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Seismic Margins and Calibration of
Piping Systems

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ABSTRACT

The Seismic Safety Margins Research Program (SSMRP) is a U.S. Nuclear Regulatory Commission-funded, multiyear program conducted by Lawrence Livermore National Laboratory (LLNL). Its objective is to develop a complete, fully coupled analysis procedure (including methods and computer codes) for estimating the risk of earthquake-induced radioactive release from a commercial nuclear power plant and to determine major contributors to the frequency of radioactive release. The analysis procedure is based upon a state-of-the-art seismic and systems analysis process and explicitly includes the uncertainties in such a process. The results will be used to improve seismic licensing requirements for nuclear power plants.

In Phase I of SSMRP, the overall seismic risk assessment methodology was developed and assembled. The application of this methodology to the seismic PRA (Probabilistic Risk Assessment) at the Zion Nuclear Power Plant has been documented.

This report documents the method deriving response factors. The response factors, which relate design calculated responses to best estimate values, were used in the seismic response determination of piping systems for a simplified seismic probabilistic risk assessment.

EXECUTIVE SUMMARY

The Seismic Safety Margins Research Program (SSMRP) is a U.S. Nuclear Regulatory Commission-funded, multiyear program conducted by Lawrence Livermore National Laboratory (LLNL). Its objective is to develop a complete, fully coupled analysis procedure (including methods and computer codes) for estimating the risk of earthquake-induced radioactive release from a commercial nuclear power plant and to determine major contributors to the frequency of radioactive release. The analysis procedure is based upon a state-of-the-art seismic and systems analysis process and explicitly includes the uncertainties in such a process. The results will be used to improve seismic licensing requirements for nuclear power plants.

In Phase I, the overall seismic risk assessment methodology was developed and assembled. The application of this methodology to the seismic PRA (Probabilistic Risk Assessment) at the Zion Nuclear Power Plant was documented. The developed methodology and its application have demonstrated that the methodology is the most complete, thorough, and comprehensive tool for the seismic PRA. However, its application is too time consuming and costly, particularly, for the seismic response determination of structures and subsystems. The objective of the simplified methods project described in the report was to develop a simplified seismic risk methodology for general use. The goal is to reduce seismic PRA costs to roughly 60 man-months over a 6 to 8 month period.

The approach of this study is:

- 1) to develop piping response factors, which relate median response (best estimate) to responses calculated by selected design

procedures in the nuclear power industry. The primary interest is the use of the response factors to calibrate the design responses in terms of parameters such as piping moments and valve accelerations; and

- 2) to investigate the differences among the selected parameters such as damping, modal combinations, directional combinations, stress component combinations, and in-structure response spectra in the design procedures.

Several tasks were identified based on our approach.

- o Identified the various seismic analysis methods adopted in the U.S. nuclear industry for piping systems, through a literature survey. The primary source of information is the Safety Analysis Reports for the nuclear plants in operation and under construction. The results of this survey are provided in Appendix A.
- o Performed a series of seismic response calculations for four representative piping systems of the Zion nuclear power plant that were analyzed during the Phase II SSMRP study. Out of the four, two piping systems are in one building and the other two are supported by two buildings. The piping systems span different elevations and comprise several different pipe sizes. In order to study the effect of the variability in the input ground motion, in-structure response spectra generated from four different ground motions were considered. The various seismic analysis methods identified were implemented for response computation to enable quantification of the differences among methods. In addition, different piping damping values were considered.

- o Computed response factors and their variability for each of the methods of analysis. The response factor is the ratio of the response generated from various analysis methods that are included in the parametric study to the SSMRP best estimate response. Effects of the seismic ground motion, structural analysis methodology, piping damping, and location/elevation of the piping system will be addressed separately.

Literature Survey

The survey covered most of the commonly used methodologies for seismic analysis of Category I piping systems in the U.S. Due to the time limitation, we did not conduct a complete survey of the Final Safety Analysis Report (FSAR) of the remaining U.S. nuclear plants, but we are confident that any method not specifically covered by the said survey would most likely be very similar to one of the methods identified through the survey.

The literature survey identified ten different response spectrum methods for the piping inertia load analysis, considering both the modal and directional response combinations; one commonly used equivalent static analysis method for the inertia loads; three pseudostatic load analysis methods to account for the effect of differential movements among pipe supports and anchors; and three ways of combining the inertia and pseudostatic loads to obtain the total loads. The piping system damping for the SSE was found to range from 1% to 5% of critical. Finally, in the response spectrum method of analysis at least three procedures have been used to specify the input spectrum based on the in-structure response spectra given at various pipe support/anchor locations. They are the envelope spectrum, the average spectrum, and the spectrum nearest to the C.G. of the piping system.

Seismic Response Calculations

Having identified the many variations in the analysis methodology, we then performed parametric seismic response calculations based on such identified methods and parameters. Four piping systems from the Zion Nuclear Power Plant were selected. They are the Residual Heat Removal (RHR), Auxiliary Feedwater (AFW), Service Water (SW) and Reactor Coolant Loop (RCL) piping systems, which include several different pipe sizes and elevation spans. The RHR and AFW piping systems run between two structures, while the SW and RCL piping systems are supported within one building. In addition, the RCL piping analysis model is different from the other three in that it consists of such large, massive components as the Reactor Pressure Vessel, steam generators, reactor coolant pumps and pressurizer. This modeling difference gave rise to different characteristics of the seismic responses for certain response spectrum methods (e.g., the SRSS-SRSS method) which we anticipated prior to the parametric study.

The in-structure response spectra from four different earthquake ground motions were used in the response calculations. The first three earthquake motions are characterized with response spectra compatible with the NRC Regulatory Guide 1.60 design spectra. The fourth earthquake motion is site specific.

The parametric study considered eleven response spectrum methods of analysis for the inertia load computations. They are the ten existing methods in the industry, plus the ARC method for modal response combination, which was recently published and did not have any industrial application yet. We, however, anticipated the results from the ARC method to be very similar to those from the double-sum technique of modal combination, and this was verified by the parametric response study. In addition to the eleven response spectrum methods of analysis, we considered the equivalent static method of

analysis, two pseudostatic load analysis methods, and three procedures for combining the inertia and pseudostatic loads. For the piping damping, 1%, 2% and 5% of critical were considered. Regarding the input spectrum for the inertia load analysis, the envelope spectrum, average spectrum, and C.G. spectrum were included.

The piping responses examined were the resultant moments in the elbows, tees, reducers, etc., in both the inertia and pseudostatic load analyses, and the resultant accelerations at selected nodal points in the inertia load analyses. The effect of the variation in the inertia load analysis method on the piping response was represented by the response ratios between the methods. We chose the SRSS-SRSS technique as the base reference method for the response spectrum method of analysis study. For the total seismic loads, the absolute sum combination method was taken to be the reference basis. For piping damping and input spectrum, the 2% damping envelope spectrum was the reference basis.

Response Factor

Response factors, F_R relate design calculated responses to best estimate values.

$$R_{BE} = R_D / F_R$$

where, the R of interest may be a moment in piping element or acceleration of a valve. R_{BE} is the calibrated value and R_D is the design response. A response factor is the multiplication of a reference response factor and other adjusting factors.

$$F_R = CF_{REF} \times F_M \times F_D \times F_I \times F_S$$

A reference response factor, CF_{Ref} , was first established for each of the three response spectrum method groups. It represents the mean ratio in responses between the particular response spectrum method and the SSMPR best-estimate approach (multiple-support time history analysis). Adjusting factors were established to supplement the reference response factor, to account for the anticipated variation in methodology. They are F_M , effect of the variation in, the analysis method; F_D , damping; F_I , input spectrum specification; and F_S , soil structural interaction analysis methodology. The reference response factors were also established separately for the pseudostatic loads and the total loads.

Based on the outcome of this study, we can draw the following conclusions:

- (1) The parametric response calculations produced a data base that was sufficient for studying the effects of the variation in response spectrum analysis method, damping, and input spectrum specification on the piping response.
- (2) The eleven response spectrum methods of analysis included in our study can be separated into three groups. They are:

Group (1): SRSS-HHV method;

Group (2): 10%-SRSS, DBS-SRSS, ARC-SRSS, and SRSS-SRSS method;

Group (3): 10% -SRSS, GRP-SRSS, DBS -SRSS, SRSS-10%, SRSS-GRP, SRSS-DBS method

It is noted that SRSS-HHV defines the combination modal of response by the square root of sum of square, then a combination of three directional components by the greater of one of two horizontal responses, plus the vertical response. In other words, the first combination is for modal response, the other for directional combination. The ten percent method (10%), the grouping method (GRP), and the double sum method (DBS) are contained in R.G. 1.92, and ARC is the advanced response combination method. With the SRSS-SRSS method as the reference basis, the response ratio statistics of the three method groups vary depending upon whether the piping analysis model includes large, massive components. The results suggested the need to distinguish a piping analysis model which does not contain any large components, from an analysis model that does, such as the RCL analysis model considered in this study. The two were referred to as the Type (a) (excluding large components) and Type (b) piping analysis models. For the Type (b) model, the SRSS-SRSS method needs to be excluded from the method Group (2) and treated as another group because it consistently produced larger seismic response than did the remaining three Group (2) methods. This resulted from the unique situation of the closely spaced modes that typically exist in a Type (b) piping analysis model.

- (3) The mean response ratio between the SRSS-SRSS and equivalent static methods was about 2.2. This suggests that the equivalent static analysis is, on the average, two times more conservative than the SRSS-SRSS method in determining the resultant moments in the pipes.
- (4) More consistent statistics for the inertia load and total load response factors were observed among the individual piping systems. The same was not true for the pseudostatic load response factors, because piping responses are very sensitive to how the pipe anchor movements are applied to the piping system.

- (5) The best estimate response generated by using the response factor approach would necessarily contain an undetermined amount of uncertainty. The coefficient of variation for the total seismic loads, which is about 0.50 for all three response spectrum method groups, is a very good indication.
- (6) The response factors suggest that the seismic loads from the industrial methods of piping analysis have an inherent margin of conservatism at the order of 5 when compared to the best estimate response. With respect to best-estimate site specific ground motion, such margin is about 10. The above mentioned margins are the general conclusion of this study with the methods of analysis considered herein.

Based on the above conclusions and the results presented in the text, we identified further studies that are needed to refine the response factor approach and, hence, reduce the variability in the methodology. Such recommended studies include:

- (1) Expand the data base by examining the responses of more piping systems. The additional study may reduce the uncertainty pertinent to the best estimate response that is to be generated through the simple response factor approach.
- (2) There are piping systems, typically in the older plants, that were originally classified as non-Category I, but later reclassified as safety related items, such as the auxiliary feedwater system in the PWR plants. For such piping systems, the response factor approach does not apply because their seismic design loads are probably not available. For the purpose of PRA applications, however, we believe it is feasible to develop a simplified approach that will directly estimate the seismic loads. So long as the estimated loads are on the conservative side, the simplified technique will be useful.

1. INTRODUCTION

1.1 Background

The Seismic Safety Margins Research Program (SSMRP) is a U.S. Nuclear Regulatory Commission-funded, multiyear program conducted by Lawrence Livermore National Laboratory (LLNL). Its objective is to develop a complete, fully coupled analysis procedure (including methods and computer codes) for estimating the risk of earthquake-induced radioactive release from a commercial nuclear power plant, and to determine major contributors to the frequency of radioactive release. The analysis procedure is based upon a state-of-the-art seismic and systems analysis process and explicitly includes the uncertainties in such a process. The results will be used to improve seismic licensing requirements for nuclear power plants.

In Phase I, the overall seismic risk assessment methodology was developed and assembled (Ref. 1). The application of this methodology to the seismic Probabilistic Risk Assessment (PRA) at the Zion Nuclear Power Plant was documented (Ref. 2). The developed methodology and its application have demonstrated that the methodology is the most complete, thorough, and comprehensive tool for the seismic PRA. However, the application of its entirety is too time consuming and costly, particularly, in the area of seismic response determination of structures and subsystems. The objective of the simplified methods project was to develop a simplified seismic risk methodology for general use. One major area of simplification was in the determination of seismic responses in Phase II for SSMRP which was done by probabilistic response calculations with the program SMACS.

There are seven steps to perform a seismic PRA: (1) plant and site familiarization; (2) earthquake hazard characterization; (3) accident sequence identification including fault trees/event trees and human factors; (4) seismic response determination of structures and subsystems; (5) fragility function determination; (6) plant seismic safety evaluation; and (7) analysis results and interpretation (Ref. 3).

In step 4, seismic response determination of structures and subsystems, probabilistic response calculations were performed based on the time history analysis approach for a number of earthquake simulations. The multi-support time history analysis technique (Ref. 4) was employed to calculate piping system responses. This procedure produces the best estimate seismic response of piping systems.

There are three types of data of responses to be used to calculate component failure probabilities. They are median level response, response variability, and correlation (Ref. 2).

Median Level Response

Given an earthquake occurrence, the best estimate or median level seismic response is required. In general, best estimate response differs from the design values, even for the same design level earthquake, because in the latter case, design analysis procedures, parameter selection, and qualification procedures are conservatively biased. An additional consideration due to analyzing for the range of earthquakes of the seismic hazard curve is the change in properties of the soil/structure/piping systems, which occurs at higher excitations leading to higher soil and structure damping characteristics. Such changes need to be taken into account when determining median level response.

Variability of Response

Variability in seismic response, resulting from variations in the earthquake excitation, the physical properties of the soil/structure/piping system and our ability to model them, must be estimated.

Correlation of Responses

Correlation of responses (which are the tendency for pairs of responses to have simultaneously high or low values) results from two sources--the level of the earthquake and the dynamic characteristics of the system. The level of the earthquake affects correlation since a large earthquake (large peak

acceleration) may cause all responses to be large, whereas a small earthquake produces the opposite effect. The second source of correlation is due to system response itself. For example, floors within a structure may all experience high levels of response simultaneously. The importance of response correlation on probabilities of system failure, core melt, and radioactive release depends on correlations between fragilities and the functional characteristics of the systems themselves.

In order to achieve the goal of the simplified methods project, it is necessary to simplify the calculational procedure for seismic response. One approach is to develop response factors which relate the median level response to the design data calculated by A-E firms, nuclear steam system suppliers, vendors, etc., in the process of nuclear power plant design. The response variability was obtained from the SSMRP Phase II information and the variability introduced by this simplified procedure. The response correlation is defined by using SSMRP Phase II information.

1.2 Objective and Scope

The objectives of this study were:

1. to develop piping response factors, which relate median response (best estimate) to responses calculated by selected design procedures in the nuclear power industry. The response factors will then be used to calibrate the design responses (piping moments and valve accelerations, etc.) to median level values; and
2. to investigate the differences among the selected parameters in the design procedures and quantify their effect on response. These parameters include damping, modal combinations, directional combinations, stress component combinations, in-structure response spectra, etc.

To accomplish the objectives of the study, several tasks were:

- o Through a literature survey, identified the various seismic analysis methods adopted in the U.S. nuclear industry for piping systems. The primary source of this information is the Safety Analysis Reports for the nuclear power plants in operation and under construction. The results of this survey are provided in Appendix A.
- o) Conducted a series of seismic response calculations for four representative piping systems of the Zion nuclear power plant that were analyzed during the Phase II SSMRP study. In order to study the effect of the variability in the input ground motion, four different ground motions were considered. Numerous seismic analysis methods were implemented for response computation purposes, to enable quantification of the differences among methods. In addition, different piping damping values were considered.
- 3) Computed response factors and their variability for each of the methods of analysis. The response factor is the ratio of the response generated from the various analysis methods included in the parametric study to a best estimate response.

The descriptions of the four Zion plant piping systems are given in Section 2. Section 3 identifies the methods of analysis and the other parameters that were considered in the study. The results of the study are presented and discussed in Section 4. Results of the response factor are given in Section 5. Finally, Section 6 presents our conclusions regarding the limitations and applicability of the response factor, and recommends future work that will enhance the results from the current project. Future enhancements are desirable because we anticipate a considerable uncertainty inherent with the best estimate responses that are to be generated from the "response factor" approach.

2. PHYSICAL CHARACTERISTICS OF PIPING SYSTEMS

Selected in this study were four representative Zion plant piping systems of which the best estimate seismic responses were determined from the multi-support time history analysis. These best estimate responses, using response spectra which meet the Nuclear Regulatory Guide 1.60 requirements, were the basis for determining the response factor in the study.

2.1 Physical Descriptions

The four Zion piping systems are, in the SSMRP designation:

- 1) Residual Heat Removal System and Safety Injection System: The piping is from containment shell to intermediate structure anchor (inside AFT building) and refueling water storage tank (between containment and AFT);
- 2) Auxiliary Feedwater to Steam Generator 1A which runs from the containment shell to the steam generator 1A;
- 3) Service Water to Feedwater Pump: The piping is from 48" service water line to the three auxiliary feedwater pumps; and
- 4) Reactor Coolant Loop: The piping includes four loops of primary coolant line and six other branch lines.

They will be denoted as RHR, AFW, SW, and RCL, respectively, in the subsequent discussions.

The RHR and the AFW piping systems run between two structures. The RHR spans between the internal structure and the auxiliary-full handling-turbine building (AFT) complex and the AFW spans the internal structure and containment shell. The RCL piping system is within the containment building, and the SW piping is in the AFT complex.

With the RHR and AFW piping systems running through two buildings, the effect of differential pipe support movement between two buildings can be compared with the effect of differential pipe support movements within the same building. The RCL is different from the other three piping systems in that its analysis model includes the large components such as the steam generators, reactor pressure vessel, reactor coolant pumps, and pressurizer.

2.2 Seismic Analysis Models

Properties of the piping models of the four selected piping systems are:

	<u>RHR</u>	<u>AFW</u>	<u>SW</u>	<u>RCL</u>
No. of Nodes	96	263	423	760
No. of Pipe Elements	71	158	322	496
No. of Modes Included (≤ 33 Hz)	18	36	57	140
Fundamental Frequency (Hz)	3.86	2.86	1.95	1.43
No. of Response Quantities:				
(a) Moment	22	23	132	118
(b) Acceleration	2	1	13	17

The analysis models except the RCL model, which is too large to be shown, are illustrated in Figs. 2-5 to 2-7, which also show the elements for the moment output and the nodes for the acceleration output. The elements selected for the moment output are, in general, elbows, branches and anchors. The nodes selected for the acceleration output represent the valve locations.

Fig. 2-1 Sketch of the RHR and SI-1 Piping Configuration

Fig. 2-2 Sketch of the AFW (Inside Containment) Piping Configuration

Fig. 2-3 Sketch of the SW to the AFW Pumps Piping Configuration

RPV (reactor pressure vessel)
SG (steam generator)

Fig. 2-4 Sketch of the Reactor Coolant Loop Piping Configuration

Fig. 2-5 RHR Piping Analysis Model

Fig. 2-6 AFM Piping Analysis Model

Fig. 2-7 SW Piping Analysis Model

3. PARAMETRIC STUDY

The seismic response of piping systems is typically separated into two parts: the inertial and the pseudostatic response due to the relative motion of the system supports. Various analysis procedures have been developed to calculate each portion of the responses separately. The process of calibrating the piping system response treats each part separately and proceeds by first identifying those aspects of seismic analysis of piping systems which may have a major influence on response prediction. For inertial response, we have identified six areas: multiple-support time history analysis procedures vs. single support response spectrum analysis procedures; within the response spectrum analysis procedure--modal response combination, accounting for three directional effects, and order between modal and directional combination; multiple-support time history analysis procedures vs. equivalent static techniques; and damping effects.

- o Multiple-support time history analysis vs. single support response spectrum analysis procedures -- Many piping systems are analyzed by simplified response spectrum analysis techniques where all piping system supports are assumed to be excited by identical response spectra for a given direction, i.e., three response spectra are defined, one for each direction of excitation (two horizontal and the vertical), and they typically apply to all support points. The conservatism introduced by this procedure, when the input response spectra are determined by enveloping over all support points, has been documented (Ref 12). This calculational margin can be very large and is dependent on the piping system size, the support locations, and the configuration.
- o Response spectrum analysis procedures and combination of modal and directional effects -- A limited survey of SARs identified response spectrum analysis techniques used in the seismic analysis and design of piping systems. All cases identified assumed uniform support excitations as described above. Major differences arose in definition of the input response spectra (e.g., envelope, average,

or center-of-gravity spectra), modal response combination, accounting for three directional effects, and the order of modal and directional response combination. Quantification of these effects leads to response factors.

- o Multiple-support time history analysis procedures vs. equivalent static techniques -- Equivalent static techniques are occasionally used to analyze piping systems. In these cases, the piping system is subjected to distributing a static load equal to its mass times a factored peak acceleration. The peak acceleration is derived from in-structure response spectra at the piping system support locations.
- o Damping of piping systems -- Design procedures typically assume very low values of modal damping (1% - 3% of critical). Seismic PRA interests are two-fold: predicting best-estimate or median level response which requires realistic parameter values such as damping; and predicting phenomenon which may occur at or near failure levels of the piping system where significantly greater energy dissipation is expected, i.e., modal damping values greater than 1% to 3% used in design. Hence, the effect of piping system damping needs to be assessed and taken into account.

For pseudostatic response, calibration concentrates on the method of analysis. Two methods of analysis were identified through a literature survey of SARs as candidates for calibration. The best estimate methodology is a multiple support time history analysis. Both methods of analysis to be calibrated are static techniques where the load is defined by maximum structure displacements at the piping system support locations. The first method applies each support displacement independently as a static loading condition, determines response, and combines the responses by SRSS. The second method applies all support displacements in a given direction simultaneously and combines the responses due to the different directions by SRSS. For piping systems spanning more than one structure, each structure is treated independently, and the responses combined by the absolute sum of resultant response induced by each structure or the absolute sum in each direction, then combined by the SRSS method for three earthquake components.

3.1 Seismic Ground Motions

Four earthquake simulations were considered in this study. In each case, the seismic input was defined by three acceleration time histories--two horizontal components and the vertical. SSI and structure response were calculated in the time domain using a substructure approach. In-structure acceleration time histories were generated at piping system support points. Response spectra were calculated from these time histories. These response spectra in various forms served as the excitation in this study.

The first three earthquakes meet the specifications of the NRC Regulatory Guide 1.60 guidelines, and the fourth one is a site specific earthquake for the Zion power plant site. These earthquakes were chosen so that the variation in characteristics of the ground motions would be sufficiently accounted for in this study.

3.2 Inertial Response

To investigate the phenomenon and analysis techniques described above, four piping systems of the Zion nuclear power plant were analyzed by different techniques, and numerous comparisons were made to develop response factors. The best estimate results were generated during the SSMRP Phase II analyses.

The inertia loads were calculated using both the response spectrum and equivalent static methods of analysis. The analyses were done using the computer code RESCOM that was developed during the course of the project. The various response spectrum methods, equivalent static analysis method, specifications of the input in-structure spectrum, and damping values of the piping systems that were considered in the current study are separately discussed in the following text. The results of the analyses are presented in Section 4.

3.2.1 Response Spectrum Method of Analysis

A limited review of SARs identified a number of analysis scenarios which have been used in the nuclear industry to analyze piping systems. Initially, let us focus our attention on response spectrum analysis procedures which assume all piping system supports to be excited by identical response spectra for a given direction. The major elements of the procedure are input definition to the piping system, modal response combination techniques, directional response combination techniques, order of modal and directional combinations, and damping of piping systems. Tables 3.1, 3.2, and 3.3 itemize alternative procedures for input definition (4 alternatives), modal response combination (7 alternatives), and directional response combination (3 alternatives), respectively. Order of modal and directional response combination (2 alternatives) and damping values of 1%, 2%, and 5% complete the alternatives. It was not feasible or necessary to explicitly treat all combinations of these alternatives in the quantification effort ($4 \times 7 \times 3 \times 2 \times 3 = 504$ alternatives per earthquake and per piping system). A first pass at reducing the number of alternatives was based on assuming envelope response spectra on 2% damping. The directional combination approach of SRSS was used for all cases but one--SRSS of modal responses in combination with HHV. Table 3.4 itemizes eleven cases which were treated in detail. These eleven cases were selected based on their use in the nuclear industry. A further grouping to three summary groups is shown in Table 3.4, i.e., the results of this investigation showed further groupings to be applicable. Summary results are presented here.

Separate studies of the effects of input definition and damping were conducted and, again, summary results are presented in the next section. In these studies, four free-field earthquake excitations were used--three were corresponding to the RG 1.60 design ground response spectra and one site specific earthquake. Input to the piping systems was defined by performing SSI and structure response analyses of the Zion nuclear power plant containment building and AFT complex (References 10 and 11) for each of the four earthquake definitions. As an illustration, the 2% damping envelope spectra for the RHR piping system are shown in Figures 3.1 through 3.12.

Table 3.1 Input Definitions for Piping System Analysis by Response Spectrum Analysis Techniques

- o Envelope spectra -- The envelope response spectra over all piping system support locations; peak broadened; one for each direction of excitation.
- o Average spectra -- The average response spectra over all piping system support locations; peak broadened; one for each direction of excitation.
- o C. G. spectra -- The response spectra at the piping system support location closest to the center-of-gravity (C.G.) of the piping system; peak broadened; one for each direction of excitation.
- o Single highest spectra -- The highest response spectra of all piping system support locations; alternatively, response spectra at the piping system support at the highest elevation in the structure; peak broadened; one for each direction of excitation.

Table 3.2 Modal Response Combination Techniques

<u>Modal Response Combination Technique</u>	<u>Abbreviation</u>	<u>Applicable Equation</u>	<u>Modal Coupling Factor C_{ij}</u>
1. Square Root Sum of Squares	SRRS	1 or 2	= 0
2. Ten percent	10%	1	= 1 if w_i and w_j differ by 10% or less;
3. Absolute Ten	10%	2	= 0 otherwise.
4. Grouping	GRP	2	= 1 for modes within any group bounded by frequencies less than 10% apart; = 0 otherwise.

5. Double Sum	DBS	1	See notes 1 and 2 below.
6. Absolute Double Sum	DBS	2	
7. Advanced Response Combination	ARC	1	Refs. (5, 6). Note 3 below.

$$R = R_1^2 + R_2^2 + \dots + 2 C_{12} |R_1 R_2| + \dots + 2 C_{ij} |R_i R_j| + \dots \quad (1)$$

$$R = R_1^2 + R_2^2 + \dots + 2 C_{12} R_1 R_2 + \dots + 2 C_{12} R_i R_j + \dots \quad (2)$$

Notes

(1) Techniques 3, 4, and 6 are the "Grouping Method; "Ten Percent Method," and the "Double Sum Method" of NRC RG 1.92, respectively.

$$(2) c_{ij} = \frac{1}{1 + [(w_i' - w_j') / (B_i' w_i' + B_j' w_j')]^2}$$

$$w_j' = w_j \sqrt{1 - B_j^2}$$

$$B_j' = B_j + 2/w_j t_d$$

w_j, B_j = modal frequency (rad/sec) and modal damping ratio, respectively

$$(3) c_{ij} = 1 - \left[\frac{\Delta^2}{\Delta^2 + 4(d + 0.01)^2} \right] H(f)$$

where $f = \frac{f_i + f_j}{2}$ = mean frequency for f_i and f_j

$W = \frac{(f_j - f_i)}{f}$ = dimensionless frequency differential

d = modal damping ratio

$H(f)$ = frequency-dependent coefficient function (see Fig. 6 of Reference 5)

Table 3.3 Directional Combination Techniques

- o SRSS - Square-root-of-the-sum-of-the-squares of the response due to each excitation direction.
- o HHV - Absolute sum of the response due to the vertical excitation with the maximum response from the two horizontal excitations.
- o ABS - Absolute sum of the response due to the three directions of excitation.

Table 3.4 Summary of Response Spectrum Analysis Scenarios for Which Response Factors Were Developed

Case No	Order of Modal(1) Directional Combination	Modal(2) Combination	Directional(3) Combination	Summary(4) Group No.
A1	M	SRSS	HHV	1
A2	M	10%	SRSS	2
A3	M	10%	SRSS	3
A4	M	GRP	SRSS	3
A5	M	DBS	SRSS	2
A6	M	DBS	SRSS	3
A7	M	ARC	SRSS	2
B8	M or D	SRSS	SRSS	2
B9	D	10%	SRSS	3
B10	D	GRP	SRSS	3
B11	D	DBS	SRSS	3

Note:

- (1) M indicates that the piping response is obtained by combining modal response first, then combining the directional component responses; D indicates that the piping response is obtained by combining directional component responses first, then combining modal responses.
- (2) Modal response combination techniques, see Table 3.2.
- (3) Directional component response combination techniques, see Table 3.3.
- (4) Summary group number is based on the mean response ratios in the element moments in Table 4-1. The analysis techniques which belong to each different group are listed on page 37 of this report.

3.2.2 Equivalent Static Method of Analysis

With this method, a static analysis was made for the piping systems subjected to a distributed static load equal to 1.5 times the mass of the piping system times an acceleration. The input acceleration is the peak acceleration on the applicable input in-structure spectrum. The 1.5 factor is assumed to account for the effects of the higher modes, i.e., those not included in the analysis. Since none of the four piping systems can be considered "rigid", using the ZPA (zero period acceleration) on the in-structure spectrum as the input is not applicable in the present study.

For the equivalent static analysis, the three damping values, i.e., 1%, 2% and 5%, were considered. However, only two types of input spectrum were considered: the envelope spectrum and the average spectrum. Therefore, for each piping model there are 24 equivalent static analyses representing the combination of four earthquake motions, three damping ratios and two input spectrum types.

3.3 Pseudostatic Load Analysis

For the differential anchor movement effect, three methods were identified in Appendix A. For the present study, two methods, Method I and Method II, were used for the calculation. Method I moves one piping support point at a time with the corresponding maximum displacement calculated from the time history analysis of the applicable building which supports the piping system. The total loading from the differential anchor movement effect is then obtained by combining the results from all individual support point movements by the SRSS method.

Method II moves all supports, attached to the same structure, in a given direction simultaneously, and the anchor movements are in phase. When there is more than one structure involved, the results from all individual structure movements in the same earthquake direction are combined by the absolute sum method. The SRSS method is then used in combining the directional results for the total pseudostatic loads.

The third method requires information of the structure mode shapes. This information was not available for the current study because of the soil-structure interaction analysis methodology adopted in the SSMRP for the Zion plant structures, therefore, was excluded.

3.4 Combination of Inertia and Pseudostatic Loads

To obtain the total seismic loads, the contributions from both the inertia and differential anchor movement effects are combined. It should be noted that the loads associated with the differential anchor movement were previously designated as the pseudostatic loads.

As described in subsection 3.2, the inertial responses were calculated by either the response spectrum analysis or the equivalent static analysis. Therefore, there are two versions of total seismic loads because the pseudostatic loads may be combined with the inertia loads from either the response spectrum analysis or the equivalent static analysis.

Three methods were used to combine the inertia loads with the pseudostatic loads. They are designated as Methods A, B, and C, and are described in the following:

Method A - absolute combination,

Method B - SRSS combination,

Method C - absolute combination in each earthquake component and the SRSS combination for the three components.

Fig. 3-1 Horizontal Envelope Spectrum for RHR, Earthquake No. 1

Fig. 3-2 Horizontal Envelope Spectrum for RHR, Earthquake No. 1

Fig. 3-3 Vertical Envelope Spectrum for RHR, Earthquake No. 1

Fig. 3-4 Horizontal Envelope Spectrum for RHR, Earthquake No. 2

Fig. 3-5 Horizontal Envelope Spectrum for RHR, Earthquake No. 2

Fig. 3-6 Vertical Envelope Spectrum for RHR, Earthquake No. 2

Fig. 3-7 Horizontal Envelope Spectrum for RHR, Earthquake No. 3

Fig. 3-8 Horizontal Envelope Spectrum for RHR, Earthquake No. 3

Fig. 3-9 Vertical Envelope Spectrum for RHR, Earthquake No. 3

Fig. 3-10 Horizontal Envelope Spectrum for RHR, Earthquake No. 4

Fig. 3-11 Envelope Spectrum for RHR, Earthquake No. 4

Fig. 3-12 Vertical Envelope Spectrum for RHR, Earthquake No. 4

4. NUMERICAL RESULTS

As discussed in Section 1, one of the objectives of this study was to develop response factors for the use of a simplified seismic PRA in piping response determination. The response factors can be viewed as the degree of conservatism introduced by the conventional response calculation methodologies used in nuclear industry.

The numerical comparisons presented here are in the form of mean ratios of response and coefficients of variations (COVs) for resultant accelerations of valves and resultant moments of piping components. The two steps to generate the ratios of response were 1) to analyze each piping system for each earthquake (a total of four earthquakes used); and 2) to calculate the ratios of response at each corresponding piping location for the scenario to be compared. The mean ratio would then be computed for all the response ratios of interest from four earthquakes.

4.1 Inertial Response

The inertial response of piping systems is typically analyzed by two types of analysis procedures: 1) the response spectrum method; and 2) the equivalent static method.

4.1.1 Response Spectrum Analysis Procedures

A comparison of inertial responses for the four piping systems for a various analysis procedures is presented. The major elements of the procedure are modal response combination techniques, directional response combination techniques, order of modal and directional combinations, input definitions to the piping system, and damping of piping systems.

Modal and Directional Combination Procedures vs. SRSS-SRSS

The SRSS-SRSS technique (case B8 in Table 3.4) when applied to singly supported systems, many times, yields results which compare well with responses calculated by time history procedures. Hence, comparisons of cases A1-A7 and B9-B11 with case B8 were made to provide a benchmark. Table 4.1 compares responses for the four piping systems of interest. A further grouping of the eleven techniques resulted from a detailed evaluation of each technique's characteristics and the results displayed in Table 4.1. The result was three summary groups of techniques as shown in Table 3.4.

The following observations can be made:

(1) For each method, accelerations and moments have comparable response ratios within the same piping model.

(2) The first listed method, i.e., the SRSS-HHV method, which uses the SRSS technique for modal combination and then uses the absolute sum technique combining the greater horizontal component with the vertical component to obtain the total inertia loads, is different in nature from the other methods in the directional combination. Except for the RCL model, this method yielded higher responses than the other methods.

For the RCL model, Methods (3), (4), (6), (9), (10), and (11), in which the absolute values of response were used in the modal combination, yielded mean responses up to 65% higher than that from Method (8), the SRSS-SRSS method. However, except for Method (1) (the SRSS-HHV method), the remaining methods in which the algebraic values of response were used in the modal combination yielded mean responses more than 7% lower than that from the SRSS method.

By inspection of the mean response ratios in the element moments in Table 4-1, except for the RCL piping system, the response spectrum methods

considered in the study can be categorized into three groups which are:

- o Group (1) - SRSS-HHV method;
- o Group (2) - 10%-SRSS, DBS-SRSS, ARC-SRSS and SRSS-SRSS method;
- o Group (3) - Absolute 10% Modal Combination, SRSS Direction Combination; DBS Modal Combination, SRSS Direction Combination; Grouping Modal Combination, SRSS direction; 10% Direction Combination, SRSS Modal Combination; Grouping Direction Combination, SRSS Modal Combination; DBS Direction Combination, SRSS Modal Combination.

Figures 4-1 to 4-3 show the histograms of the response ratios in element moment for one representative method selected from each group. They are the SRSS-HHV method, the DBS-SRSS method and the [DBS]-SRSS method representing method Groups 1, 2, and 3, respectively. Each figure shows the response ratio histograms for the individual piping systems.

Combining the response ratio statistics of the four piping systems for all methods included in each group generated the overall statistical results per method group. In the combination among piping systems, the results from the RHR, AFW and SW piping systems were considered as one category, and the RCL piping system alone as another category. We anticipated that the RCL piping system would produce different results in the response ratios owing to the large contrast in mass between the large components (steam generators, RPV, reactor coolant pumps, pressurizer) and the piping. From our past experience, the large contrast in mass within the seismic model typically generates closely spaced modes which can give rise to a very conservative response in certain elements even when the modal responses are combined by the SRSS technique (Refs. 8, 9, 10). This is one of the reasons why the ARC method was proposed (Ref. 7). Therefore, for the RCL piping system the SRSS-SRSS method itself forms one group, while the grouping for the rest of methods remains the same as in the RHR, AFW and SW piping systems.

Based on the above reasoning, it is appropriate to categorize the piping system analysis models into two types: type (a) piping analysis model that does not include any large, massive components (e.g. the Zion RHR,

AFW and SW piping systems); and type (b) model (e.g. the Zion RCL piping system analysis model). In accordance with such categorization, the response ratio statistics for each method group expressed in the histograms are illustrated in Figs. 4-4 to 4-6. Table 4-2 summarizes the statistical means and COVs of the response ratios for the various method groups and for both types of piping analysis models.

Envelope Spectra vs. C.G. and Average

Table 4.3 summarizes the effects of specifying input response spectra at the C.G. of the piping system or an average spectra over support point locations for each of the four piping systems. Table 4.3 demonstrates that the more extensive the piping system in terms of support locations throughout the buildings is, the more conservative the envelope spectrum approach is. The overall statistics for all four piping systems are shown in Table 4-4. Fig. 4-7 shows the histograms of the individual piping systems, and Fig. 4-8 shows the overall histograms for the case of the average spectrum.

Damping Effects

Damping effects as measured by responses calculated by response spectrum analysis procedures are quantified in Table 4.5. Means and COVs of the response ratio for each model were calculated from a total of 132 response spectrum analyses corresponding to the combination of 11 methods, 4 earthquakes and 3 spectrum types ($11 \times 4 \times 3$).

Between each two damping values, the numbers of response ratios used to calculate the means and standard deviations are listed as follows:

	<u>RHR</u>	<u>AFW</u>	<u>SW</u>	<u>RCL</u>
Number of Moment Data	2904	3036	17424	15576
Number of Acceleration Data	264	132	1716	2244

The histograms of the moment response ratios for the four piping systems are shown in Figs. 4-9 and 4-10 representing the results of 1%/5% and 2%/5%, respectively. The overall histograms combining the ratios for all models are shown in Fig. 4-11. Table 4-6 tabulates the statistical means and COVs for the overall response ratio.

The results indicate that, from the four piping systems, the mean moment response ratio is about 2.0 for 1% damping vs. 5%, 1.5 for 2% vs. 5%, and 1.3 for 1% damping vs. 2%. As to modal acceleration, the mean ratios are 1.8 and 1.4, respectively. These results are based on response spectrum analyses.

To investigate the damping effect on piping response generated by time history analysis, we examined the piping response data present in Figures 4.16 (1% damping) and 4.18 (2% damping) of Reference 13. These responses are pipe element moments for the RHR piping model. The mean response ratio between 1% damping and 2% is 1.25 with 0.06 of coefficient of variation. This value is in close agreement with the mean response ratio of 1.29 (see Table 4-5, $1.78 \div 1.38$). This is an indication that the response ratio between different damping is comparable between two methods of analysis, response spectrum or time history analysis.

4.1.2 Comparison Between Equivalent Static and Response Spectrum Methods

The equivalent static method is sometimes used in the industry to calculate the inertia loads. In this method, the piping system is subjected to a distributed static load equal to its own mass times 1.5 times the peak acceleration of the applicable in-structure response spectrum. The method was carried out for each individual earthquake component first, and then the results of the three components were combined by the SRSS method to obtain the inertia loads.

The inertia loads calculated by the equivalent static method were compared to the SRSS-SRSS response spectrum method of analysis. The comparison is represented by the response ratio of the SRSS-SRSS method to the equivalent static method.

The means, medians, and COVs of the ratios are shown in the following table:

RESPONSE RATIO OF RESPONSE SPECTRUM METHOD vs. EQUIVALENT STATIC

	<u>RHR</u>	<u>AFW</u>	<u>SW</u>	<u>RCL</u>	Overall (<u>Excluding RCL</u>)
Mean	0.28	0.43	0.47	8.96	0.44
Median	0.28	0.48	0.43	0.52	----
COV	0.36	0.63	0.51	3.55	0.54

As can be seen in the above table, the RCL has a large mean and COV. This is because the moments in some pipe elements calculated by the equivalent static method are so small that the ratio can be as large as 400 or vice versa. The reason for this large variation is not immediately known. Therefore, the median is more meaningful for the RCL piping. Based on the statistics, it may be concluded that the equivalent static method is more conservative than the SRSS-SRSS response spectrum method.

4.2 Combination of Inertia and Pseudostatic Loads

The following table summarizes the work done in the combination of the pseudostatic loads with the inertia loads using the methods A, B, and C as described in Section 3.4. The pseudostatic loads were computed using Method I and II as previously described in Section 3.3

Combination Methods of Inertial and Pseudostatic Responses

<u>Case No.</u>	<u>Combination Method</u>	<u>Pseudostatic Loads</u>	<u>Inertia Loads</u>	<u>Piping Model</u>
(1)	A (Absolute sum)	I	R	A11
(2)	B (SRSS)	I	R	A11
(3)	A	II	R	A11
(4)	B	II	R	A11
(5)	C	II	E	A11
(6)	C	II	R	RHR

It is noted that, as defined in Section 3.4 Method A is referred to absolute combination of inertial and pseudostatic responses; Method B is SRSS combination; and Method C is absolute combination in each earthquake component and SRSS combination for the three components.

In the Table I, II, R, and E denote the loads calculated by Method I, Method II, the response spectrum method, and the equivalent static method, respectively. Each of the cases (1), (2), (3) and (4) represents 144 sets of analyses spanning the 4 earthquakes, 4 models, 3 damping ratios, and 3 spectrum types. Case (5) represents 4 sets of analyses corresponding to the 4 models, and each set contains results for the 4 earthquakes. For the combination depicted by Cases (5) and (6), only the envelope spectrum for 2% damping was used.

We computed the response ratio of combination Method (B) to (A), and Method (C) to (B). For the response ratio of Method (B) to (A), we utilized the response results from Cases (4) and (3), respectively, where the inertia loads were based on the 2% damping envelope spectrum as the input. For the response ratio of Method (C) to (B), we utilized the response results of Cases (6) and (4), again based on the 2% damping envelope spectrum as input. The results are summarized in Table 4-7, which shows that Method (B) responses are about 15% lower than those from Method (A), and that Method (C) responses are about 10% lower than those from Method (B).

To investigate the effects of piping system damping and input spectrum type on the total seismic loads, we computed the ratio of total responses between the different parameters. For damping, we considered the 1%, 2% and 5% values for the inertia part, which was based on the envelope spectrum as input, and the pseudostatic part was based on Method II. The combination of the two parts was based on Method A. Table 4-8 summarizes the response ratios of 1% to 2%, 1% to 5%, and 2% to 5% damping. Similarly, we computed the ratio of total response of average spectrum to envelope spectrum, where the inertia part was based on 2% damping only. The results are shown in Table 4-9. Both Tables 4-8 and 4-9 indicate that the total response ratios are closer to 1.0 than are the corresponding inertia ratios listed in Tables 4-2, to 4-6. This is what should be anticipated because the pseudostatic part of the total loads is independent of the damping value and input spectrum type.

Table 4-1 Response Ratios of Different Response Spectrum Analysis Techniques Vs. SRSS-SRSS Technique
Envelope Spectra 2% Damping

Piping Model	Response	Response Ratio	(A) Modal - Directional Combination					(B) Directional - Modal Combination				
			HHV (1)	SRSS (2)	10% SRSS (3)	10% SRSS (4)	GRP - SRSS (5)	DBS - SRSS (6)	DBS - SRSS (7)	ARC - 10% SRSS (9)	SRSS-GRP (10)	SRSS-DBS (11)
RHR	Element Moment	Mean	1.12	1.00	1.02	1.02	1.00	1.06	.99	1.03	1.03	1.09
		COV	0.111	0.023	0.032	0.027	0.024	0.059	0.083	0.048	0.040	0.077
	Modal Accel.	Mean	1.25	1.04	1.09	1.08	1.02	1.09	1.00	1.12	1.10	1.12
		COV	0.094	0.057	0.059	0.051	0.061	0.055	0.132	0.081	0.071	0.074
AFW	Element Moment	Mean	1.29	1.00	1.07	1.02	1.00	1.05	1.00	1.09	1.03	1.07
		COV	0.051	0.089	0.093	0.018	0.044	0.060	0.059	0.107	0.025	0.076
	Modal Accel.	Mean	1.28	0.94	1.11	1.09	0.96	1.12	0.91	1.14	1.11	1.16
		COV	0.040	0.041	0.051	0.042	0.032	0.091	0.047	0.057	0.044	0.116
SW	Element Moment	Mean	1.20	0.98	1.08	1.07	0.98	1.11	0.99	1.09	1.08	1.13
		COV	0.093	0.075	0.096	0.091	0.064	0.096	0.136	0.107	0.096	0.112
	Modal Accel.	Mean	1.17	0.98	1.11	1.08	0.99	1.14	1.03	1.13	1.09	1.17
		COV	0.078	0.078	0.111	0.093	0.082	0.127	0.185	0.134	0.094	0.148
RCL	Element Moment	Mean	1.12	0.90	1.57	1.49	0.91	1.44	0.83	1.77	1.64	1.61
		COV	0.122	0.248	0.184	0.215	0.205	0.156	0.232	0.225	0.268	0.195
	Modal Accel.	Mean	1.12	0.86	1.57	1.47	0.88	1.49	0.93	1.77	1.61	1.65
		COV	0.059	0.366	0.131	0.142	0.333	0.142	0.424	0.133	0.147	0.160

Table 4-2 Overall Inertia Response Ratio Statistics Between Response Spectrum Method Groups and SRSS-SRSS Technique.

		<u>Group (1)</u>		<u>Group (2)</u>		<u>Group (3)</u>	
		<u>(a)*</u>	<u>(b)*</u>	<u>(a)</u>	<u>(b)</u>	<u>(a)</u>	<u>(b)</u>
Element Moment	Mean,	1.20	1.12	0.99	0.88	1.07	1.59
	COV	0.097	0.122	0.089	0.233	0.101	0.223
<hr/>							
Nodal Accel.	Mean,	1.19	1.12	1.00	0.89	1.12	1.59
	COV	0.087	0.059	0.120	0.380	0.112	0.157
<hr/>							

*Refer to piping models Type (a) and (b) that excludes and includes large massive components, respectively.

Table 4-3 Response Ratios of Envelope Spectra vs. C.G. and Average Spectra

Piping Model	Piping Response	Response Ratio	Spectrum Specification	
			Ave./Env.	C.G./Env.
RHR	Element Moment	Mean	0.84	0.83
		COV	0.060	0.083
	Nodal Accel.	Mean	0.80	0.78
		COV	0.068	0.119
AFW	Element Moment	Mean	0.55	0.55
		COV	0.241	0.240
	Nodal Accel.	Mean	0.55	0.55
		COV	0.120	0.084
SW	Element Moment	Mean	0.41	0.92
		COV	0.344	0.082
	Nodal Accel.	Mean	0.35	0.89
		COV	0.209	0.099
RCL	Element Moment	Mean	0.44	0.39
		COV	0.262	0.276
	Nodal Accel.	Mean	0.47	0.42
		COV	0.177	0.170

**Table 4-4 Overall Inertia Response Ratio Statistics Between Different
Input Spectrum Types and Envelope Spectrum**

		<u>Ave./Env</u>	<u>C.G./Env</u>
Element Moment	Mean,	0.46	0.67
	COV	0.367	0.400
<hr/>			
Nodal Accel.	Mean,	0.45	0.63
	COV	0.298	0.381

Table 4-5 Response Ratios for Damping Effects

Piping Model	Piping Response	Response Ratio	Damping	
			1%/5%	2%/5%
RHR	Element Moment	Mean	1.78	1.38
		COV	0.147	0.103
	Nodal Accel.	Mean	1.45	1.21
		COV	0.320	0.188
AFW	Element Moment	Mean	2.04	1.56
		COV	0.138	0.078
	Nodal Accel.	Mean	2.00	1.53
		COV	0.131	0.074
SW	Element Moment	Mean	2.14	1.56
		COV	0.178	0.132
	Nodal Accel.	Mean	2.12	1.54
		COV	0.200	0.137
RCL	Element Moment	Mean	1.86	1.43
		COV	0.171	0.118
	Nodal Accel.	Mean	1.62	1.30
		COV	0.246	0.162

**Table 4-6 Overall Inertia Response Ratio Statistics Between
Different Damping Values and 5% Damping**

		<u>1% / 5%</u>	<u>2% / 5%</u>
Element Moment	Mean,	1.99	1.49
	COV	0.186	0.130
<hr/>			
Nodal Accel.	Mean,	1.82	1.40
	COV	0.256	0.174

**Table 4-7 Response Ratio Statistics Between Methods
of Combination for Total Seismic Loads***

Piping System	Method B/Method A		Method C/Method B	
	Mean	COV	Mean	COV
RHR	0.867	0.110	0.900	0.067
AFW	0.862	0.096	(Not Available)	
SW	(Not Available)		(Not Available)	
RCL	0.863	0.108	(Not Available)	
Overall	0.863	0.115	0.900	0.067

***Note:** Inertia loads are based on response spectrum methods using 2% damping envelope spectrum as input, and pseudostatic loads are based on Method II. This is why results for SW are not available for ratio of Method B to A.

Table 4-8 Ratios of Total Responses Between Different Damping Values in the Inertia Part*

Piping Model	Response Ratio	Damping		
		1%/2%	1%/5%	2%/5%
RHR	Mean	1.22	1.57	1.27
	COV	0.082	0.194	0.124
AFW	Mean	1.22	1.80	1.48
	COV	0.099	0.215	0.196
RCL	Mean	1.24	1.74	1.40
	COV	0.086	0.182	0.113
Over-all	Mean	1.23	1.73	1.39
	COV	0.089	0.194	0.139

*The inertia part is based on envelope input spectrum, the pseudostatic part is based on Method II, and the combination of the two parts is based on Method A (i.e., abs. sum)

Table 4-9 Ratios of Total Responses of Average Input Spectrum to Envelope Spectrum in Inertia Part*

Piping Model	Response Ratio	Ave/Env
RHR	Mean	0.93
	COV	0.425
AFW	Mean	0.77
	COV	0.242
RCL	Mean	0.816
	COV	0.260
Overall	Mean	0.82
	COV	0.53

* The inertia part is based on 2% damping, the pseudostatic part is based on Method II, and the combination of the two parts is based on Method A (i.e., abs. sum).

Fig. 4-1 Response Ratio Histograms for Individual Piping
 Between SRSS-HHV and SRSS-SRSS Method

Fig. 4-2 Response Ratio Histograms for Individual Pipings
 Between DBS-SRSS and SRSS-SRSS Method

Fig. 4-3 Response Ratio Histograms for Individual Pipings
 Between |UBS| - SRSS and SRSS - SRSS Method

Fig. 4-4 Response Ratio Histograms for Both Type (a) and (b) Piping Models Between Method Group (1) and SRSS-SRSS Method

Fig. 4-5 Response Ratio Histograms for Both Type (a) and (b) Piping Models Between Method Group (2) and SRSS-SRSS Method

Fig. 4-6 Response Ratio Histograms for Both Type (a) and (b) Piping Models Between Method Group (3) and SRSS-SRSS Method

Fig. 4-7 Response Ratio Histograms for Individual Pippings
 Between Average and Envelope Input Spectrum

Fig. 4-8 Overall Response Ratio Histogram Between
Average and Envelope Input Spectrum

Fig. 4-9 Response Ratio Histograms for Individual
 Pippings Between 1% and 5% Damping

Fig. 4-10 Response Ratio Histograms for Individual
Pipings Between 2% and 5% Damping

Fig. 4-11 Overall Response Ratio Histograms for (a) 1%/5%
 and (b) 2%/5% Damping

5. RESPONSE FACTORS AND DESIGN MARGINS

Significant conservatisms in calculated piping system response is due to the use of the response spectrum analyses method, acceptable to the Standard Review Plan. In this section, response comparisons are made between responses calculated by the response spectrum analysis method and its multi-support time history analysis techniques. Two sets of best-estimate response resulting from time history analyses are presented. One is based on the seismic input defined by ground response spectra which meet the Regulatory Guide 1.60 requirements, and the other is Zion site-specific.

5.1 Input to Piping Systems

Multi-support time history analyses of piping systems were performed for two cases: best estimate and RG 1.60. In both cases, the SSMRP SMACS technology was used (Ref. 1). Differences in the two cases arose principally from the definition of the seismic input. For the best estimate case, an ensemble of ninety earthquakes was used. Each earthquake was defined by three acceleration time histories--one in each of the two horizontal and the vertical directions. For the RG 1.60 case, an ensemble of thirty earthquakes was used--the components of each earthquake were acceleration time histories whose response spectra essentially enveloped those of RG 1.60. Also, in the SMACS methodology, uncertainty in the SSI, structures, and piping systems can be treated explicitly by assigning probability distributions to the selected parameters and vary their values from simulation-to-simulation based on a Latin hypercube experimental design. This capability was used in the best estimate analyses for SSI, structures, and piping systems. For the RG 1.60 analysis, only variability in the SSI and structures area were included. Figure 5.1 shows the two different response spectra.

5.2 Response Factors

One objective of this study was to develop response factors which, when applied to the SSE seismic design loads of the piping systems, produces the corresponding best estimate seismic loads. The best estimate loads can then

be utilized in the seismic PRA of the plant. Because the seismic design loads are usually calculated by using one of the seismic response analysis methods and the pertinent parameters included in the previous parametric study, the response factor approach is sufficiently general. It then follows that the best estimate seismic loads determined in such a manner will undoubtedly contain an uncertainty much greater than that associated with the best estimate response generated from the SSMRP detailed calculations.

The response factor approach may be simply represented by one pair of parameters, i.e., a mean response factor, F_R , and the associated COV (coefficient of variation). In general, F_R may be represented by a reference response factor, CF_{Ref} , and four adjusting factors as follows:

$$F_R = CF_{Ref} \cdot F_M \cdot F_D \cdot F_I \cdot F_S \quad (5-1)$$

The reference response factor represents the mean ratio between the seismic response based on a response spectrum method with analysis method and the best estimate seismic response. The adjusting factors, F_M , F_D and F_I , are required to account for the deviations in analysis method, damping, and specification of input pipe support spectrum, respectively, from those used in computing the reference response factor, etc. The fourth adjusting factor, F_S , is intended to account for the effect of the uncertainty in soil-structure interaction analysis methodology on the seismic response of the piping. Such adjustment may be necessary because, in a nuclear plant, the in-structure response spectra may be generated based on a soil-structure interaction analysis method that is not best estimate.

Given the SSE seismic design loads, R_D , in a piping system, the response factor approach predicts the best estimate responses R_{BE} in accordance with the following equation:

$$R_{BE} \text{ (Best Estimate Responses)} = R_D \text{ (Original Design)} / F_R \quad (5-2)$$

The COV for R_{BE} is assumed the same as that associated with the CF_{Ref} .

In the following, we will discuss the determination of the reference response factors, adjusting factors, uncertainties, etc., for the inertial seismic loads, the pseudostatic (differential pipe support movement) seismic loads, and the combined total seismic loads, separately. The Appendix b shows the detailed definitions of the inertial and pseudostatic loads in the SSMRP time history analysis methodology.

5.2.1 Response factors for Inertial Loads

To quantify the effects of the response simplified spectrum analysis procedures, the three summary group responses were compared with response calculated by the multiple-support time history analysis procedure of the SSMRP. Table 5.1 summarizes the results.

Having determined the reference response factor, we then determined the adjusting factors.

- F_M - It is to account for the effect of the deviation in analysis method. Since we already developed the reference response factors for all response spectrum method groups, the adjusting factor F_M is only required for the equivalent static analysis method. The results presented in section 4.1.2 were used to estimate the F_M . With respect to the SRSS-SRSS method, hence the method Group (2), F_M for the equivalent static method is about 0.45.
- F_D - It is to account for the effect of piping damping other than the 2% value used in developing the reference response factors. The response ratio statistics shown in Table 4-6 were used to derive the approximate values of the adjusting factor F_D . We assumed that F_D for 5% damping is approximately equal to the inverse of the mean response ratio between 2% and 5% damping. Furthermore, the adjusting factor for 1% damping was assumed to be equal to the F_D for 5% damping times the mean response ratio between 1% and 2% damping. The resulting values of F_D are shown in Table 5-2.

- 0 F_I - This factor accounts for the effect of the input spectrum specified other than the envelope spectrum. Table 4-3 was used to develop the factor, F_I . Table 5-3 shows the results.
- 0 F_S - Deviation of the structural analysis methodology, seismic input motion definition, and, in particular, the soil-structure interaction technique used in the SSMRP would produce uncertainty in the in-structure response spectra as a result of uncertainty carried over to the piping response. Effect of the variation in the zero period acceleration (ZPA) on the in-structure spectrum must also be accounted for. This effect will also vary from site to site (Refs. 10 and 11).

5.2.2 Response Factors for Pseudostatic Loads

The reference response factor was based on the statistical mean of the ratios in resultant pipe moment between the pseudostatic analysis method described in Section 3.3 and the SSMRP time history analysis approach. Table 5-4 shows the results for the individual piping systems and for all four piping systems overall.

The only adjusting factor required in Eq. (5-1) for the pseudostatic loads is F_S structural response factor due to SSI analysis procedures. F_S for the pseudostatic loads is generally less than that for the inertial loads.

5.2.3 Response Factors for Total Seismic Loads

In the previous parametric study, we considered three methods of combination i.e., Method A, B and C, between the inertia and pseudostatic loads in arriving at the total seismic loads. The combination was only applicable to the resultant moments in the pipe elements because it was not needed for the nodal accelerations.

We computed the reference response factors for the combination Method A only i.e., absolute sum combination. The inertia loads included in the combination were based on the various response spectrum methods using the 2% damping envelope spectrum as input, and the pseudostatic loads were based on the Method II. Method II moves all supports and anchors attached to the same structure in a given direction simultaneously, and the support movements are in phase. Table 5-5 shows the resulting reference response factors for the RHR, AFW and RCL piping systems. The results for the SW piping system were not included in Table 5-5 because the Method II pseudostatic loads for the SW system were not available. Table 5-5 shows the overall reference response factors for total seismic loads from the three piping systems.

Under the particular condition that the inertia loads were based on the 2% damping envelope spectrum for the response spectrum method and the pseudostatic loads based on Method II, the results in Table 4-7 can be used to infer the adjusting factor F_M for the combination Method B and C, as shown in Table 5-6. The adjusting factors, F_D and F_I , are shown in Tables 5-7 and 5-8, respectively.

The alternative way to derive the calibrated total seismic response is as follows:

Use appropriate response factors to calibrate design inertial loads and pseudostatic loads respectively, and then combine these two calibrated loads by the absolute sum scheme to obtain the median value of the calibrated total seismic response.

5.3 Design Margins

The design margins represent the ratios of the seismic design loads to the best estimate loads. The seismic design loads were the values calculated in the design process by using any one of the response spectrum methods and pertinent parameters identified in Appendix A. The best estimate response calculational procedure for response margin differs somewhat from the best estimate response as described previously.

The design or calculational margins of inertia load for various groups of response spectrum methods are presented in Table 5-9. Like the response factor calculations, the design margins in each piping model were calculated in such a way that the ratios of two responses (response spectrum method vs. best-estimate response) were calculated first at each corresponding pipe element, then the mean ratios and associated variability were computed among the ratios for all elements. The design margin is the mean ratio for that piping model. The uncertainty for this design margin is the response variability. Table 5-10 shows the design margins and their variabilities for all piping models studies in this report.

Table 5-11 presents the design margins and their variabilities for pseudostatic loads for each piping model and for all models. Comparison of results between analysis Method I and Method II shows that Method I is more conservative than Method II. Recall that Method I moves one piping support point at a time with the corresponding maximum displacement calculated from the time history analysis of the applicable building which supports the piping system. The piping response due to differential anchor movement is determined by combining the results from all individual support point movements by the SRSS method. Method II moves all support points in a given direction within the same structure simultaneously. In other words, the piping support points within the same structure move in phase with the individual maximum support displacement. The piping responses generated for each individual structure's motion are combined by the absolute sum method for each earthquake direction. The piping responses due to differential anchor movement effect are calculated by combining the responses in each direction by the SRSS method.

Table 5-12 presents the design margins for total loads, namely, combination of pseudostatic and inertia loads. The inertia load for the response spectrum method was calculated by using 2% damping envelope spectrum, and the pseudostatic load was based on Method II. Absolute sum method (Method A) was used to combine these two response components (inertia and pseudostatic loads) to generate the piping total response. It can be seen from Tables 5-10 through 5-12 that the overall design margins for total loads

of pipe resultant moment lie between the margins for inertia loads and pseudostatic loads (e.g., 10.3, 13.0, and 8.6, respectively, for response spectrum Method Group 1).

The COVs for the design margins of total response are fairly constant among the three groups of response spectrum method, i.e., 0.47, 0.51, and 0.50, respectively. This shows that the data spread is pretty much proportional to the mean value of the data.

5.4 Comparison of Response Factors and Design Margins

The response factors are the ratios of response of the response spectrum methods to the time history method, both based on the R.G. 1.60 response spectra as ground motion. The design margins are the ratios of response of the response spectrum methods (based on R.G. 160 ground motion spectra) to the time history analyses (best-estimate site-specific response spectra). Therefore, the main difference between these two factors is in the response spectra representing the ground motion (see Figure 5-1) used to compute the structure response and the subsequent piping response.

It can be seen from Tables 5-5 and 5-12, that the design margins are approximately two times of the corresponding response factors. Let us compare the two ground motion response spectra mentioned above. If one computes the mean resultant spectral accelerations for the frequency range of 1 Hz through 33 Hz, the ratio of the two mean spectral accelerations (R.G. 1.60 spectrum to best-estimate site-specific spectrum) is approximately 1.65. This value is less than the ratio between design margins and response factors. This indicates that the piping system has a secondary amplification of the difference in the ground motion. Nevertheless, the mean spectrum acceleration ratio can serve as the adjusting factor due to different input motion.

Table 5-1 Inertia Load Reference Response Factors of Summary Group
Responses vs. Multiple-support Time History Analysis

Inertia Load	Piping System	Group (1)*		Group (2)*		Group (3)*	
		Mean	COV	Mean	COV	Mean	COV
Element Moment	RHR	2.3	0.41	2.0	0.35	2.1	0.38
	AFW	5.0	0.23	3.9	0.25	4.1	0.24
	RCL	5.1	0.43	4.3	0.43	8.0	0.48
Nodal Accel.	RHR	7.7	0.24	6.5	0.37	6.9	0.36
	AFW	6.4	0.15	4.5	0.16	5.5	0.12
	RCL	7.8	0.30	6.3	0.42	12.1	0.42
Element Moment	ALL	4.7	0.46	3.9	0.46	6.6	0.60
Nodal Accel.	ALL	7.7	0.29	6.2	0.41	11.3	0.46

*See Table 3.4 for group members.

Table 5-2 Adjusting Factor F_D for 1% and 5% Damping
With Respect to 2% Damping for Inertial Loads

<u>Piping Damping</u>	<u>Element Moment</u>	<u>Nodal Accel.</u>
1%	1.33	1.30
5%	0.67	0.71

Table 5-3 Adjusting Factor F_I for Average and C.G. Spectrum
With Respect to Envelope spectrum for Inertial Loads

<u>Spectrum Specification</u>	<u>Element Moment</u>	<u>Nodal Accel.</u>
Ave. Spectrum	0.46	0.45
C.G. Spectrum	0.67	0.63

Table 5-4 Reference Response Factor for Pseudostatic Loads

<u>Piping System</u>	<u>Method I</u>		<u>Method II</u>	
	<u>Mean</u>	<u>COV</u>	<u>Mean</u>	<u>COV</u>
RHR	37.7	1.11	1.0	0.46
AFW	12.5	1.33	5.3	0.60
RCL	13.0	0.82	4.4	1.48
Overall	16.2	1.27	4.1	1.55

**Table 5-5 Reference Response Factor for Total Loads -
Pipe Element Resultant Moment**

Piping System	Response Spectrum		Response Spectrum		Response Spectrum	
	Method Group (1)		Method Group (2)		Method Group (3)	
	Mean	COV	Mean	COV	Mean	COV
RHR	2.1	0.37	1.9	0.29	1.9	0.30
AFW	6.4	0.24	5.4	0.31	5.6	0.29
RCL	5.7	0.42	4.9	0.43	7.8	0.40
Overall	5.3	0.47	4.6	0.48	6.1	0.51

Note: Total load is based on combination of inertia and pseudostatic loads by Method A. Inertia load is based on response spectrum method using 2% damping envelope spectrum, and pseudostatic load is based on Method II.

Table 5-6 Adjusting Factor F_M for Combination Method B
and C for Total Seismic Loads

Method B		Method C	
Mean	COV	Mean	COV
0.86	0.115	0.77	0.133

Note: This F_M is valid for the particular condition that the inertial loads be based on response spectrum methods using 2% damping envelope spectrum as input, and pseudostatic loads based on Method II.

Table 5-7 Adjusting Factor F_D for Total Seismic Loads
to Account for Effect of Damping Other than 2%

<u>Piping Damping</u>	<u>F_D</u>
1%	1.23
5%	0.72

Note: Validity of F_D is subject to the Same conditions as for F_M in Table 6-7.

Table 5-8 Adjusting Factor F_I for Total Seismic Loads to Account
for Input Spectrum between Average and Envelope

$$F_I = 0.82$$

**Table 5-9 Inertia Load Design Margins for Response
Spectrum Methods of Analysis**

Inertia Load	Piping	Group (1)*		Group (2)*		Group (3)*	
	System	Mean	COV	Mean	COV	Mean	COV
Element Moment	RHR	4.4	0.34	3.8	0.30	4.0	0.31
	AFW	8.8	0.23	6.8	0.26	7.2	0.24
	SW	17.1	0.64	15.0	0.72	16.1	0.67
	RCL	10.8	0.42	9.1	0.44	17.1	0.52
Nodal Accel.	RHR	3.3	0.53	2.5	0.37	2.6	0.37
	AFW	8.8	0.15	6.1	0.15	7.6	0.16
	SW	39.8	0.36	35.8	0.43	38.1	0.35
	RCL	8.7	0.67	6.1	0.57	13.7	0.80

* Group (1): SRSS-HHV Method;

Group (2): 10%-SRSS, DBS-SRSS, ARC-SRSS, SRSS-SRSS Method;

Group (3): Remaining six methods.

**Table 5-10 Overall Inertial Load Design Margins for
Individual Response Spectrum Method Groups**

Inertial Load	Group (1)		Group (2)		Group (3)	
	Mean	COV	Mean	COV	Mean	COV
Element Moment	13.0	0.68	11.2	0.76	14.9	0.67
Nodal Accel.	20.6	0.89	17.6	1.01	22.5	0.77

Table 5-11 Design Margins for Pseudostatic Loads

Piping System	Method I		Method II	
	Mean	COV	Mean	COV
RHR	126.9	0.86	3.9	0.45
AFW	23.5	1.29	9.7	0.60
SW	(Not Available)			
RCL	27.3	0.83	9.3	1.50
Overall	40.2	1.02	8.6	1.42

Table 5-12 Design Margins for Total Loads -
Pipe Element Resultant Moment

Piping System	Response Spectrum Method Group (1)		Response Spectrum Method Group (2)		Response Spectrum Method Group (3)	
	Mean	COV	Mean	COV	Mean	COV
RHR	4.4	0.28	3.9	0.24	4.0	0.24
AFW	11.0	0.27	8.8	0.34	9.0	0.32
SW	(Not Available)					
RCL	11.2	0.43	9.8	0.47	15.4	0.37
Overall	10.3	0.47	8.9	0.51	13.0	0.50

Note: Total load is based on combination of inertia and pseudostatic loads by Method A. Inertia load is based on response spectrum method using 2% damping envelope spectrum, and pseudostatic load is based on Method II for which results for SW were not available.

Fig. 5-1 Comparison of Mean Response Spectra -- Best-Estimate and RG 1.60: a) North-South, b) East-West, c) Vertical.

6. CONCLUSIONS AND RECOMMENDATIONS

The goal of the current project was to develop an appropriate response factor that can be applied to existing seismic design loads for Category I piping systems in a nuclear power plant, to generate the corresponding best estimate seismic loads. The best estimate seismic loads can then be used as one input to the seismic probabilistic risk assessment (PRA) of the plant. On the other hand, the response factor may be viewed as the margin of conservatism of a particular piping seismic analysis methodology with respect to the best estimate procedure.

Because a variety of seismic analysis methods have been used for the analysis of Category I piping systems in the U.S. nuclear industry, a suitable response factor must be established for each individual method. To identify the possible variation in methodology, we first conducted a survey of the relevant literature, in particular, the Final Safety Analysis Reports (FSAR) that are available at the Region V Office of NRC and the standard SARs from several architect/engineering firms and reactor suppliers. The survey covered most of the commonly used methodologies for seismic analysis of Category I piping systems in the U.S. Due to the time limitation, we did not conduct a complete survey of FSARs of the remaining U.S. nuclear plants, but we are confident that any method not specifically covered by the said survey would be very similar to one of the methods identified through the survey.

The literature survey identified ten different response spectrum analysis methods (other than the absolute sum method) for the piping inertia load analysis considering both modal and directional response combinations; one commonly used equivalent static analysis method for the inertia loads; three pseudostatic load analysis methods to account for the effect of differential movements of pipe supports and anchors; and three ways of combining the inertia and pseudostatic loads to obtain the total loads. The piping system damping for the SSE was found to range from 1% to 5% of critical. Finally, in the response spectrum method of analysis at least three ways have been used to specify the input spectrum based on floor spectra given at the various pipe support/anchor locations. They are the envelope spectrum, the average spectrum, and the spectrum nearest to the C.G. of the piping system.

Having identified the many variations in the analysis methodology, we next performed parametric seismic response calculations based on these identified methods and parameters. Four piping systems from the Zion Nuclear Power Plant were selected. They were the RHR, AFW, SW and RCL piping systems, which include several different pipe sizes and span elevations in the buildings, as described in Section 2. The RHR and AFW piping systems run between structure, while the SW and RCL piping systems are supported within one building. In addition, the RCL piping analysis model is different from the other three in that it consists of such large, massive components as the RPV, steam generators, reactor coolant pumps and pressurizer. This modeling difference gave rise to different characteristics of the seismic responses for certain response spectrum methods (e.g., the SRSS-SRSS method) as we anticipated prior to the parametric study.

Floor response spectra from four different earthquake ground motions were used in the response calculations. The first three earthquake motions were characterized by response spectra compatible with the NRC Regulatory Guide 1.60 design spectra. The fourth earthquake motion was site specific. The four ground motions represent the SSE motions at the Zion plant site, having a peak acceleration of about 0.17g.

The parametric study considered eleven response spectrum methods of analysis for the inertia load computations. They are the ten existing methods in the industry as noted in Subsection 3.2.1 (Methods (1) to (6), and (8) to (11)), plus the ARC method for modal response combination (Method (7)), which was recently published and did not have any industrial application yet. We, however, anticipated the results from the ARC method to be very similar to those from the double-sum technique of modal combination, i.e., Method (5), and this was verified by the parametric response study. In addition to the eleven response spectrum methods of analysis, we considered the equivalent static method of analysis, two pseudostatic load analysis methods (Method I and II as described in Section 3.3), and three ways for combining the inertia and pseudostatic loads (Methods A, B and C as described in Section 3.4). For the piping damping, 1%, 2% and 5% of critical were considered. Regarding the input spectrum for the inertia load analysis, the envelope spectrum, average spectrum, and C.G. spectrum were included. A very limited study was also performed for the RHR piping system to investigate the effect of a spectrum peak frequency shift on the piping response.

The statistical results from the parametric study were presented in Section 5. The piping responses examined were the resultant moments in the elbows, tees, reducers, etc., in both the inertia and pseudostatic load analyses, and the resultant accelerations at selected nodal points in the inertia load analyses. The effect of the variation in the inertia load analysis method on the piping response was represented by the ratio in response between the methods. We choose the SRSS-SRSS technique as the base reference method for the response ratio study. For the total seismic loads, the combination Method (A) (i.e., absolute sum combination) was taken to be the reference basis. For piping damping and input spectrum, the 2% damping envelope spectrum was the reference basis.

Section 5 described the response factor calculations. A reference response factor, CF_{Ref} , was first established for each of the three response spectrum method groups defined in Section 5.1. It represents the mean ratio in response between the particular response spectrum method and the SSMRP best-estimate approach. Adjusting factors were established to supplement the reference response factor, to account for the anticipated variation in methodology. They are F_M , F_D , F_I and F_S , intended to account for the effect of the variation in, respectively, the analysis method, damping, input spectrum specification, and soil-structure interaction analysis methodology. The reference response factors were also established separately for the pseudostatic loads and the total loads.

Based on the outcome of the previous study, we can draw the following conclusions:

- (1) The parametric response calculations produced a data base that was sufficient for studying the effects of the variation in response spectrum analysis method, damping, and input spectrum specification on the piping system response.

- (2) The eleven response spectrum methods of analysis included in our study can be separated into three groups. They are:

Group (1): SRSS-HHV method;

Group (2): 10%-SRSS, DBS-SRSS, ARC-SRSS, and SRSS-SRSS method;

Group (3): The remaining six methods.

With the SRSS-SRSS method as the reference basis, the response ratio statistics of the three method groups vary depending upon whether the piping analysis model includes large, massive components. The results suggested the need to distinguish between a piping analysis model which does not contain any large components, from an analysis model that does, such as the RCL analysis model considered in this study. The two were referred to as the Type (a) (excluding large components) and Type (b) piping analysis models in Section 4. For the Type (b) model, the SRSS-SRSS method needs to be excluded from the method Group (2) and treated as another group because it consistently produced larger seismic response than did the remaining three Group (2) methods. As discussed in Section 4, this results from the unique situation of closely spaced modes that typically exist in a Type (b) piping analysis model.

- (3) The mean response ratio between the SRSS-SRSS and equivalent static methods was about 2.2. This suggests that the equivalent static analysis is, on the average, two times more conservative than the SRSS-SRSS method in determining the resultant moments in the pipes.
- (4) More consistent statistics for the inertia load and total load response factors were observed among the individual piping systems. The same was not true for the pseudostatic load response factors, because piping responses are very sensitive to how the pipe anchor movements are applied to the piping system. This is due mainly to the erratic statistics in the response factor for the pseudostatic loads. Prior to the parametric study, we have anticipated that the greatest uncertainty would take place in the pseudostatic loads because they are very sensitive to how the pipe anchor movements are applied to the piping system.

- (5) The best estimate response generated by using the response factor approach would necessarily contain moderate large uncertainty. The COV from both Table 5-7 and 5-15 for the total seismic loads, which is about 0.50 for all three response spectrum method groups, is a very good indication.
- (6) The response factors in Table 5-7 suggest that the seismic loads from the industrial methods of piping analysis have an inherent margin of conservatism of the order of 5 when compared to the best estimate response. With respect to best-estimate site specific ground motion, such margin is about 10 in accordance with Table 5-15.

Based on the above conclusions and the results presented in the text, we identified further studies that are needed to refine the response factor approach and, hence, reduce the variability in the methodology. Such recommended studies include:

- (1) Expand the data base by examining the responses of more piping systems. The additional study should reduce the uncertainty pertinent to the best estimate might response that is to be generated through the simple response factor approach.
- (2) There are piping systems, typically in the older plants, that were originally classified as non-Category I but later reclassified as safety related items, such as the auxiliary feedwater system in the PWR plants. For such piping systems the response factor approach does not apply because their seismic design loads are most probably not available. For the purpose of PRA applications, however, we believe it is feasible to develop a simplified approach that will directly estimate the seismic loads. So long as the loads so estimated are on the conservative side, the simplified technique will be useful.

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APPENDIX A

EXISTING SEISMIC ANALYSIS METHODS FOR NUCLEAR PIPING

The first task for the simplified methodology project is to identify and, qualitatively, categorize the various methods employed in the U.S. nuclear industry for the seismic analysis of Category I piping systems. These methods are to be applied to the seismic response analysis of the four selected piping systems from the Zion plant, so that the appropriate response factors along with their variabilities can be determined for the individual analysis methods.

A.1 Literature Survey

The methodology identification task was accomplished through a literature survey of conference proceedings, technical journals and, most importantly, the Final Safety Analysis Reports (FSARs) of the nuclear plants and the Standard Safety Analysis Reports (SSARs) of major architect-engineer firms and nuclear steam supplying system (NSSS) suppliers in the U.S. Our first step is to search for all SARs that are available from the NRC Western Regional Office at Walnut Creek, California, because of its proximity to our office. Altogether, the FSARs of 14 nuclear generation units and the SSARs of two architect-engineer firms and three NSSS suppliers were reviewed, as shown below:

<u>Plant Specific FSAR</u>	<u>Standard SAR</u>
Diablo Canyon, Units 1, 2	Combustion Engineers (CESSAR)
Palo Verde, Units 1, 2, 3	Ebasco Services (ESSAR)
Rancho Seco, Unit 1	General Electric (GESSAR)
San Onofre, Unit 1	Stone & Webster (SWESSAR)
San Onofre, Units 2, 3	Westinghouse (RESAR)
Skagit Unit 1, 2	
Trojan	
WPPSS Unit 2	
WPPSS Unit 3	

Through a separate source, we also reviewed the SSAR of Bechtel Power Corporation.

5.2.2 each SAR reviewed, the information pertaining to the method of seismic analysis of piping was identified. An overall summary of this information is shown in Table A-1. In Table A-1, each number in the parenthesis denotes the number of cases encountered that use the same particular technique/method.

To our best judgment, the seismic piping analysis methods we have thus far identified from the SAR survey represent almost all possible variations in the U.S. nuclear industry. In the event a certain method is not covered by the ones identified from the previous literature survey, we strongly believe that it would be so similar to one of the already identified methods that the seismic responses from such method can easily be estimated with reasonable degree of accuracy. We therefore decided that it would not be necessary to also review the SARs that are located in the other NRC regional offices.

A.2 Summary of Seismic Analysis Methods

Our SAR survey, as summarized in Table A-1, indicates that the time history method of seismic analysis has rarely been applied to the Category I piping. The most probable reason is that the time history method is very costly although it is the most straight-forward and desirable from the technical point of view. The majority of the piping systems are analyzed with the response spectrum method of analysis. Depending on the occasion, the equivalent static method of analysis is sometimes used. The seismic loads computed with either one of the two methods are referred to as the "inertial loads" in all subsequent discussions, to be distinguished from the loads caused by the differential pipe anchor movements. The loads due to the differential anchor movement are referred to as the "pseudostatic loads." Combining the inertial loads with the pseudostatic loads gives the total seismic loads in the piping system.

The various methods for the response spectrum analysis and differential anchor movement analysis that we identified from the SAR survey are separately discussed in the following.

A.2.1 Response Spectrum method of Analysis

The various methods differ from each other in three aspects, i.e., the technique for modal response combination, the technique for combining the effects from the three earthquake components, and the order between the modal and the earthquake component combinations. For the modal response combination, six techniques have been identified. They can be conveniently represented by either one of the following general expressions:

$$R = R_1^2 + R_2^2 + \dots + 2 C_{12} R_1 R_2 + \dots + 2 C_{ij} R_i R_j + \dots \quad (A-1)$$

or

$$R = R_1^2 + R_2^2 + \dots + 2 C_{12} |R_1 R_2| + \dots + 2 C_{ij} |R_i R_j| + \dots \quad (A-2)$$

The six modal response combination techniques can then be described as shown in Table A-2. They are the square-root-of-the-sum-of-the-squares (SRSS), ten percent (10%), absolute ten percent (|10%|), grouping (GRP), double sum (DBS), and absolute double sum (|DBS|) techniques. The absolute ten percent, grouping and absolute double sum techniques are currently listed in the NRC Regulatory Guide 1.92.

Three techniques have been identified for the combination of the effects from the three earthquake components:

- (1) SRSS - The square root of the sum of the squares among the three components;
- (2) HHV - The absolute sum of the vertical component (V) and the larger one of the two horizontal components (H_1 , H_2);
- (3) ABS - Absolute sum of all three components.

The HHV technique was typically used in the nuclear industry prior to 1970.

Regarding the priority between the modal and earthquake component combinations, most plants did the modal combination first while the others did in the reversed order. In view of the above, each response spectrum method of analysis is composed of three elements, i.e., the modal response combination technique, the directional combination technique, and the order of execution between the two combinations. Although there could be as many as 36 possible methods resulting from the combination of the six modal combination techniques, three directional combination techniques and two different orders of execution, our SAR review identified only 11 methods. They are represented by the matrix shown in Table A-3.

A.2.2 Specification of Input Floor Spectrum

The SAR survey indicated that there have been four ways of designating an input floor spectrum from the floor response spectra associated with the various pipe supports. They are denoted by:

- (1) Envelope Spectrum - This is obtained from the envelope of all pipe support location floor spectra.
- (2) Average Spectrum - This is the spectrum representing the average of all pipe support location floor spectra.
- (3) C.G. Spectrum - This is the one floor spectrum that is nearest to the center of gravity (C.G.) of the piping system. The C.G. is usually located by inspection in lieu of a precise calculation and, hence, an inherent uncertainty always exists.
- (4) Single Worst or Highest Elevation Spectrum - This is the one single floor spectrum judged to be the worst or associated with the pipe support located at the highest elevation among all pipe supports under consideration. We observed that such spectrum is usually very close or identical to the envelope spectrum, due simply to the fact that the amplitude of the floor spectrum usually increases with elevation within the same building.

A.2.3 Equivalent Static Method of Analysis

The equivalent static method of analysis is intended as a simple and approximate substitution for the response spectrum method of analysis in computing the inertial seismic loads in the piping system. Only a static analysis of the piping is required for this method, and the seismic input is a uniform acceleration applied to the entire system in each earthquake direction. Such acceleration is conservatively taken to be the peak spectral acceleration response on the input floor spectrum. Unless it can be ascertained that the system is seismically rigid (e.g., the fundamental frequency exceeds, say, 33 Hz), the analysis results are further increased by a factor of 1.5 to account for the effect of the higher modes. In the event the piping system can be demonstrated as seismically rigid, the uniform seismic acceleration to be applied in the static analysis is the floor acceleration or, as commonly called, the ZPA (zero period acceleration) on the input floor spectrum and no increase factor of 1.5 is used.

A.2.4 Analysis for Differential Anchor Movement

Both the response spectrum and the equivalent static method of analysis determine the inertial seismic loads that do not account for the effect from the differential pipe support movements. Such effect, denoted as the pseudostatic loads, is determined by a static analysis of the piping system in which the input is not the seismic acceleration, but the pipe anchor movements as computed during the seismic analysis of the building. The pseudostatic loads are then combined with the inertial loads in determining the total seismic loads.

Our SAR survey as summarized in Table A-7 revealed that there are essentially three ways of obtaining the pseudostatic loads. They are discussed as follows:

- (1) Method I - Apply one support movement at a time in the static analysis while the other supports are held fixed. Perform as many analyses as the number of supports/anchors, and the results from these analyses are combined using the SRSS rule.

- (2) Method II - Apply the support/anchor movements in the most critical manner for the analysis. None of the SARs we reviewed gives specific details on how the support movements are to be applied, and it appears there is no one unique way for inputting the support movements that would be most critical, simultaneously, for all elements of the piping system.
- (3) Method III - To execute this method, one must have the information of the anchor movements per structural mode from the seismic analysis of the building. The pipe support movements per structural mode are then applied to the piping analysis in accordance with the phase relationships dictated by the particular structural mode shape. As many analyses as the number of significant structural modes are performed, and their results are combined on the SRSS basis to determine the total loads.

From the above discussions, only Methods I and III are straightforward and will produce a unique set of pseudostatic pipe loads. Method II is very loosely defined, but is a widely adopted method.

Table A-1 Summary of SAR Survey for Category-I
Piping Seismic Analysis Methods

(A) Summary:

	Time History Method	Analysis Method		Equivalent Static Method
		Response Spectrum Method (A)**	(B)**	
NSSS Piping	[1]*	[10]	[3]	[6]
Other than NSSS Piping	---	[6]	[3]	[8]

(B) Response Spectrum Methods:

(a) Modal & Directional Combination Techniques

Component Combination	Modal Combination	SRSS	Ten Percent, Absolute Ten Percent & Grouping	Double Sum & Abs. Double Sum
Larger of H1+V and H2+V		[1]	---	---
SRSS for H1, H2 & V		[3]	[9]	[2]
Abs. Sum for H1, H2 & V		---	[1]	---

(b) Method for Specifying Input Spectrum from Multi-Support Spectra

	Worst Single or Highest Elev.	Envelope	Average	At. C. G. or Mass Concentration
In Same Bldg.	[8]	[3]	--	[1]
Between Bldgs.	[1]	[9]	[1]	---

Notes: * Number in bracket indicates the number of cases encountered that use the same methodology.
 ** (A) means modal combination prior to directional combination, and (B) means the reverse.

Table A-1 (continued)

(C) Equivalent Static Methods:

- (a) Using 1.5 times floor spectrum peak as acceleration coef. . . [6]
- (b) Using ZPA on floor spectrum as acceleration coef. [1]
- (c) Simplified analysis using first mode spectrum
acceleration for the longest span. [1]

(D) Methods for Considering Differential Anchor Movements:

- (a) Applying support displacements in such a manner as to
produce the most critical stresses. [6]
- (b) Applying one support displacement at a time, and
combining all analyses by SRSS. [1]
- (c) Applying maximum modal displacements according to
each structural mode, and combining all modal results
by SRSS or Double Sum. [4]

(E) Piping Damping

- (a) R.G. 1.61 Damping. [13]
- (b) Prior to R.G. 1.61:
 - o OBE: 0.5% [10]
 - 1.0% [1]
 - 2.0% [1]
 - o SSE: 0.5% [7]
 - 1.0% [4]
 - 2.0% [1]
 - 4.0% [1]

Table A-1 (continued)

(F) Miscellaneous Information:

(a) Ground Input Motion Spectrum:

Housner Spectrum [2]

Newmark Spectrum [3]

R.G. 1.60 Spectrum [3]

(b) Cut-off Frequency for "Rigid" Piping:

20 Hz. [2]

33 Hz. [7]

Table A-2 Modal Response Combination Techniques
Identified from the SAR Survey

Modal Response Combination Technique	Abbreviation	Applicable Equation	Model Coupling Factor c_{ij}
1. Square Root Sum of Squares	SRSS	(A-1) or (A-2)	= 0
2. Ten Percent	10%	(A-1)	= 1 if f_i and f_j differ by 10% or less;
*3. Absolute Ten Percent	10%	(A-2)	= 0 otherwise.
*4. Grouping	GRP	(A-2)	= 1 for modes within any group bounded by frequencies less than 10% apart; = 0 otherwise.
5. Double Sum	DBS	(A-1)	See note ** below.
*6. Absolute Double Sum	DBS	(A-2)	

* These are techniques listed in Reg. Guide 1.92 also.

$$^{**} c_{ij} = \frac{1}{1 + [(w_i' - w_j') / (B_i' w_i + B_j' w_j)]^2}$$

$$w_j' = w_j \sqrt{1 - B_j^2}$$

$$B_j' = B_j + 2/w_j t_d$$

w_j, B_j = modal frequency (rad/sec) and modal damping ratio, respectively

Table A-3 The Eleven Response Spectrum Methods of
Analysis Identified from the SAR Survey

Directional Combination Technique	Modal Combination Technique					
	SRSS	GRP	10%	10%	DBS	DBS
SRSS	A	A,B	A	A,B	A	A,B
HHV	A	--	--	--	--	--
Abs. Sum	--	A	--	--	--	--

- Notes: (1) See Table A-2 for abbreviations of the modal response combination techniques.
- (2) A = modal combination prior to directional combination, and B = the reverse of "A".
- (3) HHV = larger of H_{1+V} and H_{2+V} .

APPENDIX B

SSMRP APPROACH FOR TIME HISTORY ANALYSIS OF PIPING SYSTEMS

The equation of motion of a multi-support piping system can be expressed as follows:

$$\begin{matrix} M_1 & & & & & & & & \\ & x_1 & + & C_{11} & C_{12} & & x_1 & + & K_{11} & K_{12} & & x_1 & = & 0 \\ & M_2 & x_2 & + & C_{21} & C_{22} & x_2 & + & K_{21} & K_{22} & x_2 & = & P_2 \end{matrix} \quad (B-1)$$

in which x_1 and x_2 are the absolute displacements for the active degrees-of-freedom and specified support degrees-of-freedom, respectively. Equ. (B-1) can be rewritten as:

$$[M_1] \ddot{x}_1 + [C_{11}] \dot{x}_1 + [K_{11}] x_1 = -[C_{12}] \dot{x}_2 - [K_{12}] x_2 \quad (B-2a)$$

and

$$[M_2] \ddot{x}_2 + [C_{22}] \dot{x}_2 + [K_{22}] x_2 = -[C_{21}] \dot{x}_1 - [K_{21}] x_1 + P_2 \quad (B-2b)$$

Separate the absolute displacement (x_1) into two parts, i.e.,

$$x_1 = x_1^s + x_1^d \quad (B-3)$$

in which the first term x_1^s is defined by

$$[k_{11}] x_1^s = -[k_{12}] x_2 \quad (B-4)$$

and is termed the "pseudostatic" component of x_1 . Substituting Equ. (B-3) into Equ. (B-2a) and neglecting all damping force terms associated with x_1^s and x_2 , we have

$$[M_1] \ddot{x}_1^d + [C_{11}] \dot{x}_1^d + [K_{11}] x_1^d = -[M_1][K_{11}]^{-1}[K_{12}] x_2 \quad (B-5)$$

Assuming that the damping matrix $[C_{11}]$ can be diagonalized by the mode shapes associated with $[M_1]$ and $[K_{11}]$, Equ. (B-5) can then be solved by the normal mode superposition technique, with the damping now specified in terms of the modal damping.

The solution of Equ. (B-5) gives the nodal absolute acceleration response, $\ddot{x}_1^d$, and the "inertial" component of the displacement response, x_1^d . Equ. (B-4) is then solved for the pseudostatic component, x_1^s . Both $\ddot{x}_1^d$ and x_1^s can then be used to compute the inertial and pseudostatic components, respectively, of the stresses and bending moments in the pipe elements.

In summary, the nodal accelerations are due only to the inertial component, and the pipe element stresses/moments are contributed by both the inertial and pseudostatic parts of the response.