 will be one for which each of its ordinates has an exceedance probability of 0.5. For each component of base mat motion, Fourier amplitude spectra corresponding to different probability levels will then be obtained. The random variable Z_b can then be defined as the "energy" associated with three translational components of motion. Note again that Z_b has many alternate representations and is essentially a convenient identifier for selecting a set of 5 Fourier amplitude spectra at a given probability level.

B.2.2.2 Three-dimensional Analysis

A three-dimensional SSI analysis will provide a sixth base mat motion. However, the randomness in the base-mat motions obtained from the three-dimensional SSI analysis cannot properly be represented by one random variable Z_b as proposed for the two-dimensional SSI analysis. In a two-dimensional analysis, the effect of the azimuth angle θ is reflected satisfactorily in the base mat motions in an average sense; however, this may not be appropriate for a three-dimensional analysis.

In the two-dimensional SSI analysis, the two horizontal components of input motion have identical Fourier amplitude spectrum and act along fixed directions, the resulting horizontal base mat motions are thus highly correlated in that the increasing intensity of free-field motion will result in simultaneous increase in the intensity of both horizontal components of base mat motion. Thus, associating one horizontal component of base mat motion at a probability level p with the orthogonal component of base mat motion at the same probability level p in a deterministic manner will, in a reasonable way, reflect this correlation. This is, however, not the case in a three-dimensional SSI analysis where the presence of the random variable θ destroys this correlation. This is illustrated by Figure B.7 in which a source A will induce a high y-acceleration component and a low x-acceleration component at the site, whereas a source located at B would have exactly opposite effect.

FIGURE 8.7 EFFECT OF EPICENTER LOCATION ON
HORIZONTAL COMPONENTS OF BASE MAT MOTION

The effect of θ in three-dimensional SSI analysis will, therefore, be included by characterizing base mat motion by two random variables, Z_x and Z_y , in which Z_x will measure the "energy" associated with horizontal components of base mat acceleration along x direction and Z_y measures the "energy" associated with the horizontal component along y direction. Note that $Z_x + Z_y$ is invariant with coordinate frame transformation in the horizontal plane.

Let the Fourier amplitude spectra of the six base mat motions be $f_x(\omega)$, $f_y(\omega)$, $f_z(\omega)$, $f_{xx}(\omega)$, $f_{yy}(\omega)$, $f_{zz}(\omega)$, in which subscripts x and y define two horizontal translational directions, z represents translation along vertical axis and xx, yy, and zz define rotational components along X, Y, and Z axes. For each ω , $f_x(\omega)$, $f_y(\omega)$, ... $f_{zz}(\omega)$ represent six random variables. Given an ensemble of $f(\omega)$ curves for each component of base mat motion, the probability distribution of each $f(\omega)$ for each value of ω can be estimated. The Fourier amplitude spectrum $g(\omega)$ with an exceedance probability p is then defined by

$$\text{Prob. } [f(\omega) > g(\omega)] = p \quad \text{for each } \omega \quad (9)$$

Note that $g(\omega)$ may not be identical to any $f(\omega)$ in the ensemble. Curves $g(\omega)$ corresponding to different p levels can thus be obtained for all six components of motion.

To represent the complete set of spectra by as few random variables as possible, define Z_x , Z_y , and Z_H as follows

$$Z_x = \int_0^{\infty} f_x^2(\omega) d\omega \quad (10)$$

$$Z_y = \int_0^{\infty} f_y^2(\omega) d\omega \quad (11)$$

$$\text{and } Z_H = Z_x + Z_y \quad (12)$$

Of these three random variables only two need to be known, the third variable is then completely defined. The exceedance probability values for all the three random variables thus defined can be determined by analyzing the set of values for each obtained from the SSI analysis for a fixed Z_f (free-field acceleration variable) level. The selection of a set of base mat Fourier amplitude spectra $g(\omega)$ can now be made as follows.

Randomly select values of Z_x and Z_y . Set the probability levels associated with each p_x and p_y respectively. Obtain Z_H from equation (12) and let the associated probability level be p_H , then the Fourier amplitude spectra are selected such that $g_x(\omega)$ and $g_{yy}(\omega)$ are at probability level p_x , $g_y(\omega)$ and $g_{xx}(\omega)$ are at probability level p_y and $g_z(\omega)$ and $g_{zz}(\omega)$ are at probability level p_H .

B.2.4 Random and Modeling Uncertainties

The random uncertainties in the SSI analysis are due to the random variation of soil properties (e.g., shear modulus, Poisson's ratio, damping, etc.), the soil layering, depth of water table, etc. For a three-dimensional analysis, in addition, the random uncertainties result from the epicenter location, denoted by angle θ and the apparent wave speed v . The distributions of these variables will be developed externally and input to the SSI analysis module.

For each value of Z_f of free-field ground motion random variables Z_x , Z_y , and Z_H and the associated Fourier amplitude spectra $g(\omega)$ will thus characterize the base mat motion. The preceding analysis can be repeated for different values of Z_f to obtain a complete range of base mat motions including all the random uncertainties.

The modeling uncertainties resulting from non-linearities, base mat flexibilities and three-dimensional and wave propagation effects for a

two-dimensional SSI analysis will be incorporated into the random variables Z_x and Z_y or Z_b by performing a comparative analysis that will assess the variations in these variables. The inclusion of uncertainty due to non-linearities is a very difficult task. Considerable judgment will have to be exercised in determining the effect of nonlinearities. Partial reliance can be placed on simple analyses, for example, shear wave propagation in a nonlinear soil column; however, such analyses will only serve as guides for engineering judgment.

The modeling uncertainty in two-dimensional SSI due to three-dimensional effects can best be determined by performing comparative analysis for the same level of free-field motion and then by judgment extrapolated to other possible states.

B.2.4 Summary

The output from this module is the base-mat motions. For a two-dimensional SSI analysis, the base-mat motion is characterized by a single random variable Z_b to each value of which is associated five base-mat Fourier amplitude spectra corresponding to five components of base-mat motions. If a three-dimensional SSI analysis is performed, the base-mat motion is identified by two independent random variables Z_x and Z_y . Each Z_x defines two components of base-mat motion in terms of their Fourier amplitude spectra, each Z_y similarly defines two other components of motion. The remaining two components of base-mat motion are defined by the sum $Z_x + Z_y$.

B.3 TRANSFER FUNCTIONS

B.3.1 Transfer Functions for Building Response

B.3.1.1 Discussion

The structural building response is one of the more straightforward portions of the SSMRP program in that well-developed finite element

computer programs are available for translating the base mat motions into various structural responses of the major portion of the nuclear structure.

The structural analytical models are completely defined by mass, stiffness, and damping properties of the structural components. Of these, the first two are well-defined and little uncertainty, if any, exist about their values. The structure damping, however, is not only poorly defined, but the manner in which it is incorporated into the analysis is unsatisfactory, since it is primarily dictated by convenience. In this regard, the direct integration method of dynamic response analysis is inferior to modal superposition method since in the former the damping treatment (Rayleigh damping) is exclusively governed by computational convenience. In the mode -superposition method the modal damping is computed by weighting component damping by a procedure that seems intuitively appealing but which lacks a rational basis.

An improvement in the treatment of damping within the integration procedure could be accomplished by assembling component damping in a manner similar to the assembly of the stiffness matrix. Since a normal mode analysis would not be possible in this case, the equations of motion will have to be solved by a direct integration procedure. The implementation of such a procedure would involve some code development, since the presently available structural analysis codes do not possess such a capability. However, the large uncertainty in the structure or component damping values may reduce the utility of such a sophistication.

B.3.1.2 Evaluation of Transfer Functions

For a linear building model, the transfer functions for each vibration mode of base-mat motion can be obtained by a single analysis in which time histories of all response quantities of interest (e.g., stress, floor accelerations etc.) are obtained by exciting the base-mat

by an arbitrary time history in the vibration mode under consideration. Thus, if $x(t)$ is the time history of base-mat accelerations in its j th mode of oscillation and $y(t)$ is the k th response time history at some point in the structure, the transfer function $H_{jk}(\omega)$ is then obtained as

$$H_{jk}(\omega) = \frac{|\bar{y}(t)|}{|\bar{x}(t)|} \quad (13)$$

in which the bar over a time function denotes its Fourier transform and ω is the frequency of oscillation.

It is evident from equation (13) that for $H(\omega)$ to be defined for a wide frequency range, the Fourier transform $\bar{x}(t)$ must not be zero in this range. Thus, $x(t)$ must be selected as a wide band acceleration time-history. This is the only limitation on $x(t)$; all choices of $x(t)$ satisfying this restriction will yield the same transfer function.

The evaluation of $H(\omega)$ for linear systems can be performed either by modal superposition technique or by direct integration of equations of motion. In the former procedure the response is expressed in terms of normal modes which are obtained from the free vibration analysis of the undamped structural system. If the response $y(t)$ of a point in the structure is of interest, it can be shown that in general

$$\bar{y}(t) = \sum_{j=1}^N \frac{a_j \omega^2 + i b_j \omega + c_j}{(\omega^2 - p_j^2) + 2\omega p_j \xi_j i} * \bar{x}(t) \quad (14)$$

in which $i = \sqrt{-1}$,

p_j 's are the structure natural frequencies and ξ_j 's the associated damping values; a_j , b_j and c_j are coefficients which are functions of the structure stiffness and mass properties and the mode shapes and depend on the nature of the response quantity (e.g., acceleration,

displacement, stress etc.); N is the number of modes included in the analysis and $x(t)$ is the time history of base-mat excitation. The amplitude $H(\omega)$ of the transfer function is thus given by

$$H(\omega) = \sum_{j=1}^N \left| \frac{a_j \omega^2 + i b_j \omega + c_j}{(\omega^2 - p_j^2) + 2i p_j \xi_j} \right| \quad (15)$$

If ξ_j 's are small, it is obvious from equation (3) that $H(\omega)$ will be sharply peaked for $\omega = p_j$ ($j = 1, 2, \dots$). For well-separated natural frequencies, $H(p_k)$ may be obtained by ignoring terms for which $j \neq k$; thus

$$\begin{aligned} H(p_k) &= \left| \frac{a_k p_k^2 + i b_k p_k + c_k}{2p_k^2 \xi_k i} \right| \\ &= \frac{1}{2p_k^2 \xi_k} [(a_k p_k^2 + c_k)^2 + b_k^2 p_k^2] \end{aligned} \quad (16)$$

B.3.1.3 Random Uncertainties

The random uncertainties in structural analyses are small and result from uncertainties in the material properties particularly stiffness and damping. The random uncertainty in the latter should be distinguished from its modeling uncertainty, which is essentially a result of non-linear behavior and energy dissipation by a hysteretic mechanism.

Since random uncertainties are small and do not depend on the level of excitation and do not affect other random uncertainties in the system model of a nuclear plant, they can be incorporated in the analysis by using the expected value of $H(\omega)$. This can be achieved in an approximate way via equation (16). Thus, if the random uncertainties exist in the

material elastic properties, small perturbations in the stiffness can be transformed into perturbations in the modal vectors⁽⁷⁾ and the natural frequencies. Together with uncertainty in damping values, if any, these can be incorporated in equation (16) to yield random uncertainty in $H(p_k)$ and thus its expected value $E[H(p_k)]$ can be determined.

If the change from $H(p_k)$ to $E[H(p_k)]$ is denoted by a scale factor S_k on $H(p_k)$, then $H(\omega)$ may be approximately written as

$$H(\omega) = \left| \sum_{j=1}^N \frac{\bar{a}_j \omega^2 + i \bar{b}_j \omega + \bar{c}_j}{(\omega^2 - \bar{p}_j^2) + 2\omega \bar{p}_j \bar{c}_j i} \cdot \bar{S}_j \right| \quad (17)$$

where bars over symbols represent their expected values, and

$$\bar{S}_j = S_j H(p_j) / H(\bar{p}_j) \quad (18)$$

The random uncertainties in material properties also introduce random uncertainties in the phase angle shifts associated with transfer functions; however, as discussed in Appendix C the inclusion of phase angles may be postponed in the analysis to a later stage where these are required for inversion of Fourier transforms. The uncertainty in phase angles can be incorporated at that stage.

B.3.1.4 Modeling Uncertainty

The major contribution to modeling uncertainty results from non-linear structure behavior under highly loaded conditions. This behavior accounts for not only the degradation in the elastic properties of the structure but also in the increased damping due to hysteretic energy loss. Though non-linear computer codes are available, their limitation lies principally in the large amounts of computer time needed for their execution. Nonlinear effects and the associated increase in damping may be incorporated in the transfer functions as modeling uncertainties on the linear analysis results. This may be achieved by performing a comparative nonlinear analysis on a simplified model and determining the extent of variation in the linear model results.

The quantification of the modeling uncertainty for transfer functions will be achieved by introducing two random variables K_ω and K_a , the former of which identifies the magnitude of frequency shift and the latter identifies the amplitude scaling. Thus, if K_ω and K_a are such that a frequency shift of 0.8 and amplification of 1.1 is implied the corresponding transfer functions $H'(\omega)$ is related to $H(\omega)$ by

$$H'(\omega) = 1.1 H(\omega/0.8) \quad (19)$$

This is graphically illustrated in Figure 5.4. It should be emphasized here that one K_ω and one K_a describe frequency and amplitude scaling for all transfer functions, though the scaling factors could be different for different transfer function. Thus, the modeling uncertainty in all the transfer functions is represented by only two random variables. This is a considerable simplification over a more complex situation in which the variation on different transfer function may not be fully correlated. The assumption can be justified for the purpose of SSMRP since a nonlinear analysis introduces a unidirectional variation in all the natural frequencies and amplitudes of response, the net effect of which will be that the various response quantities on a structure will show high degree of correlation.

Another important point to note is that the maximum frequency shift and amplitude variation will be higher for higher level of Z_b , the base-mat motion. Thus, K_ω and K_a will determine different values of frequency and amplitude scale factors for different Z_b levels. The use of K_ω and K_a is illustrated by Table B.1 wherein 5 levels have been assigned to K_ω and K_a each. Each selection of K_ω and K_a determines uniquely the scale factors for different transfer functions (2 assumed for illustration) at different base-mat motion levels.

B.3.2 Transfer Function for Component Response

B.3.2.1 Discussion

Considering the large numbers of components for which transfer functions will be required in the MPS program, an elaborate dynamic

analysis which is currently performed to qualify the components will be outside the realm of SSMRP phase I program because of its high cost. An estimate of the component transfer functions has thus to rely on the existing analyses results for the Zion plant.

Where response spectra are available for the excitation and the response of a component or subsystem, the amplitude of the transfer functions can be obtained from a comparison of the input and output velocity response spectra by dividing the latter by the former. This gives a reasonably good approximation of the transfer function because of the similarities of Fourier amplitude spectra and the velocity response spectra in the high frequency regions.

Heavy reliance, however, will have to be placed on a representative sample of components for which transfer functions will be developed by performing a time history analysis, and then extended to all the components of interest. This requires a considerable amount of engineering judgment. However, in case of any definitive indication of a component behavior, large modeling uncertainty bands will be assigned to the component transfer functions.

The determination and inclusion of random and modeling uncertainties as described in Section B.3.1, can be trivially extended to the case of components and subsystems. The major difference between the two stems from the balance between the judgment and accuracy, the former playing a lesser role in the building response than in the latter. At the same time, one expects to have more confidence in the transfer functions obtained for the building response than those obtained for the component response and correspondingly larger modeling uncertainty bands on the latter than on the former.

B.3.3 Summary

Transfer functions relating the building response to base mat motions and those relating the component response to building response are expressed

		BASE MAT MOTION INTENSITY		
		LOW	MODERATE	HIGH
TRANSFER FUNCTION	K_ω	FREQUENCY SCALE FACTORS		
1	1	0.90	0.80	0.60
	2	0.95	0.90	0.75
	3	1.00	1.00	0.90
	4	1.05	1.05	1.00
	5	1.10	1.10	1.10
2	1	0.80	0.75	0.60
	2	0.90	0.87	0.70
	3	1.00	1.00	0.85
	4	1.10	1.10	1.00
	5	1.20	1.25	1.25
TRANSFER FUNCTION	K_a	AMPLITUDE SCALE FACTOR		
1	1	0.95	0.90	0.75
	2	0.97	0.95	0.82
	3	1.00	1.00	0.90
	4	1.02	1.03	1.00
	5	1.05	1.07	1.10
2	1	0.75	0.65	0.50
	2	0.87	0.76	0.70
	3	1.00	0.88	0.85
	4	1.05	1.00	1.00
	5	1.10	1.12	1.15

K_ω = Identifier for Scale Factor on Frequency

K_a = Identifier for Scale Factor on Amplitude

(Levels 1 through 5 assigned to K_ω and K_a)

TABLE B.1 MODELING UNCERTAINTY SCALE FACTORS

by the ratios of Fourier amplitude spectra of the output to input. These functions are obtained by a time history analysis. The modeling uncertainty in the transfer functions is expressed by two independent scalars on Fourier amplitude and the frequency scale.

B.4 LOADING CATEGORIES CONSIDERED

B.4.1 Discussion

Each component of the nuclear system experiences combinations of static and dynamic loading which contribute to component response and component failure. There are four general categories of loading of interest to SSMRP as shown in Table B.2.

General Category	Static	Dynamic
Seismic	no	yes
Operating	yes	no
Transients	yes	yes
LOCA	yes	yes

Table B.2
General Categories of Loading for SSMRP
on a Typical Component/Structure

There are two further classifications of loading response which are commonly used in design calculations, primary loading and secondary loading. The primary seismic loading on a typical piping component would consist of that loading which results from inertia forces while the secondary loading is associated with anchor displacement induced stresses. It is important to make this distinction for the SSMRP program because the primary responses will be the main source for possible seismically induced failures and secondary loading will contribute mainly to failure under normal operating conditions. To simplify the load combination problem for phase 1 of SSMRP, only primary loading will be explicitly considered. All components designed to the ASME Section III code must identify the primary and secondary types of stresses which are present and hence these design calculations will be an excellent source for identifying loadings on components for SSMRP.

Table B.2 indicates that seismic loading is purely dynamic and that operating loads are purely static, while transient and LOCA loads may be both static and dynamic. There are some operating loads which actually are dynamic such as steady state vibration, but they are assumed to be negligible in this phase 1 SSMRP effort.

The ASME Section III code design calculations will be an excellent source to identify possible transient and LOCA responses which are important to the performance of each component of interest. Care would need to be taken to remove conservatism of the design calculation if possible so that these responses are not overestimated for SSMRP work.

The sources for induced loading of nuclear components are quite varied. For example a great deal of uncertainty surrounds the accurate computation of LOCA type responses because complex system transients involving fluid dynamics and mechanical dynamics are strongly a function of where a pipe breaks in the first place. Since pipes can break at many random locations, the LOCA loading on any typical component is very uncertain. The reason for including static loading as characteristic of the LOCA event concerns the fact that some LOCA loadings are quasi-static compared with seismic dynamic effects. A good example of such quasi-static loading would be containment pressurization which may follow a LOCA event.

The transient responses are better defined than the LOCA forces in general because the transient responses are generally caused by system operations which can be frequently observed during plant operation even without the occurrence of a seismic or LOCA event. They consist of such things as valve openings or closures, turbine trip, water hammer, etc. and they are usually well identified in the design calculations performed under ASME Section III stress analysis. The transient events of chief interest for SSMRP are those which have a high conditional probability of occurrence given that seismic loading occurs. In a BWR

system for example, a turbine trip is a transient event which would have a high degree of dependence on the seismic event.

The typical dynamic transient primary loadings on components can be identified by time history plots having a shorter time duration and often a different frequency characteristic from seismic response. There may be some difficulty in identifying the accurate time history details of such transient loadings from the design calculations for a plant because typical design calculations often make conservative estimations of such loading.

8.4.2 Random Uncertainty

The uncertainty associated with operating, transient and LOCA responses should be classed as random. For static loads a simple uncertainty multiplier is adequate to define this random variation where PDF's can be defined based on judgement and possible perturbation analysis. For dynamic operating, transient, or LOCA responses, two multipliers may be needed to characterize the random uncertainty. The first multiplier would apply to the amplitude of the time history and the second would apply a scaling factor to time. The uncertainty distribution on both of these factors could be based on judgment and selected deterministic analysis.

B.5 LOAD COMBINATION

B.5.1 Discussion

For a given level of seismic intensity represented by the random variable(s) Z_b , the dynamic and static loads on structures/components (S/C) are characterized as follows:

- a) Seismic load S - deterministic Fourier amplitude spectrum with random phase angles
- b) Operating load W - constant with time but of random amplitude
- c) Induced dynamic load I - time dependent with random amplitude and time scale multipliers
- d) Induced static load C - constant with time but of random amplitude

The failure governing load R on the S/C depends on the loads along different directions in the S/C. For example, the maximum stress at a point will, in general, be the function of six independent components of the stress tensor at the point. If these components of stress are denoted by R_i , ($i = 1, 2, \dots, n$), where n is the maximum number of components then symbolically,

$$R = f(R_1, R_2, \dots, R_n) \quad (20)$$

in which $f()$ signifies a transformation from the components of stress to a single value R that governs failure. To determine R then, one needs to first determine the individual load components R_i , each of which is obtainable in the form of a time history as follows

$$R_i(t) = S_i(t) + W_i + I_i(t) + C_i \quad (21)$$

where S_i , W_i , I_i and C_i define the i th component of the seismic, operating, induced dynamic and induced static load on the component. The random

uncertainty in $S_i(t)$ is derived from the uncertainty in the phase angles, that in $I_i(t)$ is accounted for by randomness in scale factors on amplitude, time scale and relative time shift with respect to $S_i(t)$, denoted here by K_{i1} , K_{i2} and τ_i respectively. Thus equation (21) can be recast as follows

$$R_i(t) = \frac{1}{\pi} \int_0^{\pi} \bar{S}_i(\omega) \cos(\omega t + \theta_i(\omega)) d\omega \\ + k_{i1} I_i(k_{i2}t - \tau_i) + WC_i \quad (22)$$

in which $I_i(t)$ now represents the central estimate of the induced dynamic load, $\bar{S}_i(\omega)$ is the deterministic Fourier amplitude spectrum of $S_i(t)$ and $\theta_i(\omega)$ its phase spectrum and WC_i is the static load random variable obtained by combining W_i and C_i . The randomness is $R_i(t)$ is derived from the randomness in $\theta_i(\omega)$, k_{i1} , k_{i2} , τ_i , and WC_i .

The load combination procedure for stage II, option 1 of the MPS calculation scheme is illustrated in Figure B.8. Steps 1 through 7 of the module in Figure B.8 read the necessary inputs for the computation. These inputs are developed externally to the MPS program and their sources are identified in Figure B.8 in the right hand column. The number of components of response n of equation (20) is assumed to be 3 in Figure B.8.

Step 8 through 11 in the Figure describes the Monte Carlo loop in which the various random variables identified in equation (22) are sampled and appropriately combined to result in the peak load on the structure or component. The first step of this loop, i.e., step 8 calculates the first term of equation (22) for all $i = 1, 2, 3$. Step 9 obtains k_{i1} , k_{i2} , and τ_i and calculates the modified induced dynamic load, i.e., second term of equation (22). The static loads are sampled in step 10. Finally in step 11 all the loads are combined for each of the 3 values of i as per equation (22) and the peak load on the structure or component evaluated by employing equation (20).

1. READ FAS of 5 components of base-mat acceleration.

← Base-Mat
FAS

2. READ 15 transfer functions relating 5 components of base-mat motion to 3 components of response

← Transfer
Functions

3. Identify scale factors from K_w and K_a values and modify transfer functions

4. READ complete ensemble of phase spectra

← Phase Spectrum
Library

5. READ 3 components of induced load

6. READ probability descriptions of static loads and that of induced dynamic load scale factors

← Induced and
Operating Loads

7. READ S/C fragility curve corresponding to FC level

← Fragility
Curves

BEGIN MONTE CARLO LOOP

8. Randomly select 15 phase spectra; obtain Fourier spectra of 3 components of response; invert and obtain 3 components of response time histories.
9. Randomly select scale factors for induced loads and time shift; modify induced load time history.
10. Randomly select static load for 3 response directions.

FIGURE B.8 LOAD COMBINATION MODULE DETAILS
(continued on next page)

11. Add seismic, induced dynamic, and static load; obtain one time history for each response direction; combine and obtain a single resultant time history; scan for peak S/C 'stress'.

END MONTE CARLO LOOP

12. Obtain distribution of peak S/C load
13. Calculate S/C failure probability. STORE

FIGURE B.8 LOAD COMBINATION MODULE DETAILS

Steps 8 through 11 are repeated for a sufficient number of Monte Carlo trials at the end of which a probability density function of peak S/C load R is obtained. This PDF is determined in Step 12 from an array of peak load values generated in earlier steps. The number of Monte Carlo trials needed for estimating the PDF for R may be large; therefore, it is proposed that the PDF be assumed to possess a known parametric representation (e.g., an extreme value distribution) and the Monte Carlo trials performed only to estimate the parameters of the PDF. This will result in considerable saving in the MPS since the Monte Carlo trials in the MPS have to be repeated for so many combinations of Z_f , Z_b , S/C etc.

Steps 8 through 11 in Figure B.8 describe a very general load combination procedure. The actual procedure will be much simpler, the degree of simplicity being affected primarily by the class of structure and component being investigated. In this sense the load combination procedure outlined in Figure B.8 will be designed to permit this flexibility and thereby reduce the computation cost.

Depending upon the computation scheme adopted in MPS (see Section 7), the PDF's of R for all S/C may be saved for later use. Alternatively the PDF's of R may be convolved with the corresponding fragilities to yield failure probabilities for S/C as shown in Step 13 which can then be saved and retrieved later for use in the system model.

The procedure outlined above is simplified for S/C which lead to Initiating Events. For this case the load combination ignores the last two terms in equation (22), since these correspond to induced loads resulting from Initiating Events. The Monte Carlo computation loops are simplified in these cases because of the elimination of Step 9 and modification to Step 11.

B.5.2 Inputs and Outputs

The inputs to this module are supplied by the auxiliary programs identified in Figure B.8 on the right hand side of all the variables supplied by the AP's τ_i may be selected to be independent of the structure or component analyzed.

The output from this module is the probability density function for each structure or component or the failure probability for each S/C depending upon the MPS calculation scheme adopted.

B.6 FRAGILITY CURVES

Fragility curves are the quantitative descriptions of component or structural failure probability as a function of a random variable which represents the generalized state of "stress" on the component or structure.

Fragility curves are cumulative distribution functions of random variables representing the combined load, stress or response that causes failure. One of the more convenient forms to express the equivalent combined response is to use the same parameters which are used in the component design codes, such as ASME Section III. The ASME Section III code recognizes complex states of mechanical stress as a tensor quantity at each point of a component, but defines a set of design equations so that the complex stress states can be expressed as a simple scalar quantity across any critical section of the component. For example, if a piping component is defined as a straight section of pipe between two girth welds, the twelve force resultants at the two ends plus the internal pressure loading produce a primary stress on the component which is evaluated by equation (23) of ASME Section III NB3652.

$$B_1 \frac{PD_0}{2t} + B_2 \frac{D_0}{2I} M_i \leq 1.5 S_m \quad (23)$$

where

P is internal pressure

M_i is $\sqrt{M_1^2 + M_2^2 + M_3^2}$ measured at either end

M_1, M_2, M_3 are or the orthogonal bending moments and torque at a cross section

B_1 and B_2 are stress indices and a function of component form such as straight pipe, elbow, tee, etc.

D_0, t, I are pipe dimensional quantities

S_m is the ASME III code allowable stress value

Equation (23) has combined loading inputs due to four quantities P, M_1, M_2, M_3 at each critical cross section. The quantities M_1, M_2, M_3 consist of weight plus dynamic seismic loadings which are functions of time. In the case of transient dynamic loading, such as seismic, M_1, M_2 and M_3 represent maximum or minimum peak responses as a function of time.

If all of the quantities in the left hand side of equation (23) are given at each end of a straight section of pipe, then the ratio of the largest left hand side to $1.5S_m$ is a single scalar quantity which represents an equivalent combined response for the component. This single scalar quantity is a convenient form to reduce the 13 generalized forces (12 force resultants plus pressure) which represents the combined primary stress due to pressure, weight and seismic dynamic loading. At some sufficiently high value of this ratio, >3 , the component will have a high probability of failure, therefore this ratio is a convenient random variable in which to express the component/structure fragility. Figure B.9 illustrates a fragility curve described in this way.

Figure B.9

Fragility Curve For Pipe Component
Under Combined Load

The curve illustrates a range of primary loading values which can be applied to the component and shows quantitatively how the failure probability increases with increased combined loading. At high values of $R \geq 3$, the shape of the curve can be determined best by a series of tests on identical components where loading is increased until failure is observed. Variations in material properties and tolerances of similar components will give rise to different values of R where failure is observed. Also one would expect that different curves would be observed if the ratio of loadings were changed such as P/M_1 , M_1/M_2 , M_1/M_3 etc. since such changes may influence the mode of failure which will occur.

At low values of R , say $R = 1$, no failures would be expected and repeated testing would yield little or no information on failure. Any failures in this region of low R would have heavy contributions from such things as secondary stresses, fatigue effects, environmental chemistry effects, or flaws. The only accurate data source for such complex failure phenomena is actual performance of many similar components over many years of service at known low values of R . Such data is very difficult to obtain and therefore combinations of analysis and field failure data are usually required to quantitatively describe the low R region of the fragility curve for various components and structures.

The mode of failure is important to clearly define and, for the purposes of the SSMRP program, five idealized failure modes have been identified as stated in Table B.3.

Rupture Failure
Collapse Failure
Induced Failure
Operability Failure
Functional Failure

Table B.3
Five Idealized SSMRP Failure Modes

The above five terms have been defined in Appendix A. These five failure modes are intended to be exhaustive in terms of failure which can cause or influence radioactive release. They are distinguished from certain other incipient failure conditions also defined in Appendix A as: crack in steel, detectable leak, crack in concrete, or plastic limit load. These latter type incipient failure conditions are not in themselves direct causes for radioactive release in the SSMRP program.

For a given set of loading combinations such as P/M_1 , M_1/M_2 , M_1/M_3 which were previously discussed and a given dynamic time history characteristic of the seismic loading contribution, one of the five failure modes of Table B.3 would be expected to dominate the others for each of the different types of components. Dominate here means that a particular failure mode would occur at some lower loading state than that where the other failure modes could occur. The state where failure occurs at the lowest loading would be said to be dominant.

Since there are as many as five fragility curves, one representing each of the failure modes of Table B.3 for each component, and there are of the order of 1000 different components of interest in the SSMRP program, it is clear that some grouping of similar fragilities for classes of components will be desirable. It can be expected that 50 to 150 different classes of components may be necessary to characterize the types of fragilities associated with different components.

It should be pointed out also that the dominant fragility curve for a particular component could also be significantly changed or affected by the time history characteristic of any dynamic load applied to the component as well as any dynamic load combination. This would be particularly true for ductile components where dynamic energy absorption capability would play a major role in fragility. Thus, if one static loading plus one dynamic seismic loading were to produce one fragility

curve, then the same static and seismic dynamic loading taken in combination with say LOCA dynamic loading could be expected to produce a somewhat different dominant fragility curve. This very complex and non linear phenomenon associated with failure under combined dynamic and static loading will need to be dealt with by introducing modelling uncertainty for each different class of component. The following Figure B.10 illustrates schematically that the five failure modes which can affect each component could generally be reduced to one family of dominant fragility curves by introducing appropriate amounts of modeling uncertainty.

FIGURE B.10

The dotted fragility curves representing modeling uncertainty in the five failure modes would be caused by the previously discussed types of effects such as different ratios for P/M_1 , M_1/M_2 , M_1/M_3 as well as different time history loading characteristics for each dynamic loading function.

It is likely that the Indirect Failure mode can be eliminated from the general fragility curve by including such potential failure effects in the Systems Model (fault trees).

The Dominant Fragility curve for each class of component will have to include a combined modelling uncertainty to account for the variability of individual failure modes.

There are several alternate forms for expressing a single mode fragility curve. One simple form includes connecting straight line segments through desired fit points as illustrated in Figure B.11.

FIGURE B.11
Piece-Wise Linear Fragility Curve

Another possible form would be to pass a monotonically increasing smooth curve through desired fit points as shown in Figure B.12.

Figure B.12
Smooth Curve Fragility Fit

where for example:

$$CDF(R) = \frac{1}{2} \left[\left(\frac{R}{R_{\max}} \right)^{n_1} + \left(\frac{R}{R_{\max}} \right)^{n_2} \right] \left[\frac{1}{2} - \frac{1}{2} \cos \frac{\pi R}{R_{\max}} \right]$$

$$\text{for } 0 \leq R \leq R_{\max}$$

$$\text{and } CDF(R) = 1.0 \quad \text{for} \quad R > R_{\max}$$

Exponents n_1 and n_2 could be determined to fit the two intermediate points 2 and 3. Although some added computation complexity is introduced by use of this type fit, it does provide for realistic way to encode meager fragility data.

B.7 SYSTEM MODEL

B.7.1 Accident Sequences

The safety design of a reactor involves the postulation of potential failures or accidents and the design of engineered safety features (ESFs) whose purpose is to reduce either the probability of the initial failure or the magnitude of the consequences. Accordingly, potential reactor accidents generally require the simultaneous occurrence of several events. The Reactor Safety Study coined the term 'accident sequence' to describe such a sequence of events which typically includes an initiating event, the failure of one or more ESFs and finally the breachment of containment. The system model is basically an encoding of all physically-meaningful accident sequences. This set of accident sequences cannot be complete in a mathematical sense. However, the enormous investment in reactor safety analysis over the past 20 years and the fact that no new significant accident sequences have been found in the four years since publication of the Reactor Study Study despite exhaustive review give confidence that a concerted and organized analysis will probably include all significant accident sequences.

The RSS generated a set of accident sequences for the Surry reactor by using event trees. This is an inductive technique in which one postulates an initiating event and then sequentially examines the potential course of events depending upon the operation/failure of ESFs. Numerous event trees are displayed in Appendix I of the Reactor Safety Study. By using engineering logic, the trees can be pruned to eliminate all physically-meaningless events. The RSS then used a 1% discrimination filter to focus upon the dominant accident sequences. As discussed below, use of such a filter may not be appropriate for a common cause event such as an earthquake. As an example, the dominant accident sequences for Surry are reproduced from the RSS in Table B.4. The complete list of all physically-meaningful accident sequences for Surry are displayed in Appendix V of the RSS. The SSMRP proposes to use the

	RELEASE CATEGORIES				Core Melt				No Core Melt	
	1	2	3	4	5	6	7	8	9	
LARGE LOCA A	$AP=6$ 1×10^{-11} $AP=6$ 1×10^{-10} $ACB=6$ 1×10^{-11} $AP=6$ 1×10^{-11}	$AP=7$ 1×10^{-10} $AP=6$ 1×10^{-11} $AP=7$ 1×10^{-11}	$AP=6$ 1×10^{-6} $AP=6$ 1×10^{-6} $AP=6$ 1×10^{-6}	$ACB=6$ 1×10^{-11}	$AP=6$ 1×10^{-9} $AP=6$ 1×10^{-9}	$AP=6$ 1×10^{-9} $AP=6$ 1×10^{-10} $AP=6$ 1×10^{-10}	$AP=6$ 1×10^{-6}	$AP=6$ 1×10^{-7}	$AP=6$ 1×10^{-6}	$AP=6$ 1×10^{-6}
A Probabilistic	1×10^{-9}	1×10^{-9}	1×10^{-7}	1×10^{-6}	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-3}	1×10^{-4}	
SMALL LOCA A ₁	$S_1=6$ 1×10^{-11} $S_1=6$ 1×10^{-11} $S_1=6$ 1×10^{-10} $S_1=6$ 1×10^{-10}	$S_1=7$ 1×10^{-10} $S_1=6$ 1×10^{-10} $S_1=7$ 1×10^{-11}	$S_1=6$ 1×10^{-6} $S_1=6$ 1×10^{-6} $S_1=6$ 1×10^{-6}	$S_1=6$ 1×10^{-11}	$S_1=6$ 1×10^{-9} $S_1=6$ 1×10^{-9}	$S_1=6$ 1×10^{-10} $S_1=6$ 1×10^{-10} $S_1=6$ 1×10^{-10}	$S_1=6$ 1×10^{-6} $S_1=6$ 1×10^{-6}	$S_1=6$ 1×10^{-7}	$S_1=6$ 1×10^{-6}	$S_1=6$ 1×10^{-6}
A ₁ Probabilistic	1×10^{-9}	1×10^{-9}	1×10^{-7}	1×10^{-6}	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-3}	1×10^{-4}	
SMALL LOCA A ₂	$S_2=6$ 1×10^{-10} $S_2=6$ 1×10^{-9} $S_2=6$ 1×10^{-10} $S_2=6$ 1×10^{-10} $S_2=6$ 1×10^{-9}	$S_2=7$ 1×10^{-9} $S_2=6$ 1×10^{-10} $S_2=7$ 1×10^{-10}	$S_2=6$ 1×10^{-6} $S_2=6$ 1×10^{-6} $S_2=6$ 1×10^{-7} $S_2=6$ 1×10^{-6} $S_2=6$ 1×10^{-6}	$S_2=6$ 1×10^{-10}	$S_2=6$ 1×10^{-9} $S_2=6$ 1×10^{-9}	$S_2=6$ 1×10^{-10} $S_2=6$ 1×10^{-10} $S_2=6$ 1×10^{-10}	$S_2=6$ 1×10^{-6} $S_2=6$ 1×10^{-6}			
A ₂ Probabilistic	1×10^{-7}	1×10^{-7}	1×10^{-6}	1×10^{-7}	1×10^{-7}	1×10^{-6}	1×10^{-5}			
SMALL LOCA B	$BC=6$ 1×10^{-12} $BC=6$ 1×10^{-12} $BC=6$ 1×10^{-12}	$BC=7$ 1×10^{-11} $BC=6$ 1×10^{-12}	$BC=6$ 1×10^{-6}				$BC=6$ 1×10^{-7}			
B Probabilistic	1×10^{-12}	1×10^{-10}	1×10^{-6}	1×10^{-10}	1×10^{-6}	1×10^{-6}	1×10^{-7}			
SMALL LOCA C		$C=6$ 1×10^{-6}								
C Probabilistic	1×10^{-7}	1×10^{-6}	1×10^{-7}	1×10^{-6}						
SMALL LOCA D	$DD=6$ 1×10^{-6} $DD=6$ 1×10^{-6} $DD=6$ 1×10^{-6} $DD=6$ 1×10^{-6}	$DD=7$ 1×10^{-5} $DD=6$ 1×10^{-6} $DD=7$ 1×10^{-6}	$DD=6$ 1×10^{-6} $DD=6$ 1×10^{-6} $DD=6$ 1×10^{-6}		$DD=6$ 1×10^{-10} $DD=6$ 1×10^{-10}	$DD=6$ 1×10^{-6} $DD=6$ 1×10^{-6}	$DD=6$ 1×10^{-6} $DD=6$ 1×10^{-6}			
D Probabilistic	1×10^{-7}	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-5}			
10) SUMMARY OF ALL ACCIDENT SEQUENCES FOR RELEASE CATEGORIES										
SMALL LOCA (10% VALUE)	1×10^{-7}	1×10^{-6}	1×10^{-6}	1×10^{-7}	1×10^{-7}	1×10^{-6}	1×10^{-5}	1×10^{-5}	1×10^{-6}	
SMALL LOCA (10% VALUE)	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-5}	1×10^{-6}	1×10^{-6}	
SMALL LOCA (10% VALUE)	1×10^{-6}	1×10^{-5}	1×10^{-5}	1×10^{-6}	1×10^{-6}	1×10^{-5}	1×10^{-6}	1×10^{-6}	1×10^{-3}	

Note: The probabilities for each accident sequence for each event type and the 10% for all accident sequences are the median values of the dominant accident sequences caused by each event simulation plus a 10% overestimation from the adjacent accident category probability (see Section 4.1).

TABLE B.4 PWR DOMINANT ACCIDENT SEQUENCES
VS. RELEASE CATEGORIES

-
- A - Intermediate to large LOCA.
 - B - Failure of electric power to ESPs.
 - B' - Failure to recover either onsite or offsite electric power within about 1 to 3 hours following an initiating transient which is a loss of offsite AC power.
 - C - Failure of the containment spray injection system.
 - D - Failure of the emergency core cooling injection system.
 - F - Failure of the containment spray recirculation system.
 - G - Failure of the containment heat removal system.
 - H - Failure of the emergency core cooling recirculation system.
 - K - Failure of the reactor protection system.
 - L - Failure of the secondary system steam relief valves and the auxiliary feedwater system.
 - M - Failure of the secondary system steam relief valves and the power conversion system.
 - Q - Failure of the primary system safety relief valves to reclose after opening.
 - R - Massive rupture of the reactor vessel.
 - S₁ - A small LOCA with an equivalent diameter of about 2 to 6 inches.
 - S₂ - A small LOCA with an equivalent diameter of about 1/2 to 2 inches.
 - T - Transient event.
 - V - LPIS check valve failure.
 - α - Containment rupture due to a reactor vessel steam explosion.
 - β - Containment failure resulting from inadequate isolation of containment openings and penetrations.
 - γ - Containment failure due to hydrogen burning.
 - δ - Containment failure due to overpressure.
 - ϵ - Containment vessel melt-through.
-

TABLE B.4 (Continued) KEY TO PWR ACCIDENT SEQUENCE SYMBOLS

Zion reactor as a basis for calculation. It is envisaged that SSMRP will generate a similar set of accident sequences for Zion for use in this model.

The system model within the MPS program would be basically an encoding of each accident sequences in terms of its Release Category (defined in Section B.7.2), initiating event, subsystems involved and containment failure mode. An example of such encoding from Table B.4 is shown below.

As shown in the index to Table B.4, for the Surry reactor, the RSS identified 5 initiating events, 11 major subsystems and 5 containment failure modes. Comparable numbers of items can be expected for the Zion reactor. The RSS identified the following numbers of accident sequences for the dominant Release Categories:

	A	S ₁	S ₂	T	R	Total
PWR-1	21	20	12	51	2	106
PWR-2	23	21	22	112	4	182
PWR-3	27	28	29	13	1	98
PWR-6	13	8	12	52	-	85

The check valve sequence (V) is omitted since it is believed to be anomalous to the Surry NSSS design. Since some accident sequences are subsets of others and will be small contributors, they can be combined

with a small conservative error. We estimate that a maximum of 200 accident sequences will require consideration.

B.7.2 Release Categories

The Reactor Safety Study calculated the magnitude, composition and timing of radioactive releases to the atmosphere and geosphere with the BOIL and CORRAL programs for key accident sequences which were representative of the spectrum of potential releases. This process is described in Appendix V of the RSS. The study grouped accident sequences into a set of Release Categories and, within each Release Category, all accident sequences are assumed to have the same release. For the Surry reactor, nine Release Categories were used as stated in Table B.4 and their characteristics are stated in Table 5-1 of the Main Report (WASH-1400). Based upon other work,⁽⁸⁾ it appears likely that the same Release Categories will adequately represent potential accidents at the Zion reactor.

A major conclusion of the Reactor Safety Study was that the public risk is dominated (>90%) by potential accidents within the three largest Release Categories, PWR-1, PWR-2, and PWR-3. For this reason, the seismic risk assessment model for SSMRP need only consider accident sequences which would be assigned to these three Release Categories. These Release Categories all involve accidents with initial releases to the atmosphere. For some containment designs, the more likely initial failure mode may be a melt-through the base-mat to the geosphere. Also, for some reactor sites with proximity to aquifers or other potable water, the liquid pathways may be of greater importance. Under these circumstances, the model should be able to accommodate an additional Release Category (PWR-6). We perceive no conceptual difficulty, only an increase in required computer memory and running time.

B.7.3 Initiating Events

An initiating event is basically a disruption of the heat balance in the reactor either by a loss of coolant after which decay heat will

overheat the fuel unless emergency cooling water is supplied or by a transient which either increases the reactor power beyond the heat removal capacity or reduces the heat removal capacity below the heat generation rate. It is envisaged that initiating events at the Zion reactor will be subdivided into 5 to 10 categories. For convenience, the proposed model discussed in Section 5.7.2 was oriented around the 5 categories used by the RSS for the Surry reactor; the model and computer program would not be greatly altered by additional categories. It is assumed that only earthquakes of sufficient magnitude to cause at least a transient will be of interest in SSMRP. Thus, in the event of an earthquake, one of the following initiating events is assumed to occur.

<u>Symbol</u>	<u>Event</u>
T	Transient requiring successful cooldown of primary system
S ₂	Small-small LOCA (1/2 to 2" dia reactor coolant system (RCS) piping)
S ₁	Small LOCA (2 to 6" dia RCS piping)
A	Large LOCA (>6" dia RCS piping)
R	Reactor pressure vessel (RPV) rupture or collapse of its support

The conditional probability of each event given an earthquake will be denoted by $P(T|E)$, etc. It should be noted that the definition of event R is slightly different from that in RSS. Collapse of the RPV support is assumed to sever all RCS piping which would be equivalent to a RPV rupture. The above initiating events are assumed to be mutually

exclusive and their combined conditional probability is unity. In other words, one but not more than one event is assumed to always occur in the event of an earthquake. For small earthquakes, the conditional probabilities of events S_2 , S_1 , A and R are presumably very low and only a transient possibly requiring cooldown of the reactor will result. For larger earthquakes, LOCA's or a RPV rupture are more likely and the conditional probability of only a transient is less. It will be observed later in this section that transients may cause induced loads in the RCS piping which in combination with the direct seismic and operating loads may cause a LOCA. It is tacitly assumed within this model for initiating events that a LOCA requiring emergency cooling water is a more demanding situation than a transient requiring long-term decay heat removal.

The exact definition of initiating events and quantification of their conditional probabilities is one of the more challenging aspects of the SSMRP risk assessment model. For Phase I of SSMRP, a simple and possibly inadequate model is recommended which was discussed in Section 5.7.2. This model has some potentially severe deficiencies.

The primary coolant piping system is being treated as a collection of independent segments and pipes whereas the segments and pipes are inter-related. The failure probability of a specific segment or pipe (X) is assumed to be solely a function of its operating and direct seismic loads. However, depending upon which other segments or pipes have yielded plastically or failed, there may be other induced loads on segment or pipe X which will modify its failure probability. From the viewpoint of realistically calculating the failure probability of segment X, these induced loads cannot be overlooked. However, from a systems viewpoint, this problem may be less severe. From a systems viewpoint, the objective is to calculate $P(R|E)$, $P(A|E)$, $P(S_1|E)$ and $P(S_2|E)$ and the identities of the specific segments whose failure resulted in events A, S_1 , S_2 are relatively unimportant with respect to calculating the probabilities of system failure and radioactive release.

Suppose one calculated the probabilities of initiating events by the recommended model, one would expect to determine probabilities which decreased as a function of break size as illustrated by the solid line in Figure B.13a. If one now included the induced loads in the calculation, one might expect additional segments and/or pipes to fail which would increase the relative probabilities of large LOCA (A) and small LOCA (S_1) and possibly decrease the relative probability of a small-small LOCA (S_2); such an effect is illustrated by the dotted lines in Figure B.13a. The Reactor Safety Study found that S_2 -initiated accidents made greater contributions to public risk than those initiated by events S_1 and A . We do not perceive an inherent reason for a different finding for seismically-initiated accidents but this perception is unsupported by detailed analysis. If indeed the impact of a more sophisticated model is comparable to that illustrated in Figure B.13a and if S_2 -initiated events are more significant than A -initiated ones under earthquake conditions, then the simple model would introduce some conservatism into the estimate of the overall probability of release.

A more sophisticated model would have to determine the failure probability of a structural system as opposed to individual piping segments. Such a model would have to solve an implicit function by iteration or other methods for each seismic input and for each random operating load; it would be very time-consuming. To our knowledge, no tractable model or computer program currently exists to calculate the failure probability of a complex structural system subjected to random vibration. For Phase I of SSMRP, we propose that the model described in Section 5.7.2 be used in the risk assessment model and that an independent study be conducted to estimate the magnitude of the error (i.e., the difference between the solid and dotted lines in Figure B.13a).

There is an additional and related deficiency in the model described in Section 5.7.2. For the smaller magnitude earthquakes, the most likely initiating event will be a transient (e.g., turbine trip, loss of

FIGURE B.13a POSSIBLE EFFECT OF INDUCED LOADS ON LOCA PROBABILITIES

FIGURE B.13b POSSIBLE EFFECT OF INDUCED LOADS ON PROBABILITIES OF TRANSIENTS AND LOCAS

offsite power) and alternative heat sinks are required with the potential operation of valves, etc. Such events can introduce substantial induced loads in the primary coolant piping which, in combination with the direct seismic and operating loads, could enhance the probability of a LOCA. As a first approximation to this potential inter-relationship, one could precalculate a spectrum of these induced loads for each primary coolant piping segment in Stage I of the risk assessment model. In Stage II or III, such induced loads would be treated as a random parameter in combination with the direct seismic load and operating load (which also has random uncertainty) in the calculation of the conditional probability of failure of each segment and initiating events R , A , S_1 and S_2 . The effect of this refinement is illustrated in Figure B.13b. The conditional probability of only a transient is decreased while those for different sizes of LOCA are increased. Before introducing this refinement and complication into the SSMRP risk assessment model, we recommend an auxiliary study to assess the magnitude of its impact. As argued earlier, although such induced loads could be quite significant to an accurate calculation of the probability of a component failure, it may have a relatively small impact from a systems viewpoint. Again, the Reactor Safety Study found that transient-initiated accidents were as significant contributors to public risk as small LOCAs. If the simpler model over-estimated the relative frequency of seismically-initiated transients, the overall error may be small especially in comparison with other uncertainties.

In summary, for the Phase I SSMRP model, we recommend the use of the simpler models for the calculation of the conditional probabilities of initiating events. We recommend a parallel and independent study to develop a more sophisticated model to calculate the failure probability for a complex structural system subjected to random vibration. For a Phase II effort, this more sophisticated model could be used in auxiliary calculations to assess the modeling uncertainty or bias in the simpler model.

B.7.4 Engineered Safety Features

The engineered safety features are primarily redundant systems of structural, mechanical, and electrical components intended to provide emergency cooling water or electric power under a spectrum of accident conditions. In the RSS, potential failure modes of these systems were determined by using fault tree analysis. This is a deductive graphical technique in which one describes the undesired event (e.g., failure to deliver X gallons/min of water to vessel) and then displays with Boolean logic the combinations of events which would cause it with descending level of detail.

The fault tree is normally analyzed with a computer program to determine the minimal cut sets. Each such cut set states a minimum number of events whose joint occurrence would result in the undesired event. By assigning a probability to each event, with appropriate accounting for dependency due to common causes, and by summing the probabilities of all minimal cut sets with correct Boolean expressions for components which appear in more than one cut set, the probability of system failure may be determined. If a particular ESF is associated with more than one initiating event, then separate fault trees and minimal cut sets may be needed for each such initiating event. It is also envisaged that, for each initiating event, a spectrum of induced loads will be precalculated in Stage I for each component involved in the ESFs. It is intended that these induced loads span the potential range both with respect to amplitude and phase angle with the direct seismic load. These sets of induced loads would be treated as a random variable and would be combined with the random operating load and the direct seismic loads as described in Section 5.5. The probabilities of components failing would generally be a function of the seismic input. It is envisaged that SSMRP will analyze the Engineered Safety Features at Zion by fault trees or an equivalent method to determine the minimal cut sets.

The approach described in Section 5.7.2 has two potential deficiencies. The first is identical to one discussed in Section B.7.3 for the calculation of LOCA probability. Namely, the structural components within an ESF or between two ESFs are inter-related and their failure probabilities cannot properly be calculated independently. We do not perceive any reasonable solution to this problem and again recommend that the simple model be used for the Phase I SSMRP model and that an independent study be sponsored to assess the magnitude of the modeling error.

Second, normal fault tree analysis may be inadequate for a common cause event with such widespread impact as an earthquake. In its consideration of spontaneous initiating events (i.e., not seismically-induced), the RSS used relatively low failure rates for structural components (e.g., piping) based historical data. Therefore, the failure of safety systems was dominated by active hardware failures (e.g., pumps and valves fail to operate), human errors and test/maintenance outages since probabilities were relatively high. The probability of system failure was generally dominated by single failures with some contribution from doublets and triplets. Higher order cut sets made negligible contributions since the individual failure rates were so high. Since system failure was dominated by single failures, common cause failures, although requiring careful examination, were not a dominant factor. For this reason, one could have reasonable confidence that errors in the modeling of common cause failures would not invalidate the results. For a seismic event, the conditional probabilities of component failure could be relatively high especially for larger earthquakes and the higher order cut sets may become more significant. This result would greatly increase both the cost of the original analysis of the fault tree and the cost of evaluating the system model within the MPS program. Even more importantly, the overall modeling uncertainty would be increased since one's confidence in correctly analyzing higher order cut sets is lower. This potential difficulty merits further evaluation. A conclusion can only be reached by analyzing some representative systems.

B.7.5 Containment Failure Mode

A final subject meriting discussion is the timing of events especially as it relates to containment integrity. A major finding of the Reactor Safety Study was that, in the event of core melting, current containment designs would ultimately fail but that the initial mode and timing of this failure would strongly influence the magnitude of the consequences upon people and property. A molten core would ultimately melt through the base-mat and release the radioactive material into the geosphere. If this is the initial mode of containment failure, the consequences are relatively small since any release to the atmosphere would be filtered by the soil. However, if the initial failure mode is by steam explosion or overpressurization after the core has melted, the consequences are relatively severe since radioactive material, which has been released into the containment, would be flushed out to the atmosphere in the process of containment failure. Overpressurization would be caused by the interaction of the molten fuel with concrete. On the other hand, melting of the core would take several hours and, if containment was breeched prior to the event, there would effectively be a mechanism for pressure relief at the time of core melting and less radioactive material might be released to the atmosphere. A seismic event has the potential for causing such an earlier breach of containment. Thus, when preparing containment event trees for use in analyzing seismically-induced accidents, an additional containment failure mode should be added to reflect the timing of containment failure.

REFERENCES

1. Trifunac, M.D., "Preliminary Empirical Model for Scaling Fourier Amplitude Spectra of Strong Ground Acceleration in Terms of Earthquake Magnitude, Source-to-Station Distance, and Recording Site Conditions", Bulletin of the Seismological Society of America, Vol. 66, No. 4, pp. 1343-1373, August, 1976.
2. Cornell, C. Allin, "Engineering Seismic Risk Analysis", Bulletin of the Seismological Society of America, Vol. 58, No. 5, pp 1583-1606, October, 1968.
3. Richter, C.F., Elementary Seismology, W. H. Freeman and Co., San Francisco, 1958.
4. Kaul, M. K., "Use of Fault Displacements in the Evaluation of Seismic Risk", submitted to the International Journal of Earthquake Engineering and Structural Dynamics, John Wiley & Sons, New York.
5. Esteva, L. and Rosenbleuth, E., "Spectra of Earthquakes at Moderate and Large Distances", Soc. Mex. de Ing. Sismica, Mexico 11, pp 1-18, 1964.
6. Lysmer, J. et al, "FLUSH-A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems", University of California, Berkeley, EERC 75-30, November, 1975.
7. Collins, J. D. and Thomson, W. T., "The Eigenvalue Problem for Structural Systems with Statistical Properties", AIAA Journal, Vol. 7, No. 4, April, 1969.
8. Asselin, S.V., et al, "System Event Tree Analyses for Determining Accident Sequences that Dominate Risk in LWR Power Plants", ANS Topical Meeting on Probabilistic Analysis of Nuclear Reactor Safety Newport Beach, California, May, 1978.

APPENDIX C
FOURIER SPECTRUM AND TRANSFER FUNCTIONS

C.1 FOURIER TRANSFORM

The Fourier transform $A(\omega)$ of any time function $a(t)$ is a complex valued function that is conveniently expressed in the following form

$$A(\omega) = T(\omega)e^{i\theta(\omega)} \quad (1)$$

in which $T(\omega)$ is the amplitude of $A(\omega)$ and $\theta(\omega)$ is its argument. Since $A(\omega)$ is a harmonic representation of the time function $a(t)$, $T(\omega)$ can be interpreted as the amplitude of a harmonic of frequency ω in the time record $a(t)$ and $\theta(\omega)$ as the relative phase angle of the harmonic. Functions $T(\omega)$ and $\theta(\omega)$ are therefore usually called the Fourier amplitude and the phase spectra of function $a(t)$.

If $a(t)$ is a time record of finite duration, being zero outside an interval $(0, T)$, then by definition

$$A(\omega) = \int_0^T a(t)e^{i\omega t} dt \quad (2)$$

If $a(t)$ is shifted along the time axis by τ , the Fourier transform $A'(\omega)$ of this new function is given by

$$A'(\omega) = \int_{\tau}^{\tau+T} a(t-\tau)e^{-i\omega t} dt \quad (3)$$

By change of variables it can be shown that

$$A'(\omega) = e^{-i\omega\tau} A(\omega) \quad (4)$$

which implies that the amplitude spectrum of the time function $a(t)$ is unaffected by a time shift. Such a shift however affects the phase spectrum. In other words, by an appropriate selection of phase spectrum, a time history with any time shift can be generated from a given Fourier amplitude spectrum. This result has important implications for the load combination procedure where two time histories are desired to be combined with a random relative phasing. The preceding result enables this to be achieved in the frequency domain by variations in the phase spectrum.

C.2 Relationship with a Stochastic Process

If the phase angles $\theta(\omega)$ are assumed to be random variables, i.e., if the phase spectrum is a random process, the function $a(t)$ is also a stochastic process even when the amplitude spectrum $T(\omega)$ is a deterministic function. The process $\{a(t)\}$, however, is non-stationary, since for a stationary process, the Fourier transform may not be defined.

It can be proven that if $\theta(\omega)$ is a random variable uniformly distributed in the interval $(-\pi, \pi)$ for each value of ω then the associated process $\{a(t)\}$ is such that for each t , $a(t)$ is normally distributed. To characterize $\{a(t)\}$ properly, however, the correlation between $a(t_1)$ and $a(t_2)$ for distinct values of t_1 and t_2 should be known as a minimum. This correlation may be obtained from an analysis of actual $a(t)$ records, for example, when establishing phase spectrum of earthquake records. Or it may be assumed that phase angles $\theta(\omega_1)$ and $\theta(\omega_2)$ are independent if ω_1 and ω_2 are well separated. Given the amount of separation $\Delta\omega$ beyond which the phase angles are independent the phase spectrum can then be generated by randomly selecting values of θ at frequencies ω_i , $i = 1, 2, \dots$, (where $|\theta_i - \theta_{i+1}| > \Delta\omega$) from a uniform distribution and obtaining θ at in-between frequencies by interpolation.

C.3 Propagation of Phase Spectra

The phase spectrum $\theta_o(\omega)$ of a system output is related to phase spectrum $\theta_i(\omega)$ of the system input by

$$\theta_0(\omega) = \theta_i(\omega) + \phi(\omega) \quad (5)$$

in which $\phi(\omega)$ is the phase spectrum associated with the transfer function of the system. If a series of sub-systems were to act as a propagating medium for the phase spectrum, then one would have

$$\theta_0(\omega) = \theta_i(\omega) + \sum_{i=1}^n \phi_i(\omega) \quad (6)$$

in which subscript i would correspond to the i th subsystem in the series arrangement and n is the total number of subsystems in the chain.

If $\theta_i(\omega)$ and each of the $\phi_i(\omega)$ is independent and uniformly distributed in the interval $(-\pi, \pi)$ it can be shown that $\theta_0(\omega)$ is also uniformly distributed. For two random variables $\theta_i(\omega)$ and $\phi(\omega)$, the sum will have a symmetric triangular distribution in the interval $(-2\pi, 2\pi)$. Utilizing the periodicity property of $\exp(i\theta)$, it can be concluded that $\theta_i(\omega) + \phi(\omega)$ is uniformly distributed in $(-\pi, \pi)$. An extension to sum of more than two variables is trivial.

The preceding discussion suggests that the phase angles need not be propagated in MPS calculation chain but may be generated only when required for the inversion of Fourier spectrum. That the phase spectrum at this stage is uniformly distributed is further confirmed by the fact that this leads to a normal time history process which is always the outcome of passing a normal process through a linear system.

C.4 Phase Spectrum Library

For the purpose of the MPS program, an ensemble of phase spectra will be generated in an auxiliary program and stored for later access by the MPS. Since the overall storage requirements during MPS executions

are not anticipated to be large, availability of complete array of phase spectra to MPS will significantly add to its efficiency. Any alterations to the phase spectra, for example, introducing a time shift between concurrent dynamic loads, will be performed within the MPS.

C.5 Representation

A large amount of data in the form of Fourier Amplitude Spectra and transfer functions will have to be stored prior to the execution of the MPS program. Minimization of this storage requires that these functions be represented in an efficient manner. Some of the different representations that may be considered are:

- 1) Arrays of frequency-amplitude pairs
- 2) Polynomial representation
- 3) Rational function representation
- 4) Mixed representation

C.6 Representation by Arrays

This is the simplest manner of storing a function data. If the function is represented by N data points, the in-between values may be obtained by polynomial interpolation, the simplest form of which is linear interpolation. For evenly spaced points along the frequency axis the storage per function is only $N+1$ values, otherwise it is $2N$. For monotonic functions or piecewise monotonic functions with two or three segments of monotonicity, this representation is adequate from the viewpoint of spacing of frequency points. For oscillatory functions, a large value of N is generally required to adequately represent the function.

C.7 Polynomial Representation

A polynomial representation is superior to that discussed earlier, in that the number of data values describing the function can be considerably reduced. Polynomial representation of a function $f(x)$ is of the following form:

$$f(x) = \sum_{n=0}^N a_n x^n \quad (7)$$

in which N is the degree of the polynomial and a_n are the coefficients which completely characterize the function $f(x)$.

The coefficient a_n may be determined by interpolation at $N+1$ values of x . If the points are evenly spaced, the storage requirements for this representation are then identical to that by arrays. Polynomial representation in that case is inferior since it requires more computation to obtain $f(x)$ values. The points along the x -axis, however, do not have to be evenly spaced, in which case a much smaller value of N is required to describe $f(x)$ adequately. A proper selection of values of x can be made visually by spacing them closer in regions of high curvature. The coefficients a_n are readily obtained by employing Lagrange representation for $f(x)$.

Alternatively, coefficients a_n may be obtained by approximation techniques, in which numerous data points could be input to derive a unique set of $N+1$ a_n 's. Best approximation techniques may be used for this purpose. Depending on the choice of weighting functions used in the approximation, the polynomial representation can be explicitly written down by using generalized Fourier expansion in terms of orthogonal polynomials. The degree N of the polynomial should be kept as low as possible since the computation of each $f(x)$ value involves N multiplicative operations.

C.8 Representation by Rational Functions

Rational function approximation is very well suited for transfer functions which are generally characterized by peaks and valleys. One of the forms for rational function representation is

$$f(x) = \sum_{n=1}^N \frac{a_n x^4 + b_n x^2 + c_n}{x^2 - d_n^2 + e_n^2 x^2} \quad (8)$$

For positive values of a_n , b_n and c_n , the function $f(x)$ is positive and symmetric. This is also a characteristic of Fourier Amplitude Spectra and transfer function amplitudes. For small values of e_n , the function has local peaks near $x=d_n$. This allows an immediate determination of the parameters d_n and the number of terms N . The parameter e_n may be obtained by noting that for a single-degree-of-freedom system the representation in (8) is exact if

$$e_n^2 = 4 d_n^2 \xi_n^2 \quad (9)$$

where ξ_n is the damping of the system. Thus, e_n may be obtained in an approximate manner from equation (9) wherein the modal damping in the mode is substituted for ξ_n .

Some of the coefficients a_n , b_n and c_n may be obtained in terms of d_n and e_n or eliminated by requiring the representation in (8) to satisfy certain conditions, e.g., the transfer functions relating structure or component stress is zero at zero oscillation frequencies, implying thereby that $c_n=0$. In any event, once d_n and e_n are obtained, the remaining parameters, a_n , b_n and c_n can be obtained by curve fitting procedures, e.g., least square approximation.

It should be generally possible to represent a typical transfer function by four terms in the expansion given in (8). In such a case the transfer function can be defined by twenty parameters and the number of multiplicative operations required for calculation of each value of $f(x)$ will be multiplications and 4 divisions.

C.9 Mixed Representation

It is possible to select a proper combination of preceding three representations to describe a function $f(x)$, each representation applicable to one or more intervals on the X -axis. The decision to do so will depend on the nature of the function and the ability to strike a proper balance between storage and computation.

C.10 Effect on Cost

Though functional forms for FAS and transfer function (TF) can save considerable amount of storage, these representations may prove to be inefficient as far as computation is concerned. Thus, if 1000 points are required on a FAS and a TF to obtain a good representation in time domain, the approximation of FAS and TF by a 5th order polynomial requires 5×100 multiplications before the Fourier spectrum can be put in a proper form for inversion. Thus, though such a polynomial representation saves 1990 locations in computer storage it increases the number of operations by 5000 every time a time history is required. In case of repetitive computations it may, therefore be preferable to sacrifice efficiency in storage for efficiency in computation.