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Response Margins of the Dynamic Analysis of Piping Systems

J. J. Johnson,* B. J. Benda,* T. Y. Chuang, and P. D. Smith

Prepared for
U.S. Nuclear Regulatory Commission

*Structural Mechanics Associates, 2400 Old Crow Canyon Rd., San Ramon, CA

Lawrence Livermore National Laboratory

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Prepared by
J. J. Johnson,* B. J. Benda,* T. Y. Chuang, and P. D. Smith

Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550

Prepared for
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN No. A0387

*Structural Mechanics Associates, 2400 Old Crow Canyon Rd., San Ramon, CA

ABSTRACT

The seismic response of piping systems is frequently separated into two parts -- the inertial response and the pseudostatic response. Various analysis procedures have been developed to calculate each portion of the response separately. The analysis procedures used are frequently simplified and, in so doing, introduce significant conservatism. Conservatism in the US NRC SRP response spectrum analysis methodology is quantified here as measured against a multi-support time history analysis procedure. Also, best estimate piping system responses are compared to design values which is valuable to seismic PRA applications.

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Executive Summary

In the design of nuclear power plant piping systems, a compromise is often required between demands placed on the design by seismic and non-seismic considerations. General design objectives for seismic loads dictate a stiff piping system; objectives for thermal loads, for example, require a flexible system. The final design is seen as a trade-off between these two opposing objectives.

There has been growing concern that seismic considerations dominate the design of nuclear power plant piping systems to a greater extent than is necessary. This bias comes at the expense of design objectives specified by normal or frequent loadings and thus leads to piping systems that are relatively rigid under non-seismic loading conditions. Increased loads under normal operation and decreased piping system reliability can result.

One aspect contributing to the dominance of seismic considerations is the margin or conservatism introduced by methods of seismic analysis. These requirements were introduced because of legitimate concern regarding uncertainties in defining both analysis methods and parameters input to the analyses that dictate the dynamic characteristics of piping systems. The requirements are specified in terms of defining an acceptable calculational procedure that introduces conservatism in the seismic analysis calculations. A partial list of these requirements follows:

- three components of input motion with broad-band response spectra (US NRC Regulatory Guide RG 1.60) [1]
- damping values (RG 1.61) [2]
- broadened in-structure spectra (RG 1.122) [3]
- enveloping spectra at piping system supports (NRC Standard Review Plan 3.9.2) [4]
- modal combination rules (RG 1.92) [5]

Although these requirements successfully introduce margin in the analysis results, the quantity and variation of the margin remains undefined. The purpose of this study is to quantify the calculational margin associated with a commonly used seismic analysis procedure incorporating these requirements - a response spectrum method - relative to a "best estimate" time history analysis approach.

Three analysis methods were studied. One method employed the response spectrum techniques defined in the NRC Standard Review Plan (SRP). Quantifying the conservatism in this method is our objective. The remaining two methods, labeled herein as "RG 1.60" and "best estimate", used a multisupport time history analysis technique and formed the basis for our response comparison. Key features of the analyses are described in Table 1.

Three piping system models were considered. The characteristics of the models in terms of size, stiffness and complexity represent a range of nuclear piping configurations. However, the three models were relatively low frequency in that their fundamental modes were below 4 Hz. Piping response in the form of nodal accelerations and displacements and element forces and moments were determined. Calculational margins were quantified by taking the ratio of response defined by the SRP method to those given by the best estimate time history analyses.

Several observations and conclusions can be drawn from the analysis results. Large margins result from the analysis of piping systems by the SRP procedure. Despite representing lower bounds, ratios of response calculated by SRP methods versus best estimate time history values still range as high as 16.9. These calculational margins vary significantly from piping system to system. Factors of conservatism increase with increased complexity of the piping system. In particular, for systems having many supports, each with significantly different inputs, large calculational margins result from the SRP methods.

Table 1. Key Features of Analyses used to Estimate Calculational Margin.

Issue	Type of Analysis		
	SRP	RG 1.60	Best Estimate
Input Time Histories	Three sets of time histories which had RG 1.60 as a target were used. Peak acceleration was 0.18g.	Thirty sets of time histories which had RG 1.60 as a target were used. Peak acceleration was 0.18g.	Ninety sets of time histories which had realistic spectra were used. The median peak acceleration was 0.18g and it varied between 0.15g and 0.30g.
Uncertainty in SSI and Building Response	Broaden in-structure response spectra at piping system supports.	Shift soil/structure properties over the range of values defined by an assumed probability distribution for each of the 30 analyses.	Shift soil/structure properties over the range of values defined by an assumed probability distribution for each of the 90 analyses.
Uncertainty in Piping System Models	Not treated explicitly.	Not treated explicitly.	Shift piping system modal properties over the range of values defined by an assumed probability distribution for each of the 90 analyses.

Table 1. Key Features of Analyses used to Estimate Calculational Margin (Cont.)

Issue	Type of Analysis		
	SRP	RG 1.60	Best Estimate
Response Analysis	Time history analyses were performed for SSI and building response; free-field time histories in three directions were applied simultaneously. Broadened, enveloped, in-structure response spectra were developed for each of the three directions. Response spectrum analyses were performed on each piping system. The process was repeated three times to minimize the effects of free-field time histories.	Time history analyses were performed throughout; a total of 30 analyses including SSI, building and piping system response. Time history analyses of the piping systems used a multiple independent support approach where each support of the piping system was excited by a time history calculated in the SSI and building analyses.	Time history analyses were performed throughout; a total of 90 analyses including SSI, building and piping system response. Time history analyses of the piping systems used a multiple independent support approach where each support of the piping system was excited by a time history calculated in the SSI and building analyses.

Table 1. Key Features of Analyses used to Estimate Calculational Margin. (Cont.)

Issue	Type of Analysis		
	SRP	RG 1.60	Best Estimate
Modal Combination Rules on Piping Systems	RG 1.92 Grouping Method	Time history analyses were used for all modes up to 33 Hz, so no approximate rule for modal combination was required.	Time history analyses were used for all modes up to 33 Hz, no approximate rule for modal combination was required.
Piping System Damping	2% in-structure response spectra were used.	2% damping was used in each mode.	A median value of 2% damping was used in each mode.
Response Calculation	Mean of 3 analyses.	Median of 30 analyses.	Median of 90 analyses.
Margin Criteria	Margin calculated as the quotient of the mean of the SRP and medians of RG 1.60 or best estimate results.		

1. INTRODUCTION

The seismic response of spatially distributed systems like piping is frequently separated into two parts -- the inertial response and the pseudo-static response due to the relative motions of the system supports. Various analysis procedures have been developed to calculate each portion of the response separately. In its Standard Review Plan (SRP) [4], the US Nuclear Regulatory Commission (NRC) prescribes acceptable methods to be used in the analysis of multiply-supported equipment and components with distinct inputs. One approach is to calculate the inertial response by the response spectrum analysis method, using as input envelopes of support motions in each of three orthogonal directions (two horizontal and the vertical). Response due to the relative displacements of the supports is obtained from a static analysis by imposing support displacements on the piping system in the most unfavorable combination. A second approach prescribed by the SRP to determine total pipe response states that time histories of support motions may be used to excite the subsystems. However, due to the increased analytical effort of this second approach and the increased coordination that must exist between the analyst of the primary structure and the analyst of the subsystems, multisupport time history analyses are seldom performed.

It is generally recognized that the simpler response spectrum approach introduces conservatism or margin into the analysis, i.e. trading calculational margin for simplicity. These margins result, among other reasons, from regulatory guidelines which dictate the manner in which input spectra are broadened and enveloped (RG 1.122), specify conservative damping values (RG 1.61), and define the procedure for combining modal components of response (RG 1.92). The amount of margin associated with the simpler SRP approach measured relative to time history analyses was investigated in the present study.

Three different types of piping analyses were performed. Two were based on the multisupport time history analysis procedure used in the US NRC's Seismic Safety Margins Research Program (SSMRP) [6]. The first time history analysis method employed the best approximation to the seismicity, soil properties, structure and piping dynamic characteristics and explicitly included uncertainty in their definition. This analysis is denoted "best estimate." The second time history analysis approach differed from the first primarily in the definition of the seismic input; in this case, time histories generated by the nuclear industry to meet the requirements of US NRC Regulatory Guide 1.60 were used as input. Also, in this latter case, no uncertainty in the piping system dynamic properties were included. Results obtained by this second time history analysis are denoted "RG 1.60" later in this report. The third analysis method employed the SRP response spectrum approach.

Within the time history analysis, three components of response - inertial, pseudostatic, and total- were calculated and saved separately for comparison purposes. The SRP response spectrum method was used to calculate inertial response. Hence, direct comparison of inertial responses calculated by best estimate time history analysis and response spectrum analysis is made herein. No static analysis was conducted to calculate pseudostatic response corresponding to the simpler SRP response method. However, to permit a comparison of total response calculated by the three procedures, pseudostatic response as determined by the RG 1.60 time history method was added to the inertial response calculated by the response spectrum method to form a lower bound estimate of the total response given by the simpler SRP approach. Total responses were then compared.

Response margins associated with the SRP response spectrum method are determined by the ratio of the SRP response to the best estimate response values. Displacements, accelerations, and forces and moments were compared.

This report is organized as follows. Section 2 describes the three piping systems of the Zion nuclear power plant which formed the basis of the present study. Section 3 describes the analysis methods and the analyses performed. Section 4 presents the numerical results; the principal results presented as comparisons of response calculated by best estimate time history analysis methods vs. the SRP response spectrum technique. Section 5 draws conclusions from the results. Appendix A contains a brief description of the mathematical models that defined the structures containing the three piping systems. Response from these models provided input to the piping models. Appendix B provides a detailed derivation of the pseudostatic mode approach to the multisupport time history analysis method used in this study.

2. DESCRIPTION OF STRUCTURES AND PIPING SYSTEMS

The Zion nuclear power plant, Zion, Illinois, (Fig. 1) was the subject of the analyses conducted. Two structures, the containment building and the auxiliary-fuel handling-turbine (AFT) building complex, house the piping systems of interest in this study. These structures were combined with soil models in a soil-structure interaction analysis to obtain the support motions input to the piping systems. Models for all the structures and piping systems analyzed here were originally developed for the SSMRP [7], [8]. A brief description of the structural models appears in Appendix A.

Three piping models were considered in the study - one modeling a portion of the auxiliary feedwater system (AFW), one modeling a portion of the residual heat removal (RHR) and safety injection system, and a model of the reactor coolant loops (RCL). The AFW system provides emergency cooldown capability upon loss of the normal main feedwater system. The part of the system from one steam generator to the containment penetration was analyzed (Fig. 2). The RHR system removes residual heat from the core and reduces the temperature of the reactor coolant system. The safety injection (SI) system is designed to cool the core and to limit the metal-water reaction. A portion of the RHRSI system residing principally in the AFT complex was analyzed (Fig. 3). All supports for the RHR model were in the AFT complex except an anchor inside containment. The reactor coolant system transfers the heat generated in the core to the steam generators where steam is produced to drive the turbines. A model of the reactor coolant loop piping (Fig. 4) was used in this study. The model contains all four main reactor coolant loop piping systems, six branch lines, and all major equipment including the reactor pressure vessel, four steam generators, four reactor coolant pumps, and a pressurizer. Detailed mathematical models were used for each system.

Some parameters indicating the characteristics of the models are given in Table 2. It can be seen that the size and complexity of the piping systems varies substantially. The RHR is the smallest and least complex in terms of modes and number of supports. The RCL is the largest and most complex of the three, whereas the AFW lies in between. The AFW and RCL models are housed entirely in the containment building. The RHR model, as mentioned above, resides principally in the AFT complex. In all cases, the number of modes included in the analysis was sufficient to obtain a frequency of 33Hz. or above.

Response was determined at selected nodes and elements for each piping system model. Location of the response points were areas where we anticipated peak stresses - at elbows, reducers and tees. However, no stress calculations were performed for dead weight, thermal, and pressure loading conditions which when combined with seismic would have permitted a comparison with the allowable stress at each response location. Past experience dictated the selected locations and they are expected to be points of peak stress. Nodal accelerations, reactions in support elements, and resultant pipe element bending moments were calculated. Resultant moments were defined by the amplitude of the vector sum of the two orthogonal bending moments and the torsional moment. For the AFW model, 50 acceleration components and 51 element forces/moments were determined; for the RHR model, 28 accelerations and 37 forces/moments; for the RCL model, 51 accelerations and 210 forces/moments.

Table 2. Parameters of the Subsystem Models ·

Piping system	No. of nodes	No. of equations	No. of support motions	No. of modes considered	Fundamental frequency (Hz)
AFW	263	945	45	36	2.9
RHR	96	423	21	18	3.9
RCL	760	2941	127	130	1.4

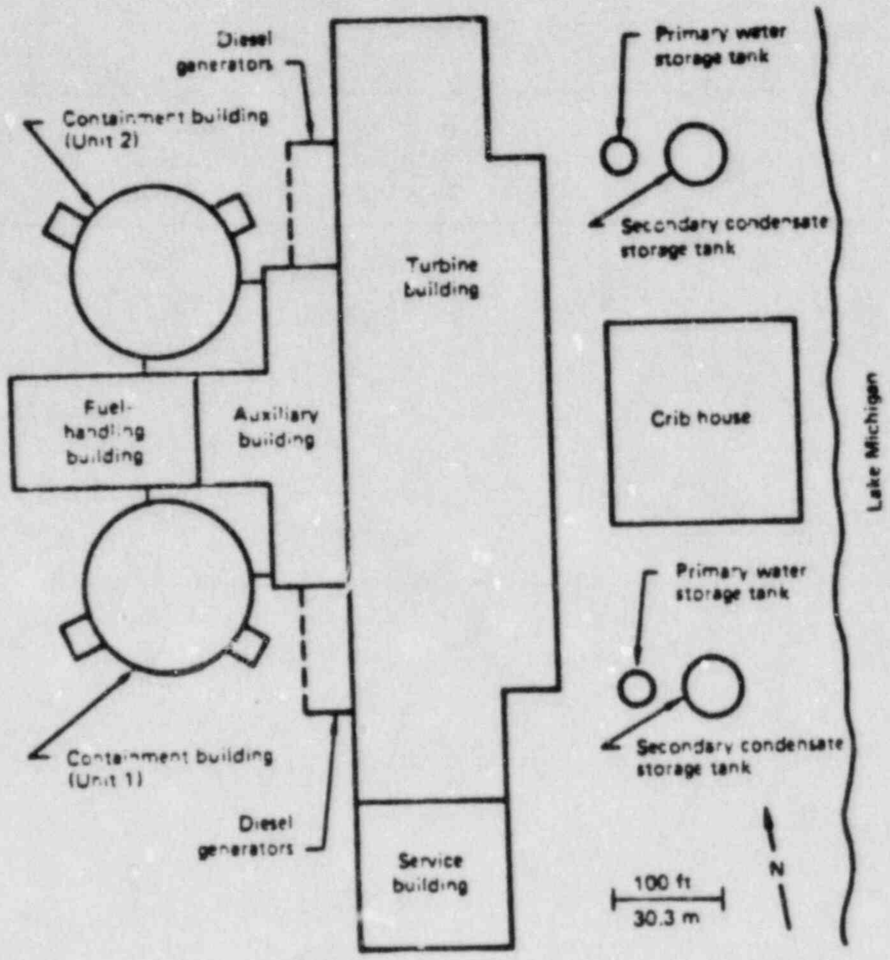


Fig. 1. Site Plan of the Zion Nuclear Power Plant.

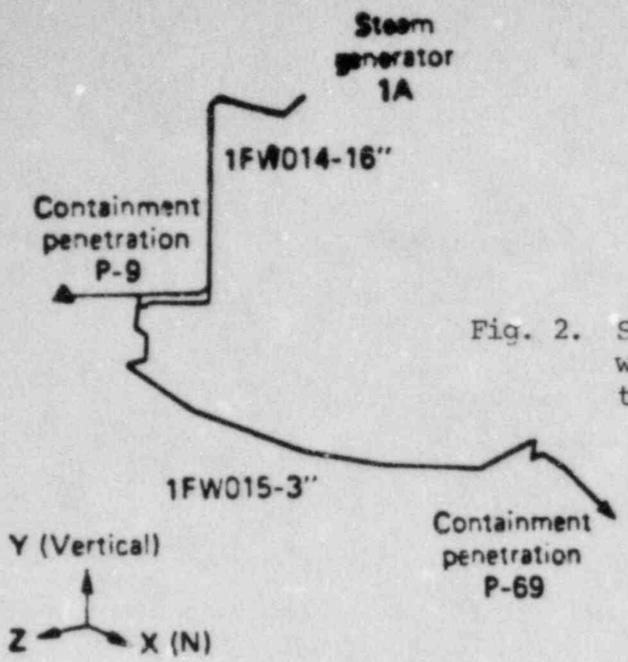


Fig. 2. Schematic Drawing of the Auxiliary Feedwater Piping System Inside Containment to Steam Generator 1A.

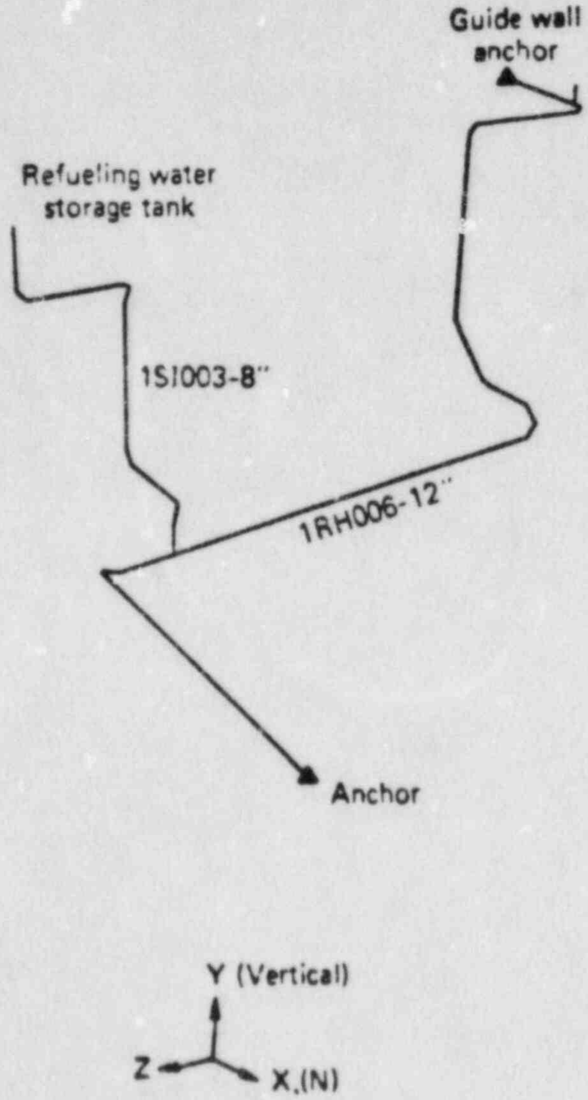


Fig. 3. Schematic Drawing of the Residual Heat Removal and Safety Injection Piping in the AFT Complex.

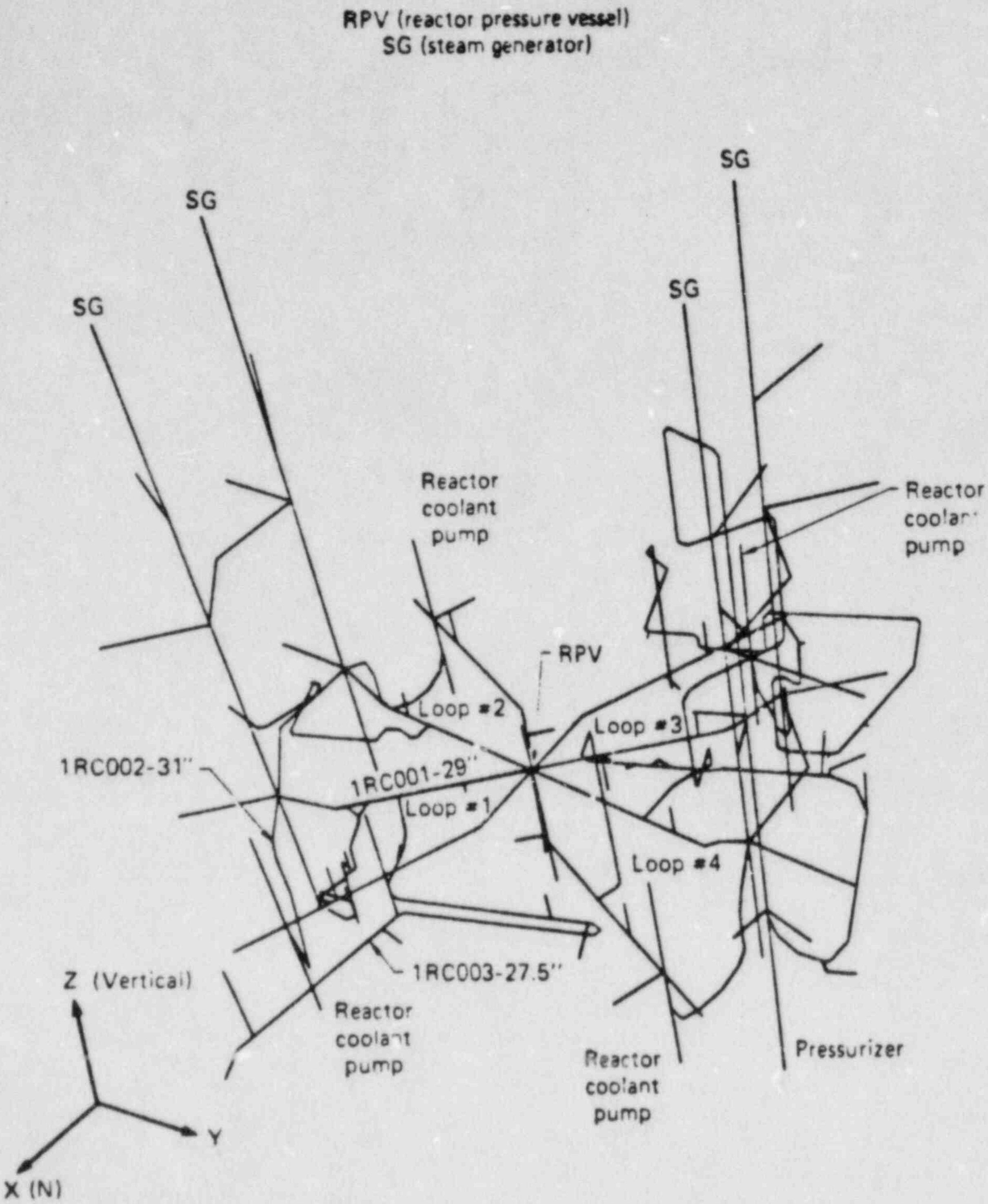


Fig. 4. Schematic Drawing of the Reactor Coolant Loop Piping.

3. METHODS OF ANALYSIS AND ANALYSES PERFORMED

As this study compares the results of different piping analysis methodologies, an understanding of the mechanics of these methods is essential to appreciate the differences in the results and to understand the conclusions that are drawn concerning these differences. In this section we give detailed descriptions of the time history and response spectrum analysis methods and of the piping system analyses conducted with these methods.

3.1 MULTI-SUPPORT TIME HISTORY ANALYSIS

The muti-support time history analysis procedure used in this study was developed for the SSMRP [6] . The computer program SMACS embodies the methodology used in the SSMRP to calculate both the seismic response of structures and piping systems and the variation in these responses. SMACS performs time history analysis linking seismic input with the calculation of soil-structure interaction (SSI), major structure response and piping system response. The seismic input is defined by an ensemble of acceleration time histories in three orthogonal directions (two horizontal and a vertical) on the surface of the soil. SSI and detailed structure response are determined simultaneously using the substructure approach. Piping systems are analyzed using the pseudostatic mode method assuming independent piping support motions obtained from the detailed structural response analyses.

The modus operandi of SMACS is to perform repeated deterministic analyses, each analysis simulating an earthquake occurrence. By performing many such analyses and by varying the values of several input parameters, we are able to account for the uncertainty inherent in any deterministic analysis. Uncertainty was explicitly considered in each step of the seismic methodology chain. Variability in the seismic input is included by sampling to obtain a different set of earthquake time histories for each simulation. Variability in the soil-structure-piping system behavior is introduced for each simulation by sampling values of the input parameters (soil shear modulus and damping, and structure and piping system frequency and damping) from assumed probability distributions according to a Latin hypercube experimental design [6] . This design efficiently spans the parameter spaces. Variations in the SMACS input parameters for the present analyses were selected to represent total uncertainty -- random and modeling. Parameter variations are discussed in Secs. 3.1.1 and 3.1.2.

Further discussions of the SMACS methodology can be found in the cited references and, for the most part, will not be presented here. However, since the thrust of the present study deals with comparisons of piping system responses, a detailed explanation of the pseudostatic mode approach to multisupport excitation analysis which was used to determine piping system response has been included in Appendix B.

3.1.1 Best Estimate Time History Analysis

As mentioned earlier, two different sets of multisupport, time history analyses were conducted. The first set was denoted "best estimate" and is described here.

To perform a time history analysis with the SMACS code, the following information must be assembled:

- Ensemble of free-field acceleration time histories which represent variability in the seismic input.
- Best estimate SSI, structure, and piping models.
- Input parameter variations (soil shear modulus and material damping; and structure, and piping frequency and damping) in the form of probability distributions
- Experimental design

Following is a brief discussion of each aspect of input

Free-field motion. An ensemble of ninety sets of three components of acceleration time histories (two horizontal and the vertical) defined the seismic input. This set of earthquakes reflects the seismicity of the Zion site but does not explicitly include local site effects. The peak horizontal acceleration is the parameter of each earthquake which corresponds to the seismic hazard curve. It is randomly aligned in the two horizontal directions for each of the ninety earthquakes. The median peak horizontal acceleration for the ninety earthquakes is 0.18g; the range of peak horizontal acceleration is from 0.15g to 0.30g. The median peak vertical acceleration is 0.08g. This ensemble of earthquakes is the best estimate seismic hazard corresponding to a safe shutdown earthquake (SSE) of 0.18g peak horizontal acceleration. Figure 5 shows the mean and the mean-plus-one-standard deviation response spectra, for 5% damping, generated for the three components of input motion; X and Y denote horizontal components, Z denotes vertical. The coefficient of variation (COV) of the peak and spectral accelerations ranged from 0.25 to 0.45 depending on the component and frequency range of interest.

Best estimate models. SSI, structure, and piping system models used in this study were originally developed for the SSMRP and are discussed in detail in Refs. 3, 4, and 5. Two aspects of the model development are highlighted here. First, SSI, structure, and piping system models were developed based on actual material data rather than design values. Second, excitation dependent parameters, e.g. soil shear modulus, soil material damping, and structure and piping system damping, were selected to correspond to stress levels developed in the respective media due to the range of excitations considered. Preliminary calculations of the response of structures and piping systems indicated low stress levels in the structures and piping systems. Consequently, nominal damping ratios shown in Table 3 were used in the analysis. Soil properties corresponding to a free-field excitation of 0.18g peak acceleration were used.

Input parameter variations. As discussed earlier, uncertainties in seismic input, SSI, structure response, and piping system response are treated explicitly in the SMACS response calculations. A limited number of input parameters are used to incorporate uncertainty: in the seismic input, an ensemble of time histories; in SSI, the mechanism to include variability is soil shear modulus and material damping in the soil; in structures and piping systems, variations in frequencies and modal damping are the mechanisms. In seismic risk and probabilistic response analyses, it is helpful to distinguish between two types of uncertainty -- random uncertainty and modeling uncertainty. Random uncertainty is fundamental to the phenomenon being represented. It is also irreducible given present state-of-the-art understanding and modeling of the phenomenon. Modeling uncertainty reflects incomplete knowledge of the model itself. Modeling uncertainty, in many cases, can be reduced within present limits of the state-of-the-art by improved analytical models, tests, etc. The combination of random and modeling uncertainty yields total uncertainty. For the present study, variability in input parameters was selected to represent total uncertainty and assumed minimal knowledge of the Zion facility. This fact is important to interpretation of the comparisons of Sec. 4. Assuming total uncertainty on the input parameters yields larger dispersion and a greater range of calculated responses. Hence, when comparing best estimate responses at a specified nonexceedance probability with SRP calculated values, the calculated conservatism will be a lower bound. Variability in the input parameters is described by assumed lognormal distributions. Table 4 tabulates the coefficients of variation (COVs) used in the present study.

Experimental design. The SMACS analysis used a Latin hypercube experimental design to efficiently sample the parameter spaces for a limited number of simulations. For our best estimate analysis, 90 earthquake simulations were performed. Hence, 90 sets of three components of motion (270 time histories) were selected. Next, the distribution of each variable input parameter was divided into 90 equal-probability intervals. A value was randomly selected from each interval, and the 90 values for each variable were rearranged randomly. The 90 sets of time histories and the permuted values of the variable parameters were then grouped to give 90 combinations of input values for the dynamic analyses. Therefore, in a series of 90 analyses, each time history set is used once, and a parameter value was selected once from each of the 90 intervals in each of the parameter distributions. The set of 90 input combinations is called a Latin hypercube sampling set.

The 90 "best estimate" analyses performed gave 90 values for every piping system response request. In addition to the total response values, for each request, the inertial and pseudostatic components of response were also calculated. Figure 6 shows the distribution of the total response for a typical component as given by the 90 analyses. From such a curve, response values corresponding to the median (50th percentile) or other non-exceedence probability values can be determined.

3.1.2 RG 1.60 Analysis

The second time history analysis method is denoted "RG 1.60" and differs only in selected aspects from the best estimate analysis. The principal difference is in the definition of the seismic input. An ensemble of thirty sets of three components of acceleration time histories (two horizontal and the vertical) defined the seismic input. Each set was generated to meet the requirements of the US NRC Regulatory Guide 1.60; hence, the name RG 1.60 analysis. This data was obtained from the nuclear industry. The three components of motion were scaled such that the two horizontal components had equal peak accelerations of 0.18g and the vertical component had a peak acceleration of 0.12g. In addition, the three components were verified to be statistically independent, i.e. correlation coefficients less than 0.16. Figure 7 shows mean and mean-plus one-standard-deviation response spectra of the RG 1.60 data set. One observes the relatively small variation in spectral acceleration due to the fact that each time history was generated to the same target response spectra. COVs of approximately 0.1 are typical for the amplified frequency range (1 Hz to 10 Hz). Smaller COVs in other ranges. A comparison of the best estimate seismic input and RG 1.60 input is shown in Fig. 8; mean response spectra are compared. These differences constitute in part the differences in piping responses presented in Sec. 4.

The SSI, structure, and piping models used in the RG 1.60 analyses were identical to those used in the best estimate analyses. Nominal values of the input parameters were likewise identical.

A second difference between the best estimate analyses and the RG 1.60 analyses was the variation assumed for the input parameters. Variability in soil and structure parameters was identical; however, no variability in the piping system parameters was included. Subsystem frequencies and modal damping were held constant at their nominal values. Table 5 summarizes the variability. Holding piping system frequencies and damping constant at their nominal values is akin to performing a design analysis where the time history approach is used and variability in the seismic input, SSI models, and structure is explicitly accounted for by the subject parameter variations.

The final difference between the best estimate and RG 1.60 analyses is the number of earthquake simulations (30 vs. 90). Hence, development of the experimental design is based on 30 simulations for every piping response request, the inertial, pseudostatic, and total responses were obtained from each of the thirty analyses. A distribution of total response for a selected component from each piping system is shown in Fig. 9. The response component is the same as that shown in Fig. 6. As before, median response and response values corresponding to given non-exceedance probabilities are obtained from such a curve.

3.2 US NRC SRP RESPONSE SPECTRUM ANALYSIS

In the US NRC Standard Review Plan (SRP) [4] Sec. 3.9.2, acceptable methods for the analysis of multiply supported equipment and components subjected to distinct input motions are specified. As discussed previously, response is often separated into two parts -- the inertial response and the pseudostatic response. One acceptable and frequently used approach is to calculate the inertial response by a response spectrum analysis. The pseudostatic response is obtained by imposing support displacements on the piping system in the most unfavorable combination and performing a static analysis.

In this study, the inertial component of response for the "SRP" results was determined using the response spectrum method. The calculational process proceeded as follows. Three sets of acceleration time histories were selected at random from the group of 30 used in the RG 1.60 analysis. SSI and structure response calculations were performed for each of the three earthquakes. No variability was included in the SSI or structure response; all input parameter values were held at their nominal values. Response spectra were generated at structure node points supporting the AFW, RHR, and RCL piping systems; each earthquake defined a unique set of support point response spectra. These raw response spectra were broadened in accordance with US NRC Regulatory Guide 1.122 [3]. After broadening, response spectra corresponding to the piping system support points were grouped according to component direction (X, Y, or Z). For each direction, an enveloped spectra was generated which defined the input for the subsequent response spectrum analysis. Figure 10 shows typical enveloped response spectra.

Three response spectrum analyses were performed for each piping system -- one for each earthquake. For each analysis, modal and directional combination rules defined in the NRC Regulatory Guide 1.92 [5] were followed. The "grouping method" for modal combination was employed, while the square-root-of-the-sum-of-the-squares (SRSS) rule was applied for directional combination. The "grouping method" proceeds by defining groups of closely spaced modes. Each group contains all modes having frequencies lying between the lowest frequency in the group and a frequency ten percent higher. Construction of the groups proceeds by starting at the lowest frequency of the system and working toward successively higher frequencies. No one mode is in more than one group. Modal responses are combined by absolute sum within a group and total modal response is determined by SRSS of group response and individual modal response for modes not in a group. Displacements, accelerations, forces, and moments were calculated. The inertial component of these response quantities for the SRP method was defined as the average of the results given by the three analyses to minimize variations due to time history characteristics.

The SRP recommended approach to calculating pseudostatic response was not conducted in this study. However, to permit a comparison of total response calculated by the time history and SRP procedures, pseudostatic response as determined by the RG 1.60 time history method was added to the inertial response calculated by the SRP approach to define an SRP total response. Total response calculated in this fashion represents a lower bound estimate since the time history method provides a less conservative value of pseudostatic response than the static analysis approach actually prescribed in the SRP.

Table 3. Nominal Modal Damping Ratios.

Containment shell	Internal structure	AFT complex	Piping systems
.02	.02	.02	.02

Table 4. Coefficients of Variation (COVs) of input parameters for the best estimate analysis

Parameter	COV
Soil shear modulus	0.7
Soil damping	1.0
Structure frequency	0.5
Structure damping	0.7
Subsystem frequency	0.5
Subsystem damping	0.7

Table 5. Coefficients of Variation (COVs) of input parameters for the RG 1.60 analysis

Parameter	COV
Soil shear modulus	0.7
Soil damping	1.0
Structure frequency	0.5
Structure damping	0.7
Subsystem frequency	No variation
Subsystem damping	No variation

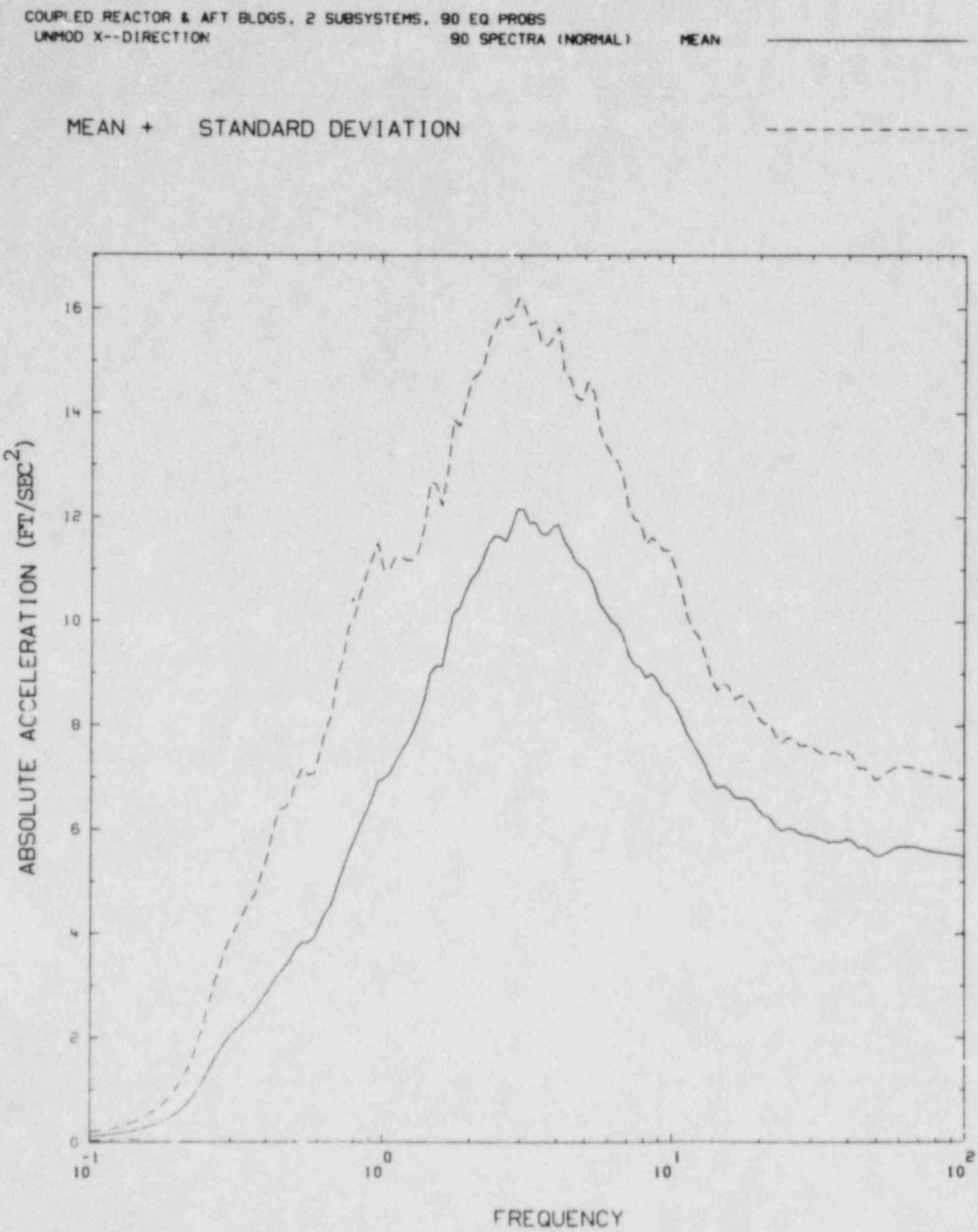


Fig. 5a. Mean and Mean-Plus-One-Standard-Deviation Response Spectra of the Best Estimate Free-Field Motion - X-Direction.

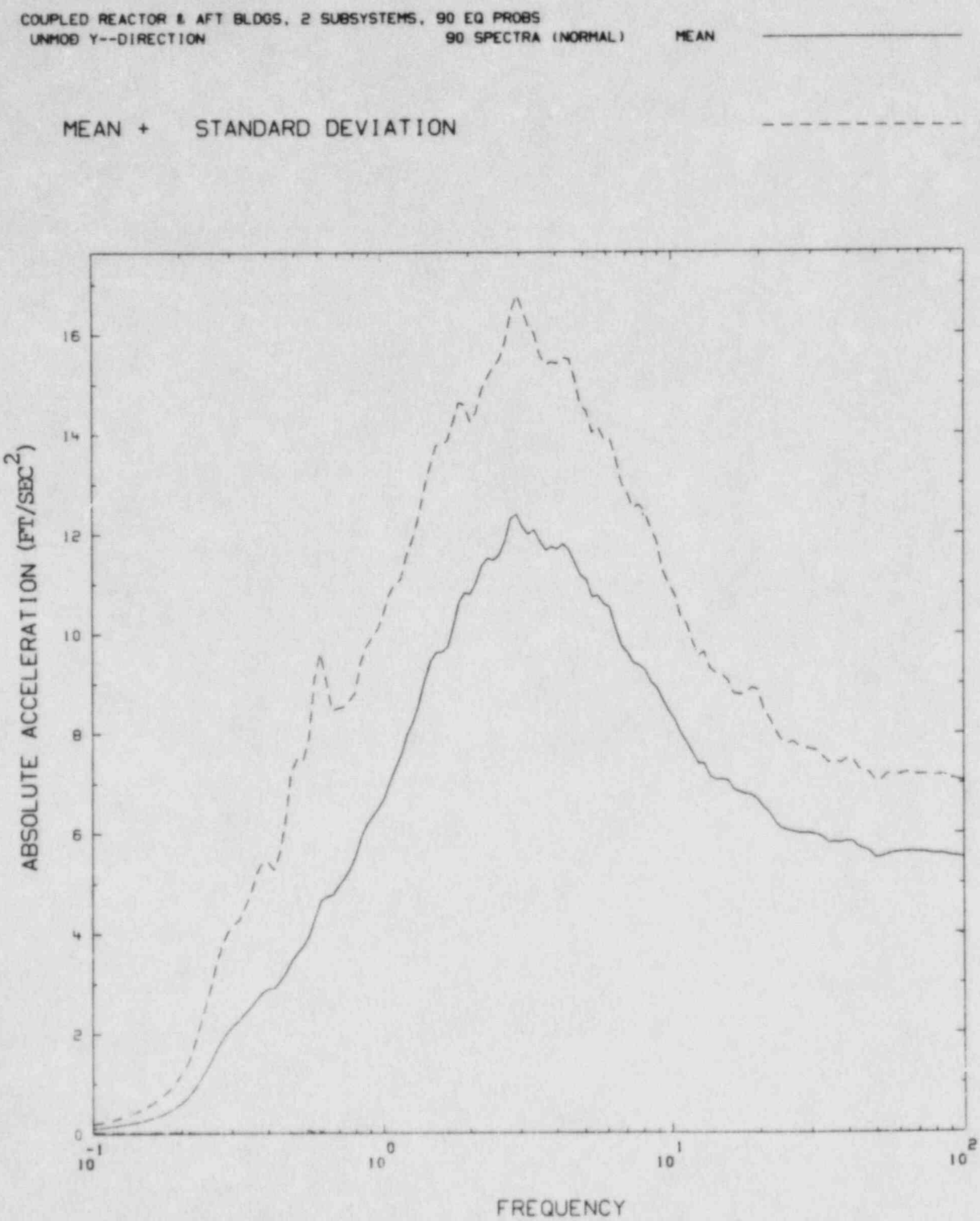


Fig. 5b. Mean and Mean-Plus-One-Standard-Deviation Response Spectra of the Best Estimate Free-Field Motion - Y-Direction.

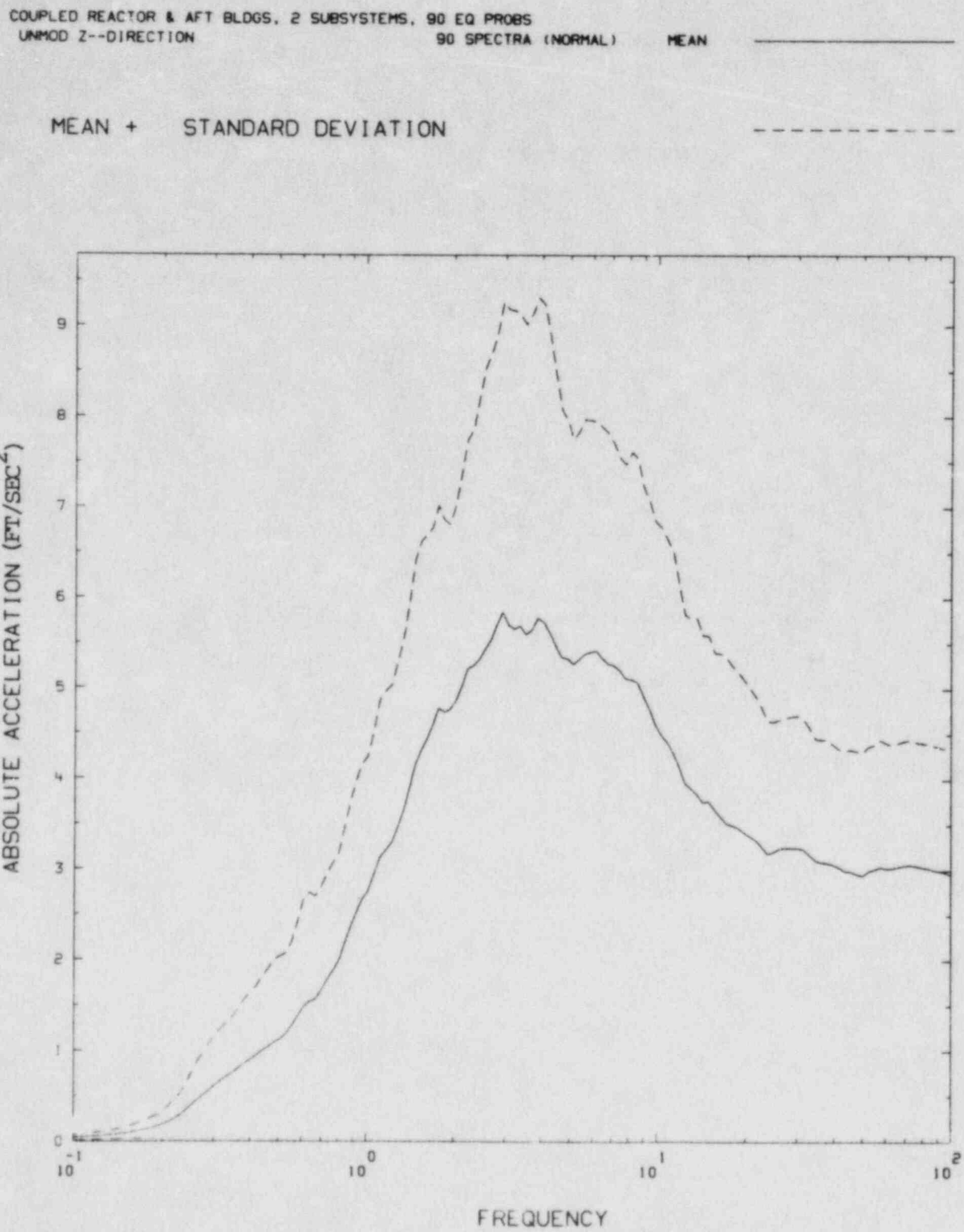
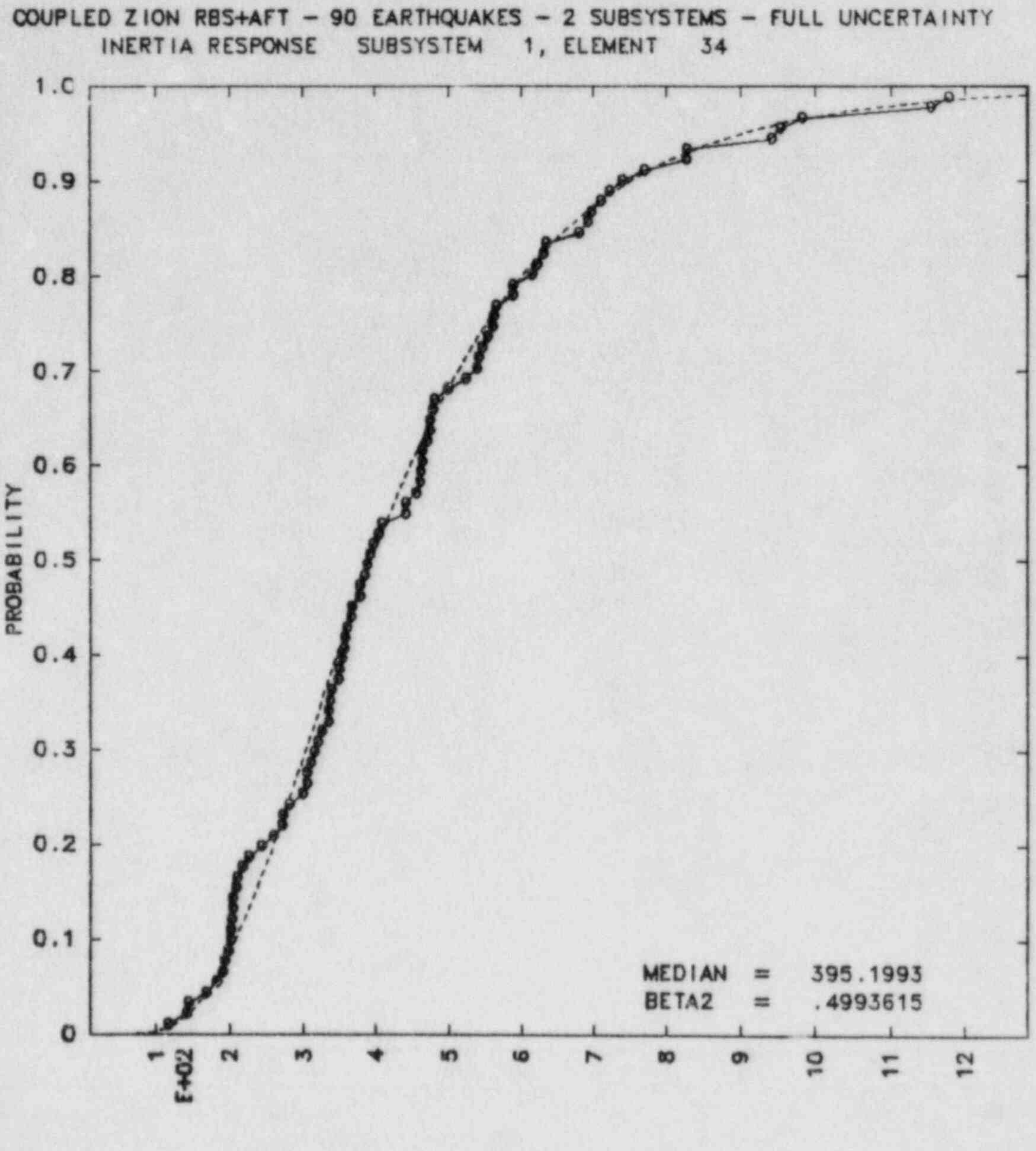


Fig. 5c. Mean and Mean-Plus-One-Standard-Deviation Response Spectra of the Best Estimate Free-Field Motion - Z-Direction.



Vector-summed Moments for AFW Element 34 (FT-LBS)

Fig. 6. Distribution of Responses for AFW Model Element 34 as given by the Best Estimate Analysis.

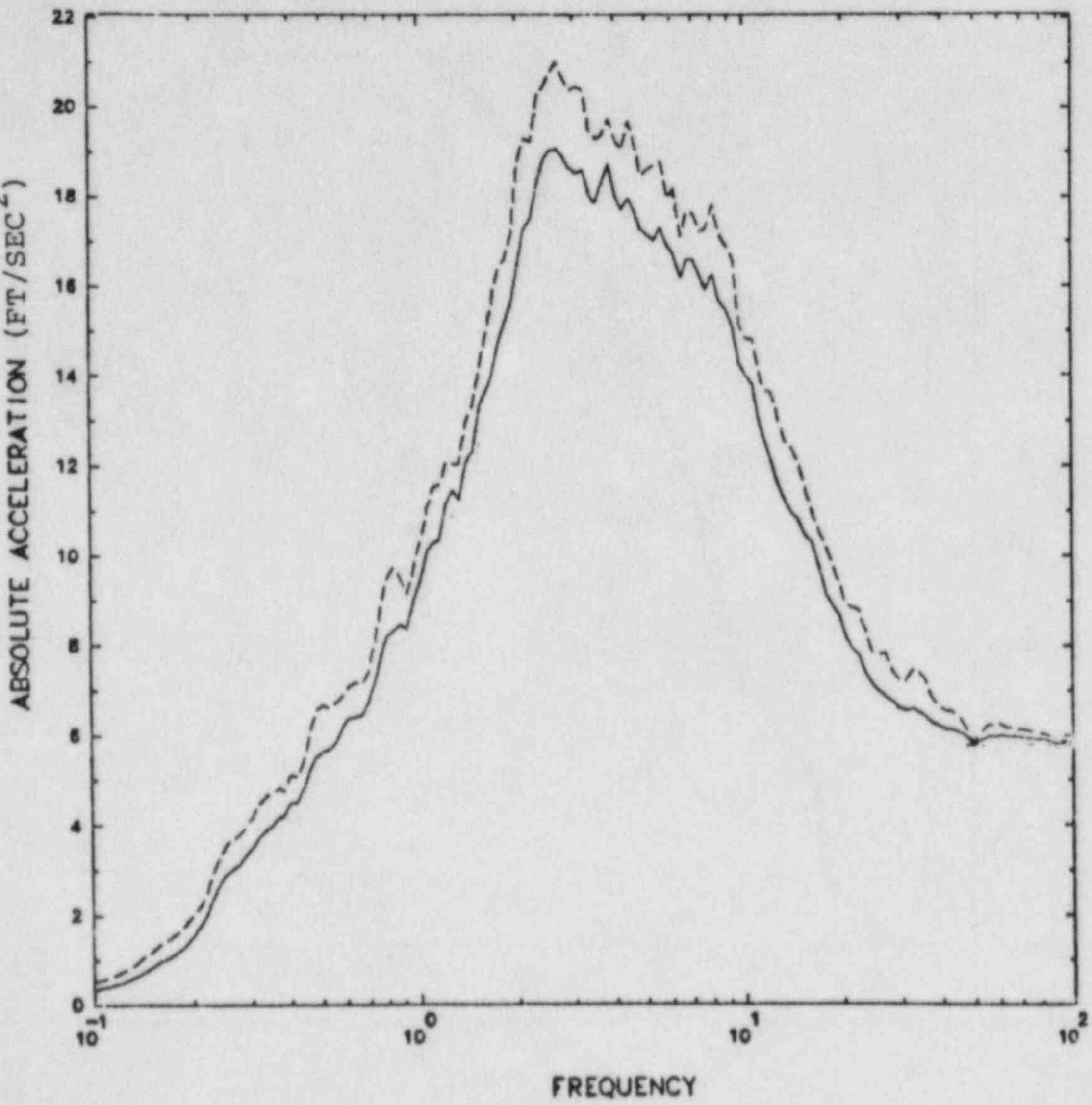


Fig. 7a. Mean and Mean-Plus-One Standard Deviation Response Spectra of the RG 1.60 Free-field Motion X-Direction (5% Damping).

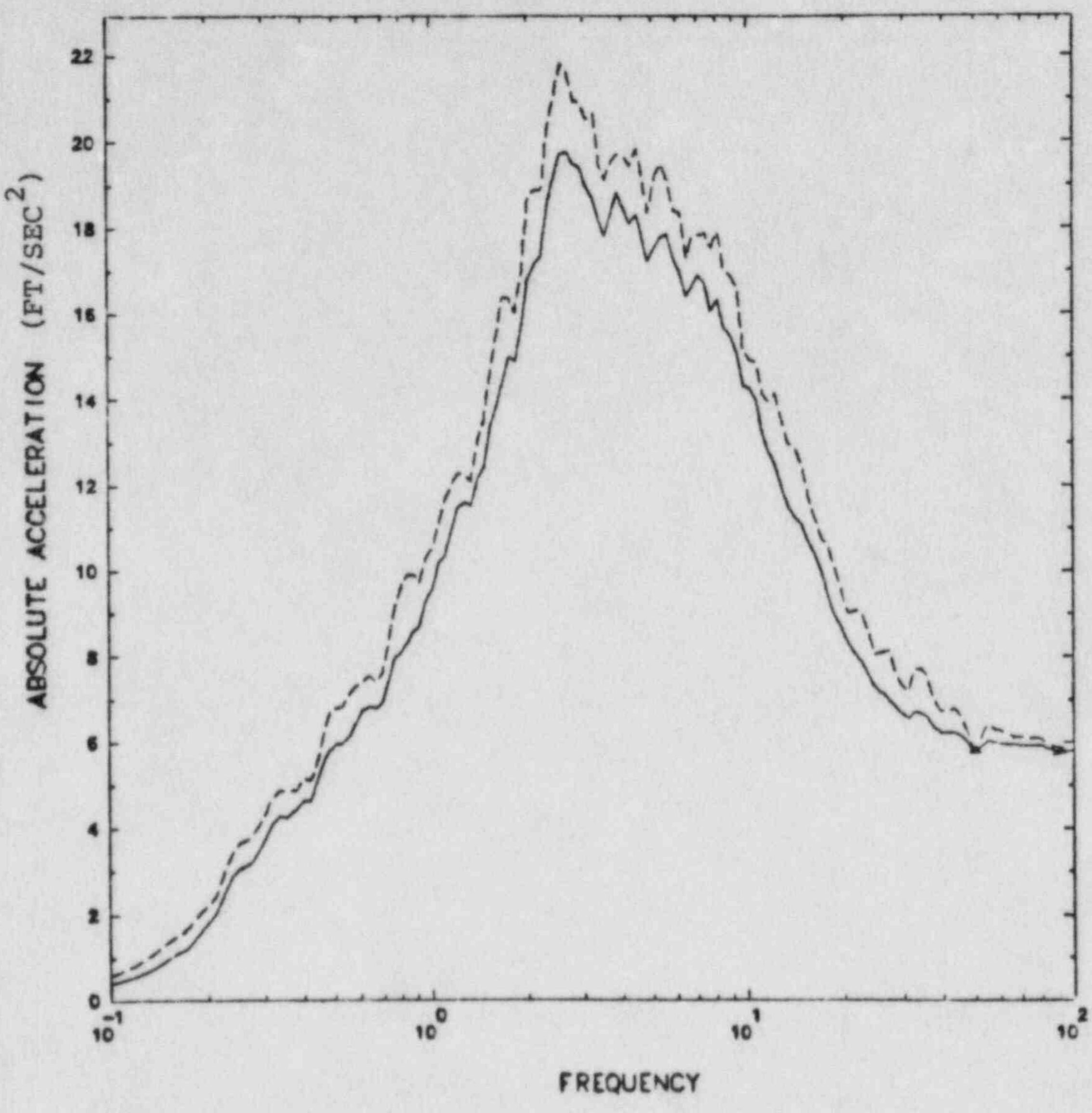


Fig. 7b. Mean and Mean-Plus-One Standard Deviation Response Spectra of the RG 1.60 Free-field Motion Y-Direction (5% Damping).

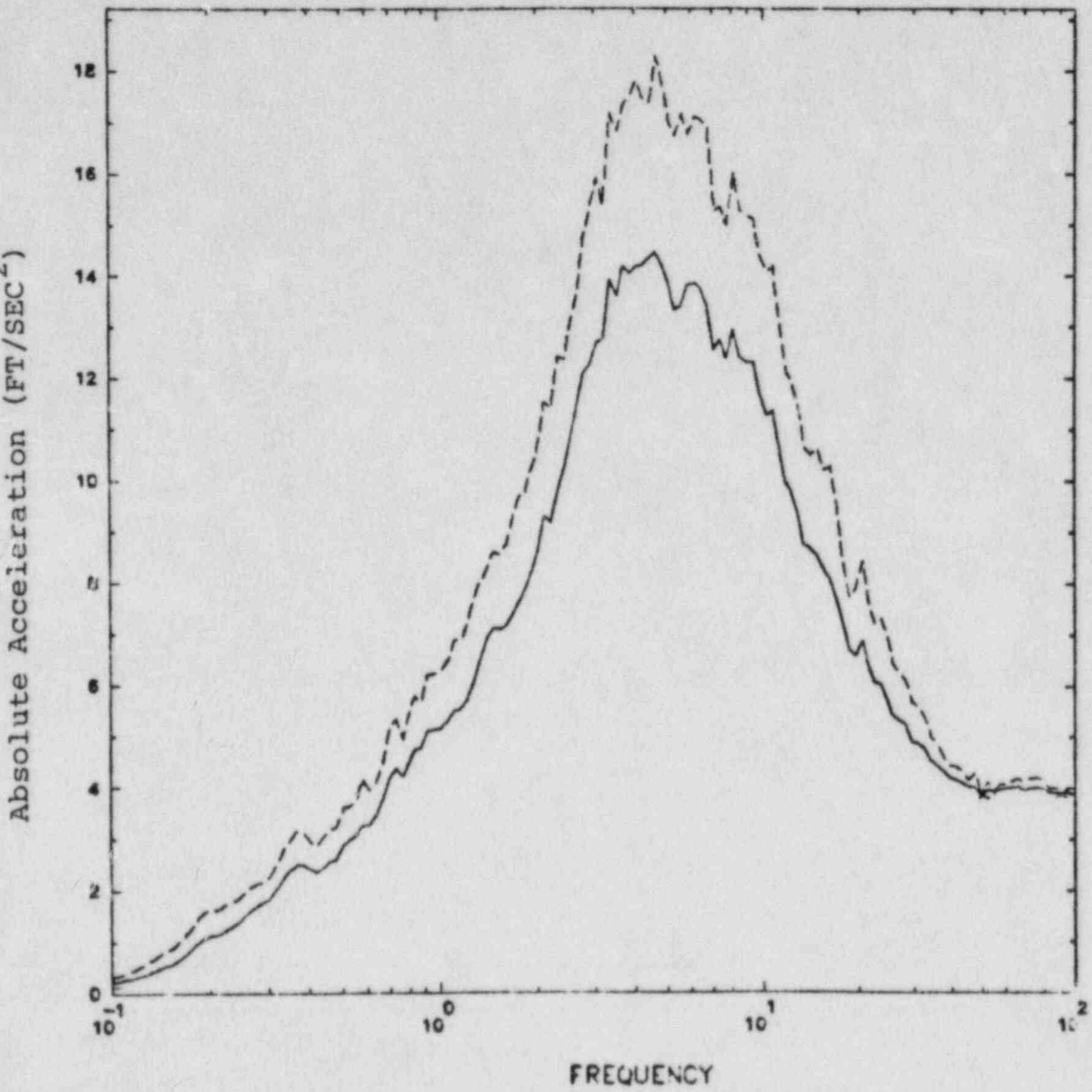


Fig. 7c. Mean and Mean-Plus-One Standard Deviation Response Spectra of the RG 1.60 Free-field Motion - Z-Direction (5% Damping).

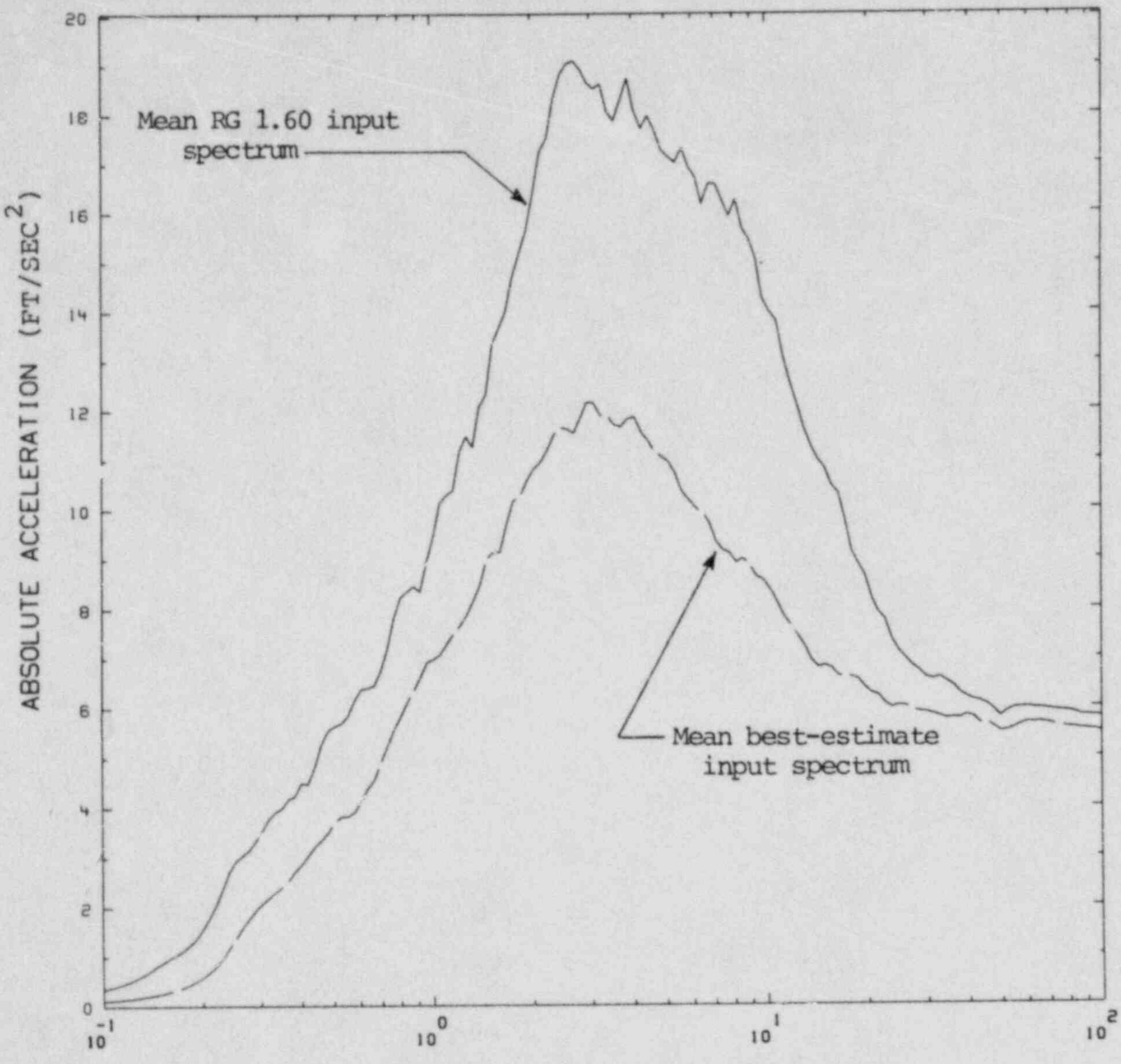


Fig. 8a. Comparison of Mean Response Spectra -- Best Estimate and RG 1.60 - X-Direction.

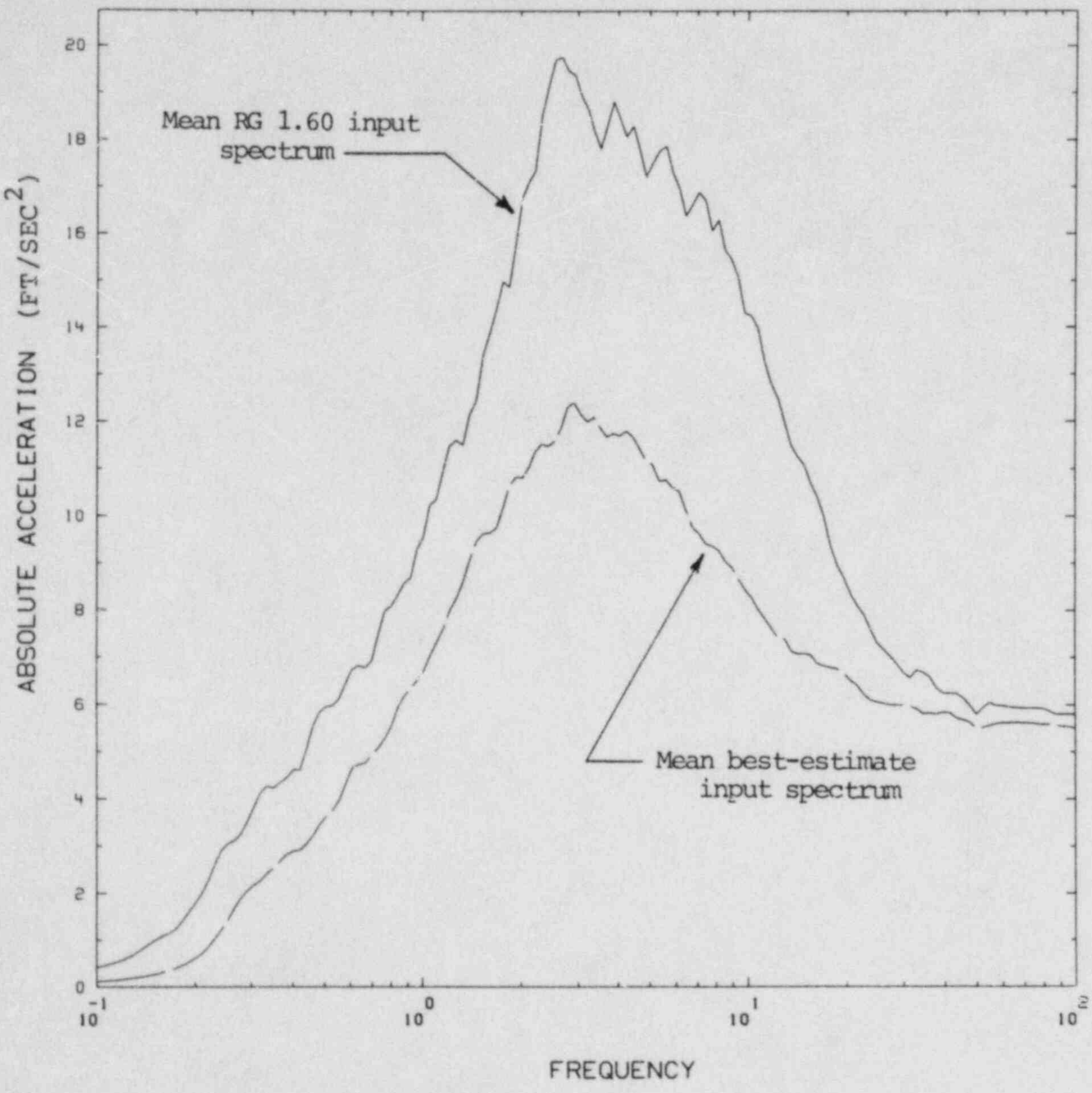


Fig. 8b. Comparison of Mean Response Spectra -- Best Estimate and RG 1.60 - Y-Direction.

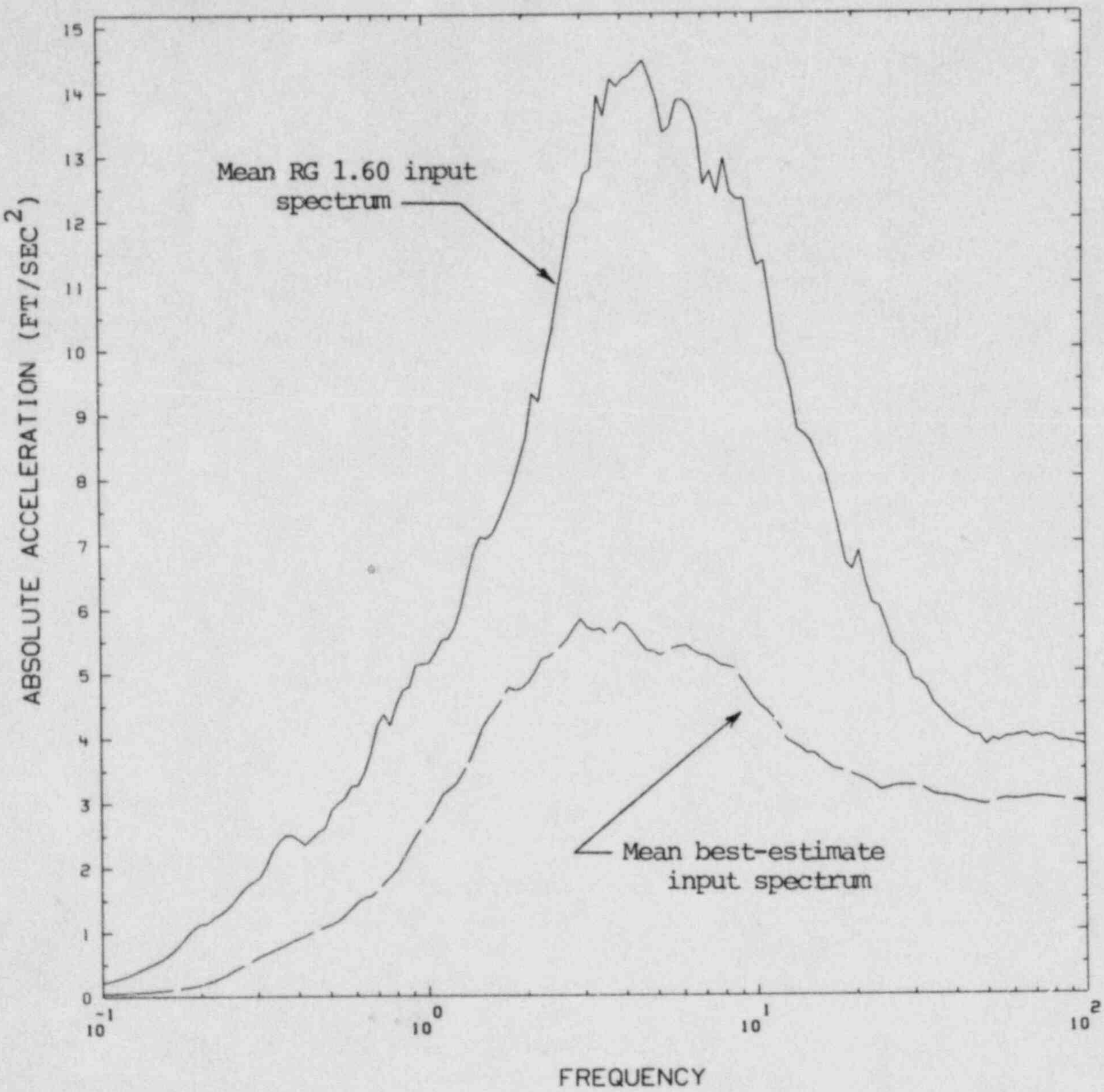


Fig. 8c. Comparison of Mean Response Spectra -- Best Estimate and RG 1.60 - Z-Direction.

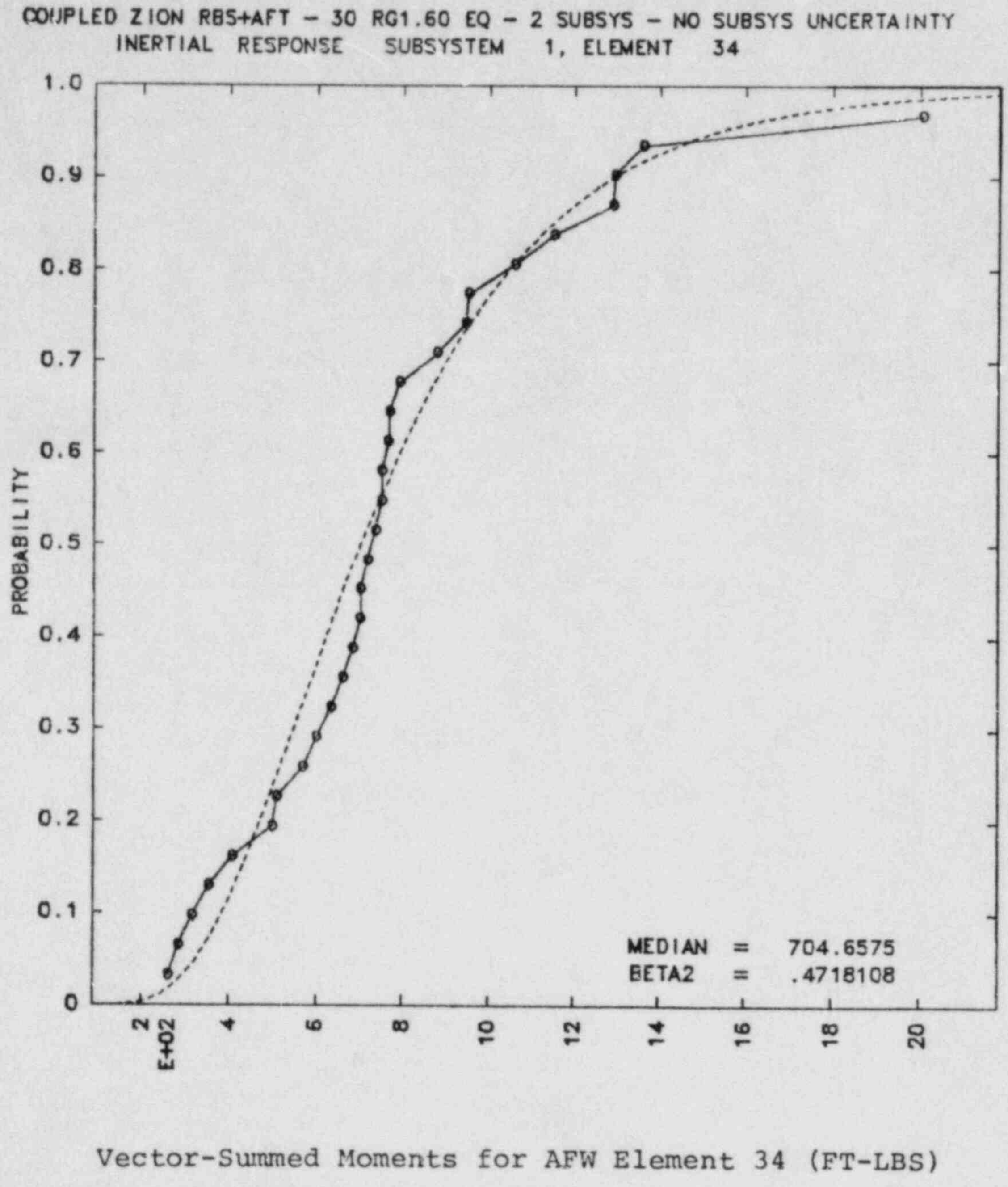


Fig. 9. Distribution of Responses for AFW Model Element 34 as given by RG 1.60 Analyses.

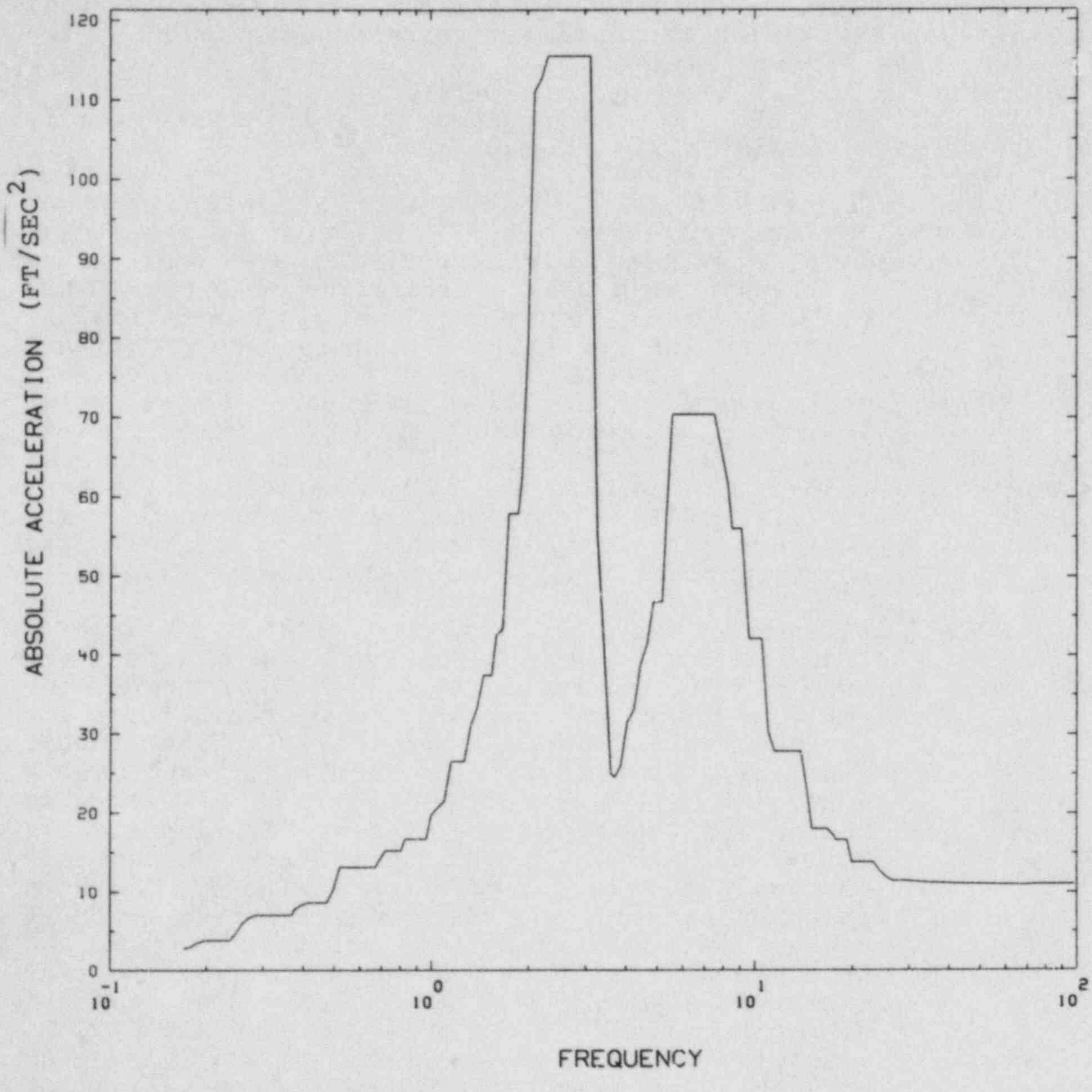


Fig. 10. Enveloped and Broadened Spectrum for the AFW Model Typical of Response Spectrum Analysis Input.

4. NUMERICAL RESULTS AND INTERPRETATION

The principal results are presented herein as comparisons of responses calculated by the best estimate time history analysis method and by the SRP response technique. For the time history method, multiple analyses were performed. The inertial component and total response values corresponding to nonexceedance probabilities (NEP) of 50% and 84% were defined for comparison purposes. Inertial response associated with the SRP method is defined by the average results of the three response spectrum analyses described in the previous section. Total SRP response is obtained as the sum of the SRP inertial response and the median pseudostatic response calculated by the R.G. 1.60 time history method.

For both the inertial component and total response values, we made the following comparisons:

- SRP method vs. best estimate 50% NEP response. The best estimate 50% NEP response is the median level response to be expected conditional on an earthquake with peak acceleration of 0.18g. This median level response, the variability of response, and correlation of response conditional on the occurrence of an earthquake of specified peak ground acceleration (PGA) are the essential seismic response quantities for a probabilistic risk analysis (PRA). The ratio between the response calculated by the SRP method and the best estimate 50% NEP response is a measure of margin that must be removed from the SRP results if used to approximate the median best estimate values.

- SRP method vs. best estimate 84% NEP response. The best estimate analysis procedure explicitly accounts for uncertainty in definition of the seismic input and in the system characteristics (properties and behavior of the soil, structures, and piping system) in a probabilistic fashion. A distribution of responses is calculated and a design goal based on a specified NEP response can be established [9]. In this study the 84% NEP response is targeted to be a design goal. Once this is established, design quantities such as piping system accelerations, support forces, and pipe moments can then be determined from the time history analysis. The SRP method recognizes that uncertainties exist and treats them in a conservative, but unquantified, manner e.g. peak broadening of response spectra. A comparison of response calculated by the SRP method with best estimate 84% NEP values is a measure of calculational margin introduced by the SRP method compared to an alternative design philosophy.

Inertial and total response are treated separately in the following subsections. Comparisons are presented in two forms:

- Figures which display ratios of response for individual node or element locations grouped according to type of response (e.g. displacements, accelerations, support forces, and piping moments).

- Tables that summarize the results and present statistics of the ratios for each piping system and each type of response.

The response quantities of most interest are accelerations, support forces, and piping moments. These enter directly into qualification or fragility assessment of valves and design or fragility assessment of piping and its supports. Displacements were also calculated for the RHR and AFW models and have been included for completeness.

4.1 INERTIAL RESPONSE

SRP method vs. best estimate 50% NEP.

Figures 11a, b, and c show ratios of inertial response calculated by the SRP method vs. best estimate time history analysis methods at the 50% NEP for the RHR, AFW, and RCL piping systems respectively. The figures are valuable in demonstrating both the variability in the ratios of response and the range of values. For example, consider the extreme case of Fig. 11c. Acceleration ratios of the RCL model for three locations range between 80 and 85. Table 6 summarizes the results in statistical form. The median ratios of response range from 3.3 to 3.8 for the RHR, 7.5 to 8.1 for the AFW, and 11.6 to 16.9 for the RCL. Therefore, if one were estimating median level responses, conditional on the occurrence of an earthquake of peak acceleration of 0.18g, given values calculated by the SRP method, median reduction factors ranging from 3.3 to 16.9 depending on the piping system and response quantity of interest would need to be applied.

Some observations can be made from this case which apply in general. Recall from Table 2 the key characteristics of the piping systems. The RHR is the smallest and least complex model - 21 independent support motions and 18 modes. The AFW is next in complexity - 45 independent support motions and 36 modes. The RCL has 127 independent support motions and 130 modes. We see from Fig. 11 and Table 6 that the ratios of response or calculational margin increase with complexity of the piping system. Variability in these ratios also increases with complexity of the piping system. The variability in ratios for piping moments is consistently less than the variability in ratios for other response quantities. This is due in large measure to the piping moments being the amplitude of vector-sum quantities whereas other quantities are components of a vector.

<u>SRP method vs. best estimate 84% NEP</u>.

Figures 12a, b, and c show ratios of inertial response calculated by the SRP method vs. best estimate time history analysis methods at the 84% NEP for the RHR, AFW, and RCL piping systems respectively. Variability in the ratios is again graphically demonstrated by the plots. Extremes exist as before. Table 7 summarizes the results in statistical form. The median ratios of response range from 0.9 to 2.4 for the RHR, 2.1 to 4.9 for the AFW, and 6.6 to 9.4 for the RCL. The ratios of displacement response are, in each case, the low values. Displacements, even though they are components of a vector, appear to be less sensitive to variations in seismic input and system parameters; hence, lower coefficients of variation and consequently lower 84% NEP values. Although interesting, this does not have a particularly important impact on design since displacements themselves are generally not design quantities.

One can interpret these ratios in the context of a design goal. If the goal of the SRP analysis methodology was to produce design quantities at the 84% NEP, conditional on the occurrence of an earthquake with specified peak acceleration, it has exceeded the goal for the three piping systems studied here. In fact, in some cases, it has exceeded the goal by very large amounts. The fact that these ratios tend to be lower bounds, increases the significance of the result.

Ratios presented here are lower bounds for a number of reasons. Variability in the input parameters for the time history analysis was selected to represent total uncertainty assuming minimal knowledge of the system. Large variability in input parameters leads to large variability in piping system responses and consequently upper bound 84% NEP values. Consistency in the SSI and structure models minimized the conservatism which is normally introduced by the SRP structure analysis procedure, e.g. considering three sets of soil properties and enveloping the results, location of the control point, etc. Doing so would have introduced additional conservatism in the responses calculated by the SRP methodology. Finally, nominal values of the input parameters, in particular structure and piping system damping, were conservative.

4.2 TOTAL RESPONSE

SRP method vs. best estimate 50% NEP.

Figures 13a, b, and c show ratios of total response defined for the SRP method versus the median total response (50% NEP) calculated by the best estimate time history analysis method. As discussed earlier, the SRP total response is the sum of the SRP inertial and the median R.G. 1.60 pseudostatic response components. Table 8 summarizes the results in statistical form. One point of interest is the relatively constant values of displacement ratios. This results from the dominance of the total response by the pseudostatic component. Other trends seen and discussed in Sec. 4.1 also occur here.

SRP method vs. best estimate 84% NEP.

Figures 14a, b, and c illustrate ratios of total response defined by the SRP method versus the best estimate time history analysis results at the 84% NEP. Table 9 summarizes the results in statistical form.

Table 6. Ratio of Inertial Responses -- SRP Method vs. Best Estimate (50% NEP).

RHR	Number of Components	Median Ratio	COV
Accelerations	28	3.4	.26
Displacements	51	3.4	.24
Support forces	15	3.3	.20
Piping moments	22	3.8	.18
AFW			
Accelerations	50	7.5	.51
Displacements	63	7.5	.41
Support forces	28	8.1	.44
Piping moments	23	8.0	.20
RCL			
Accelerations	51	13.5	1.39
Support forces	92	11.6	.61
Piping moments	118	16.9	.50

Table 7. Ratio of Inertial Responses -- SRP Method vs. Best Estimate (84% NEP).

	Number of Components	Median Ratio	COV
RHR			
Accelerations	28	2.2	.24
Displacements	51	.9	.18
Support forces	15	2.0	.17
Piping moments	22	2.4	.16
AFW			
Accelerations	50	4.7	.48
Displacements	63	2.1	.40
Support forces	28	4.9	.44
Piping moments	23	4.7	.24
RCL			
Accelerations	51	7.6	1.31
Support forces	92	6.6	.59
Piping moments	118	9.4	.49

Table 8. Ratio of Total Responses -- SRP Method vs. Best Estimate (50% NEP).

RHR	Number of Components	Median Ratio	COV
Accelerations	28	3.4	.26
Displacements	51	5.4	.09
Support forces	15	4.0	.14
Piping moments	22	3.4	.18
AFW			
Accelerations	50	7.5	.51
Displacements	63	5.5	.09
Support forces	28	6.9	.31
Piping moments	23	6.8	.50
RCL			
Accelerations	51	13.5	1.39
Support forces	92	10.8	.62
Piping moments	118	12.8	.43

Table 9. Ratio of Total Responses -- SRP Method vs. Best Estimate (84% NEP).

RHR	Number of Components	Median Ratio	COV
Accelerations	28	2.2	.24
Displacements	51	2.7	.10
Support forces	15	2.4	.25
Piping moments	22	2.1	.27
AFW			
Accelerations	50	4.7	.48
Displacements	63	2.8	.10
Support forces	28	3.9	.42
Piping moments	23	4.1	.56
RCL			
Accelerations	51	7.6	1.31
Support forces	92	6.2	.63
Piping moments	118	7.2	.43

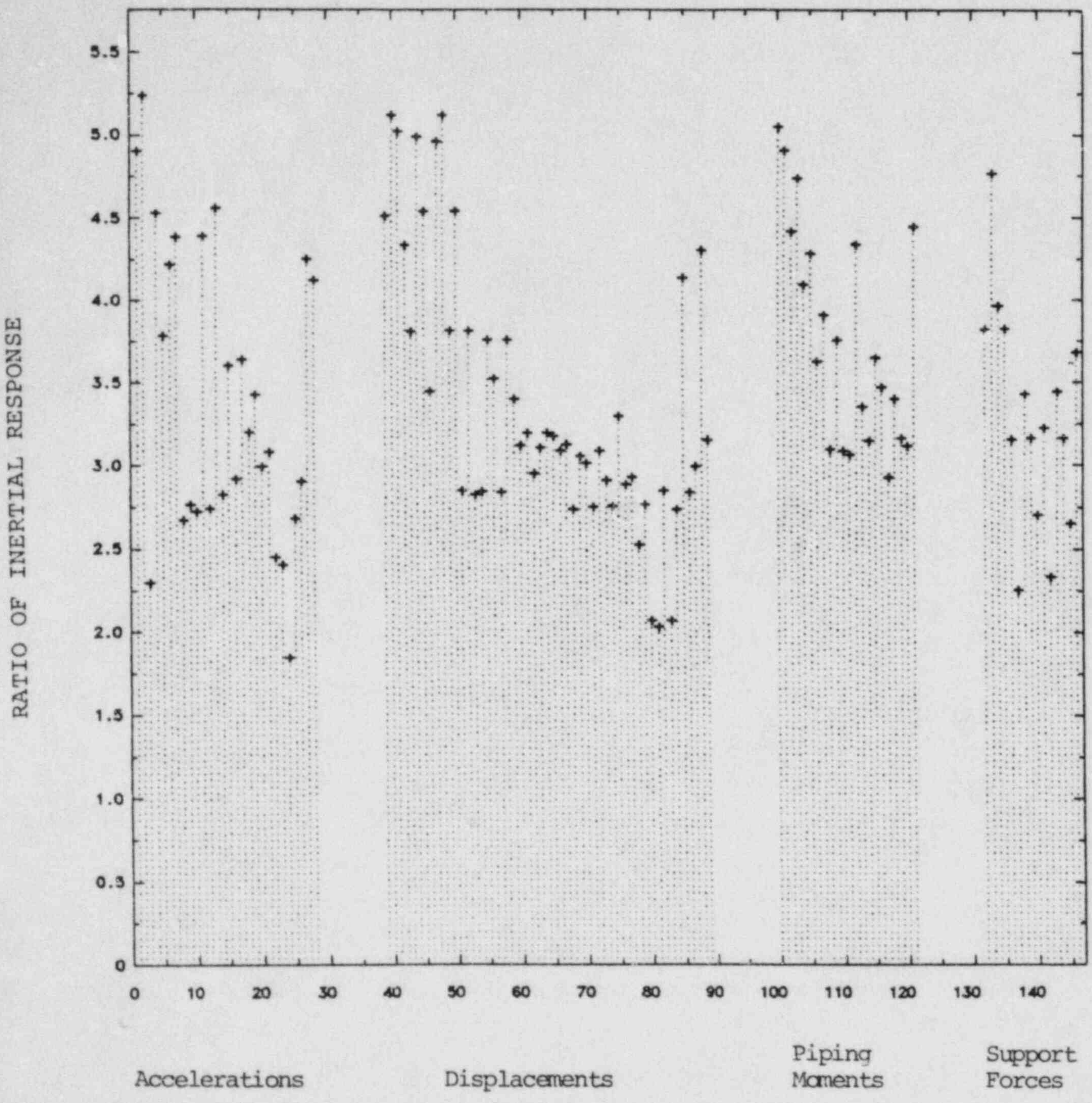


Fig. 11a. Inertial Response Ratios - SRP Method vs. Median Best Estimate Time History Response - RHR Model

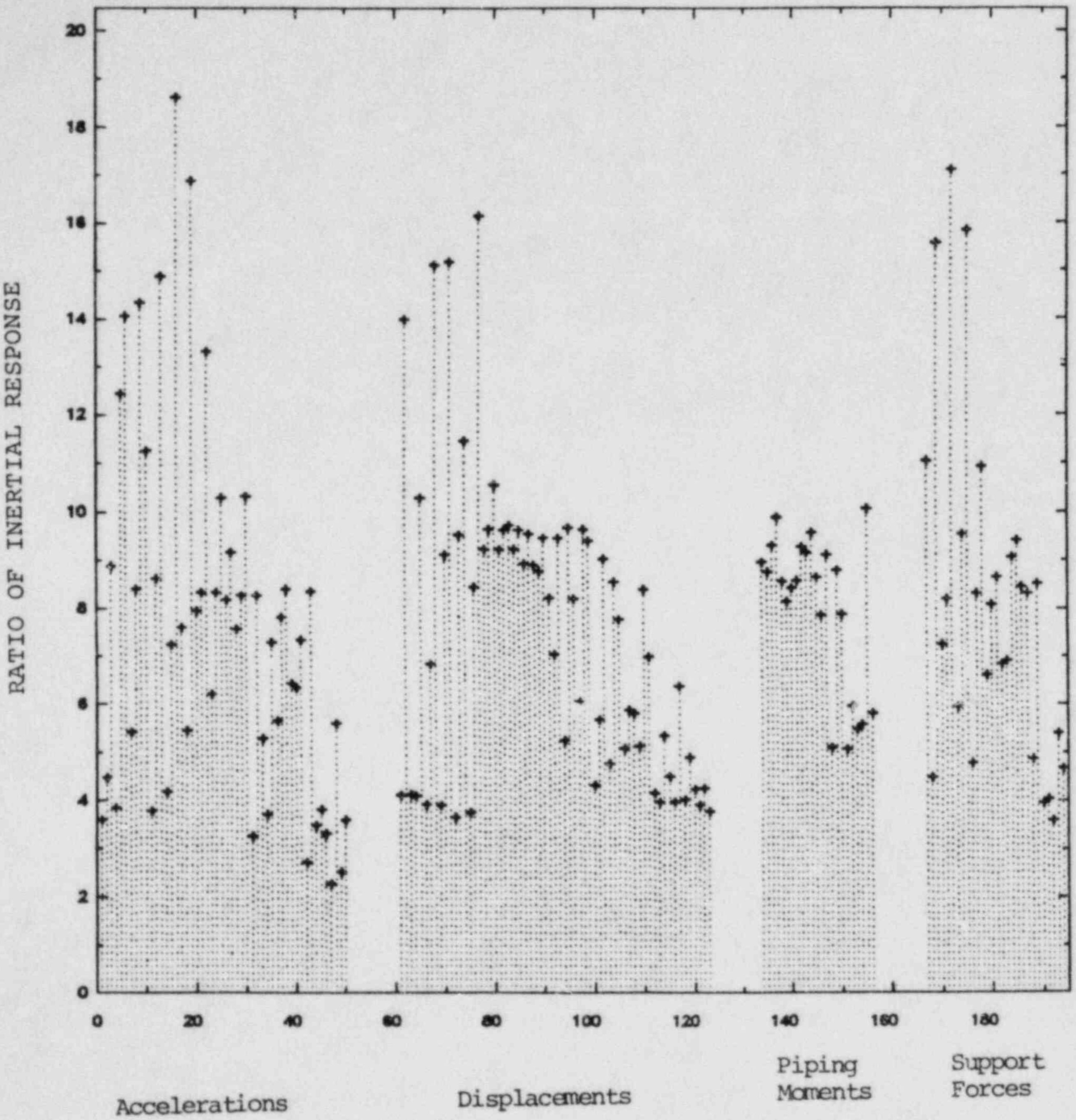


Fig. 11b. Inertial Response Ratios - SRP Method vs. Median Best Estimate Time History Response - AFW Model.

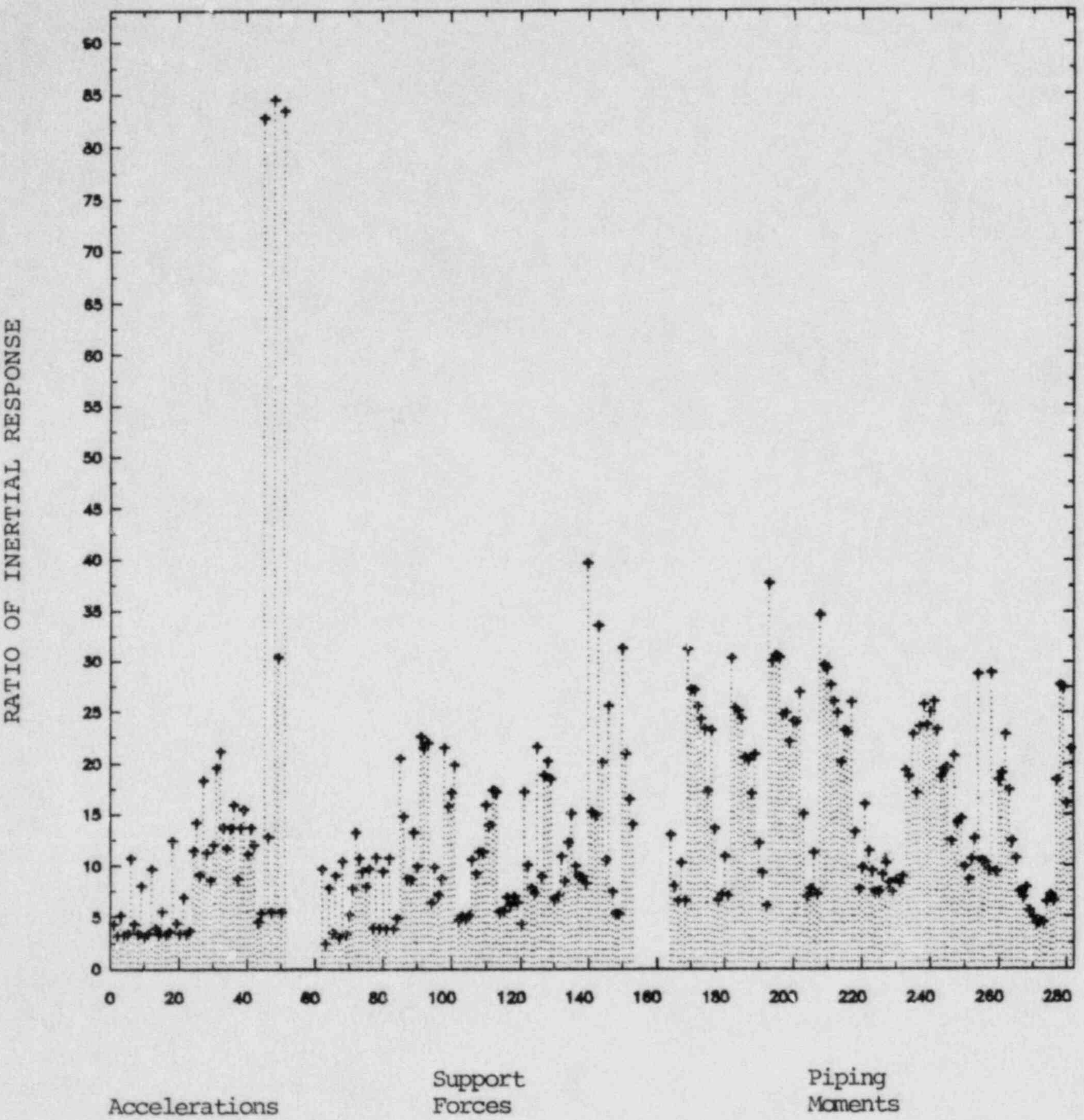


Fig. 11c. Inertial Response Ratios - SRP Method vs. Median Best Estimate Time History Response - RCL Model.

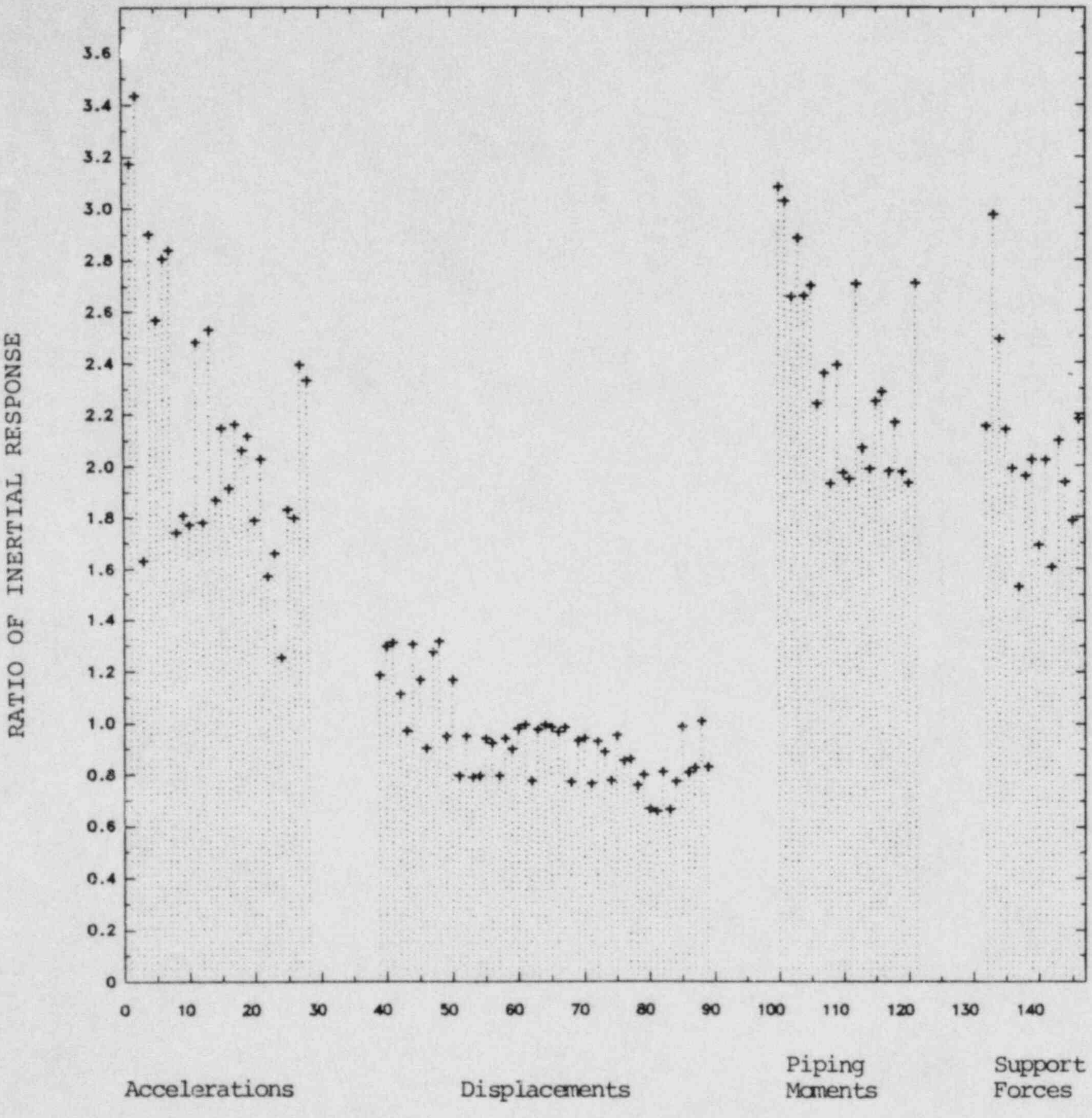


Fig. 12a. Ratios of Inertial Response Calculated by the SRP Method vs. Best Estimate 84% NEP - RHR Model.

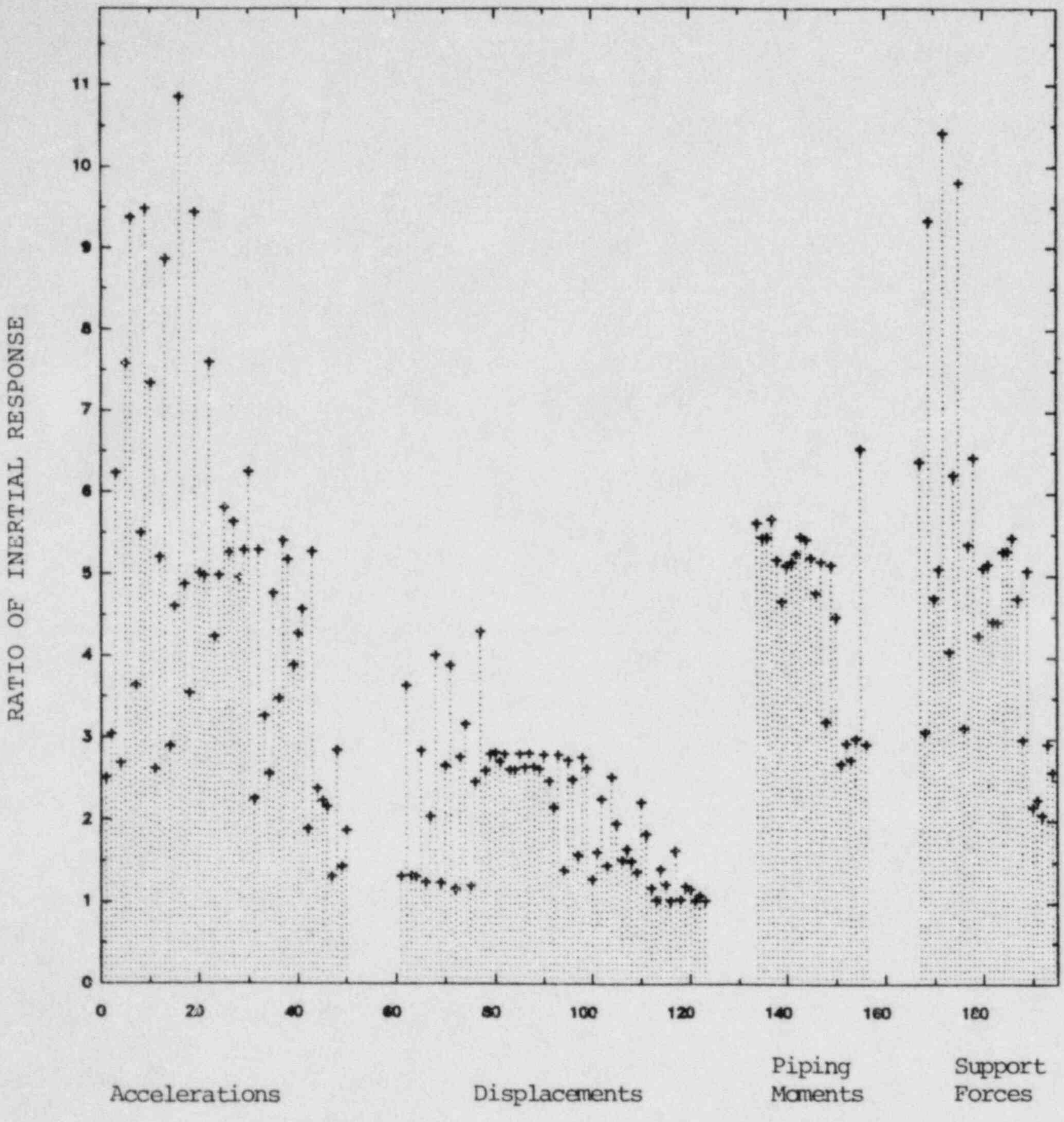


Fig. 12b. Ratios of Inertial Response Calculated by the SRP Method vs. Best Estimate 84% NEP - AFW Model.

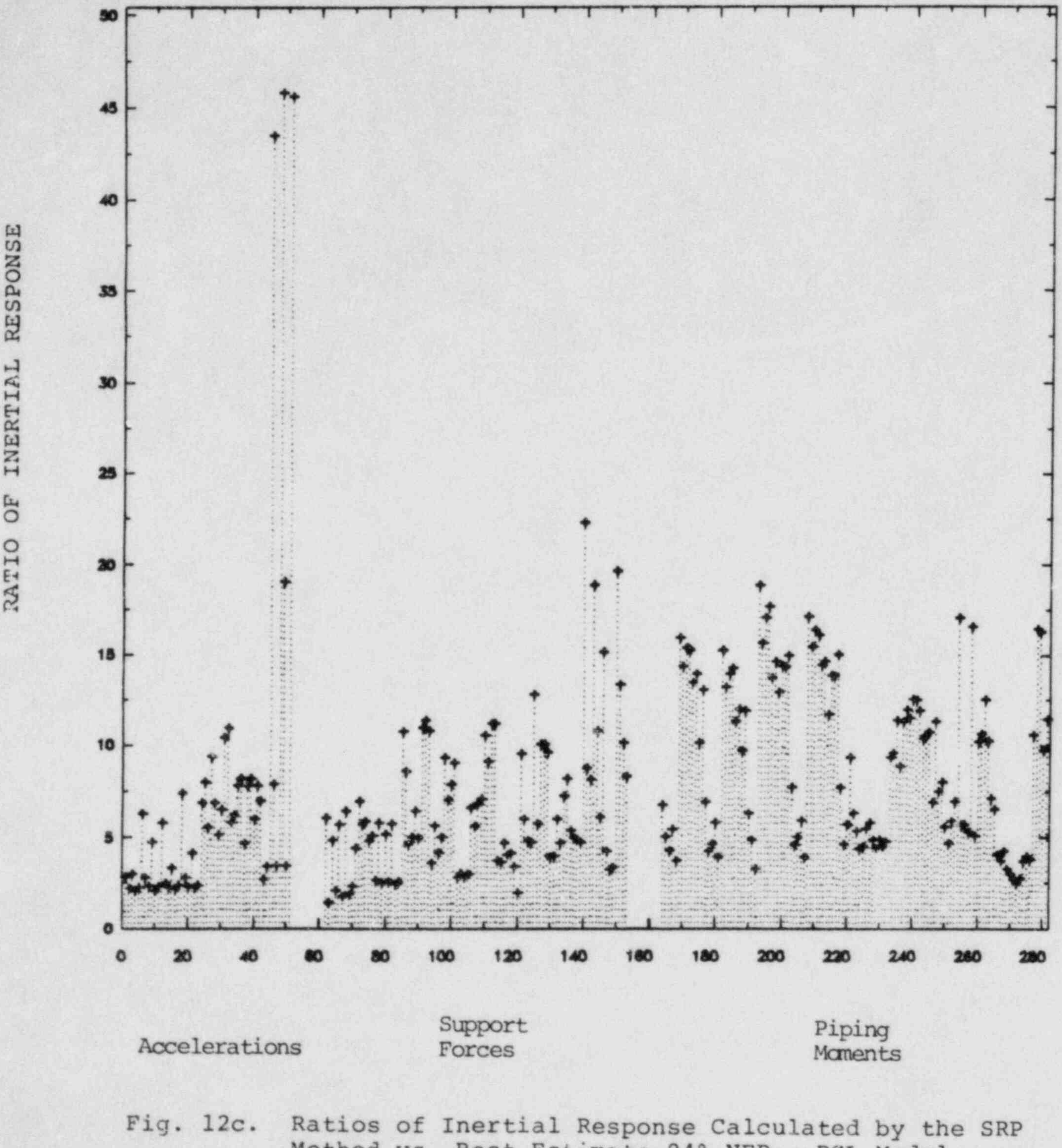


Fig. 12c. Ratios of Inertial Response Calculated by the SRP Method vs. Best Estimate 84% NEP - RCL Model.

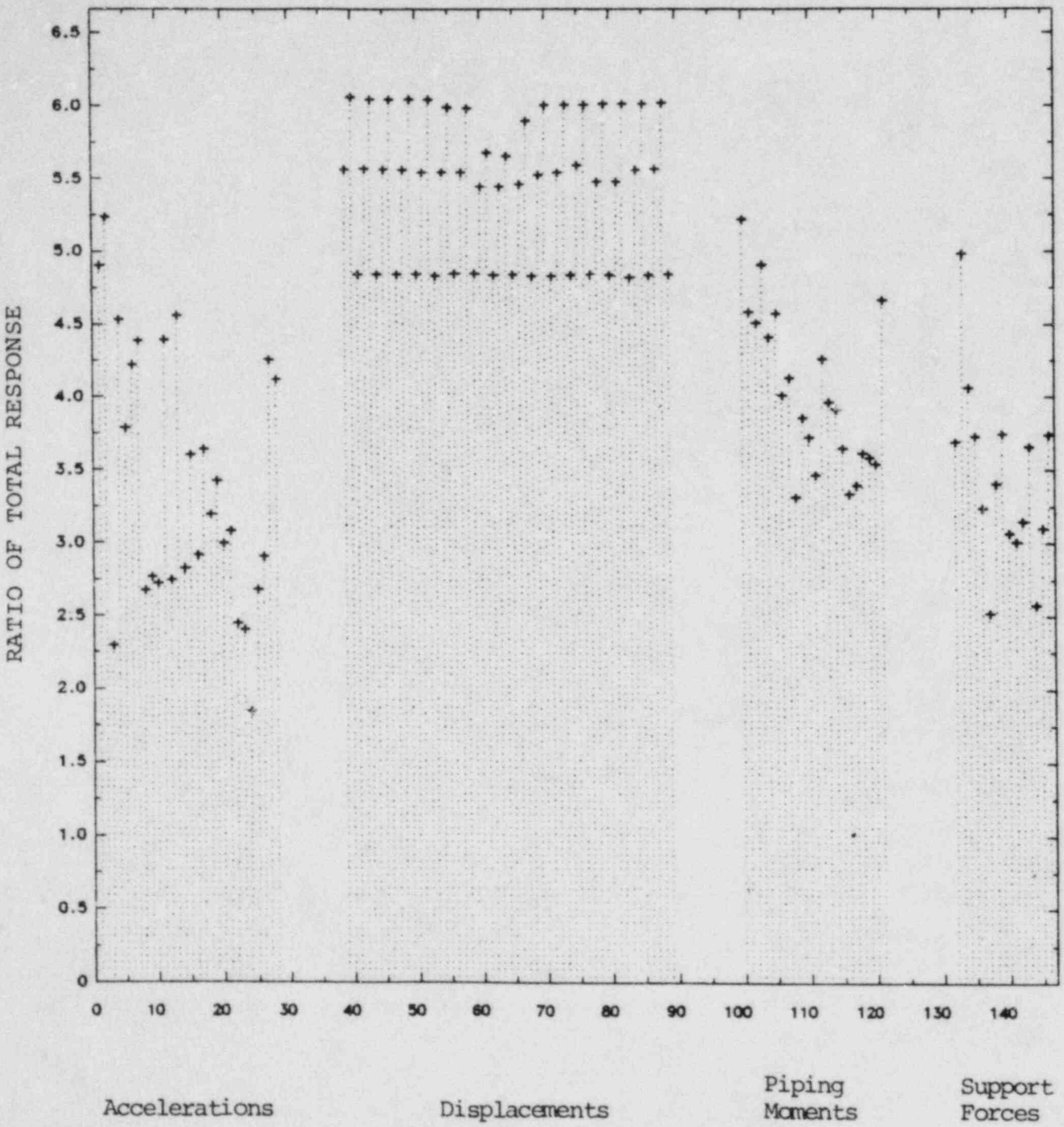


Fig. 13a. Ratios of Total Response Calculated by the SRP Method vs. Best Estimate 50% NEP - RHR Model

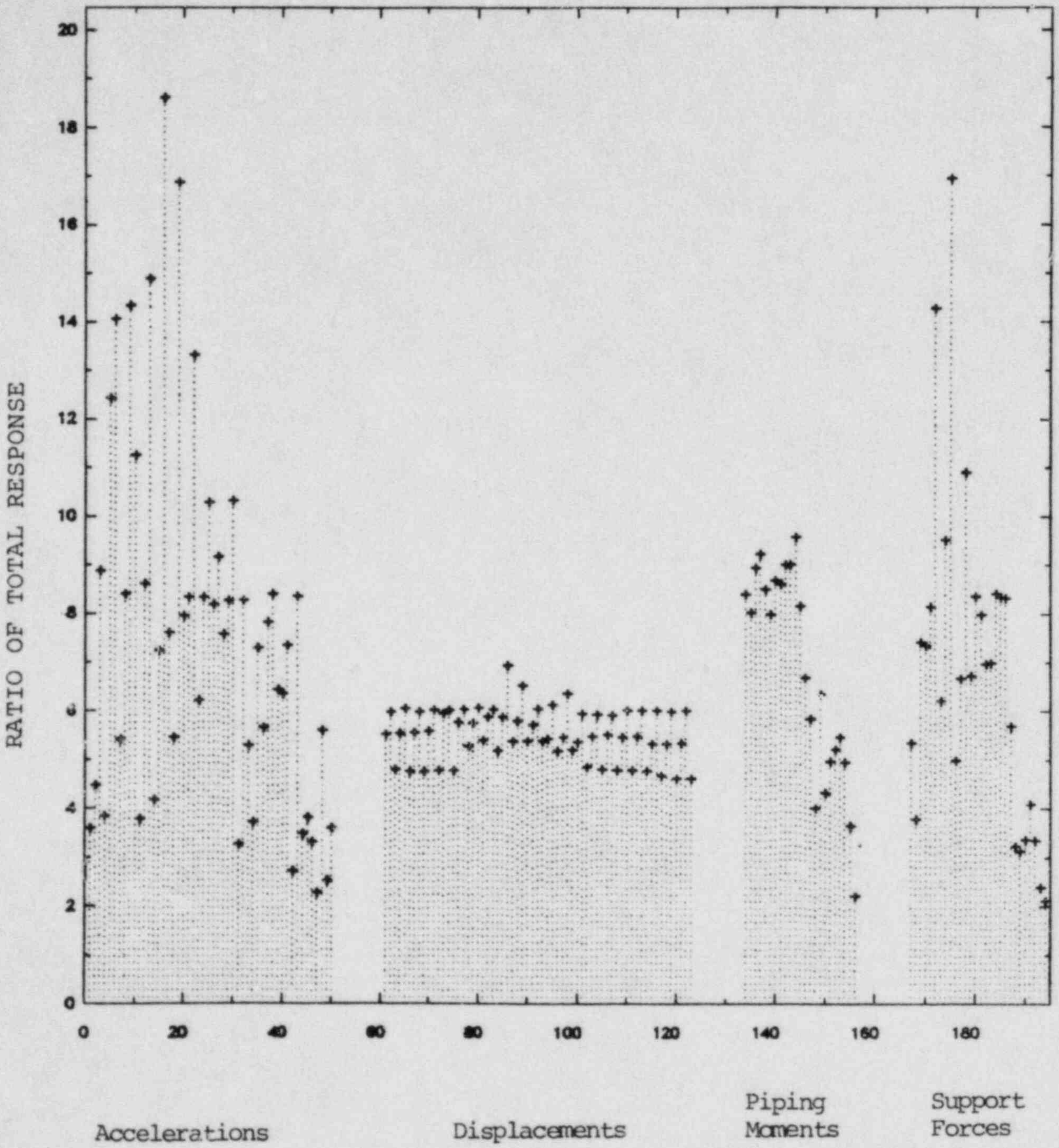


Fig. 13b. Ratios of Total Response Calculated by the SRP Method vs. Best Estimate 50% NEP - AFW Model.

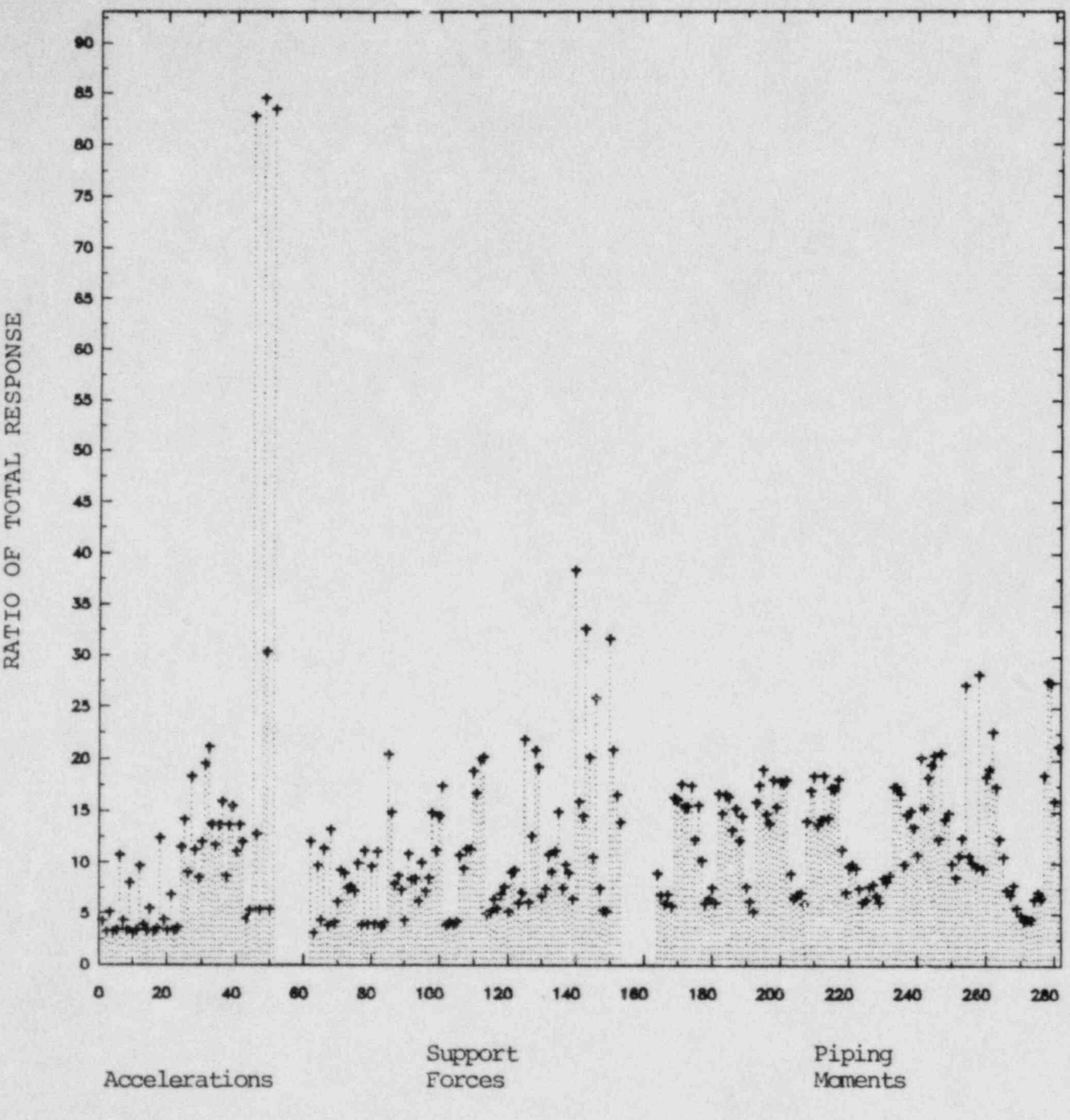


Fig. 13c. Ratios of Total Response Calculated by the SRP Method vs. Best Estimate 50% NEP - RCL Model.

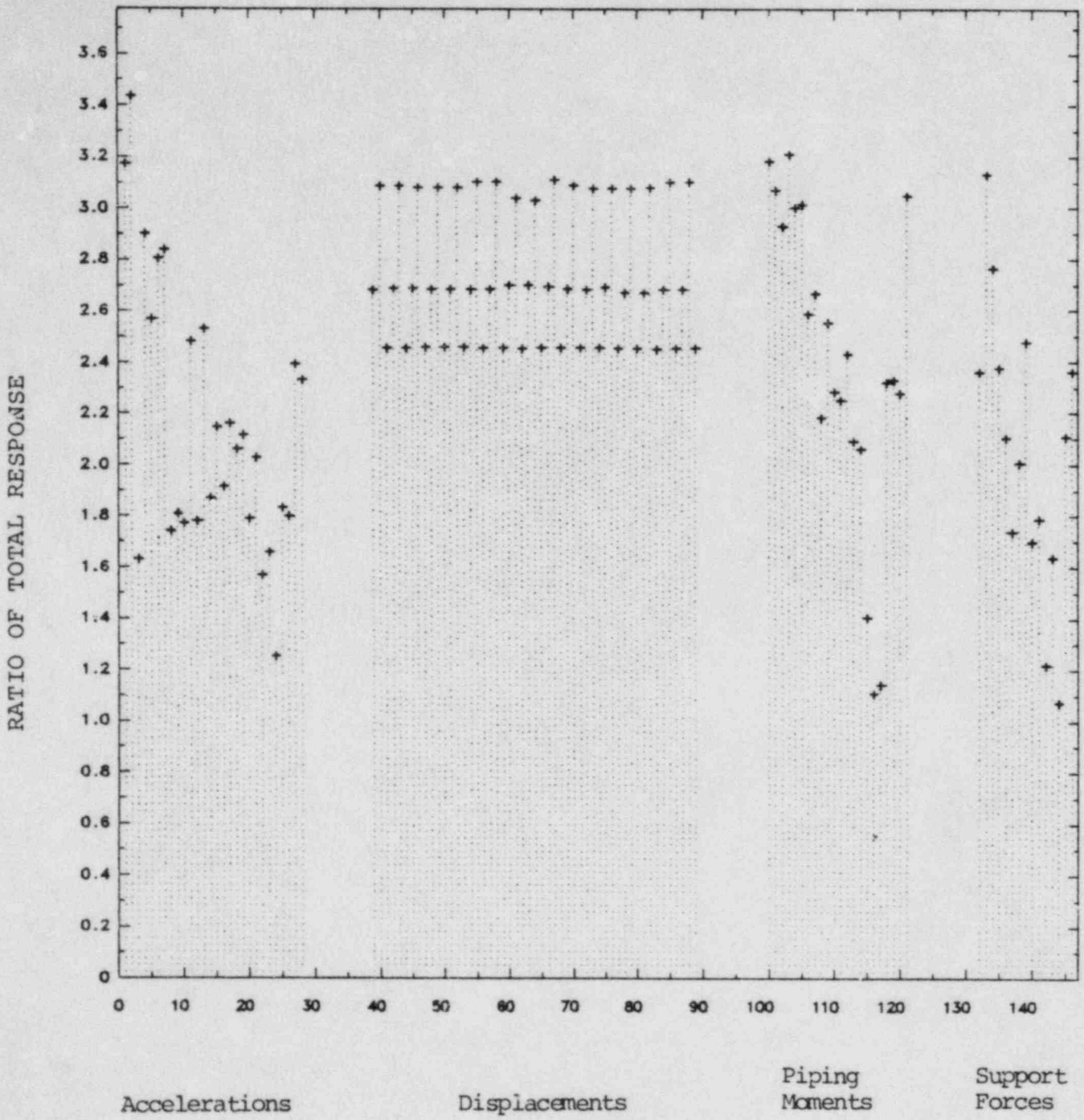


Fig. 14a. Ratios of Total Response Calculated by the SRP Method vs. Best Estimate 84% NEP - RHR Model.

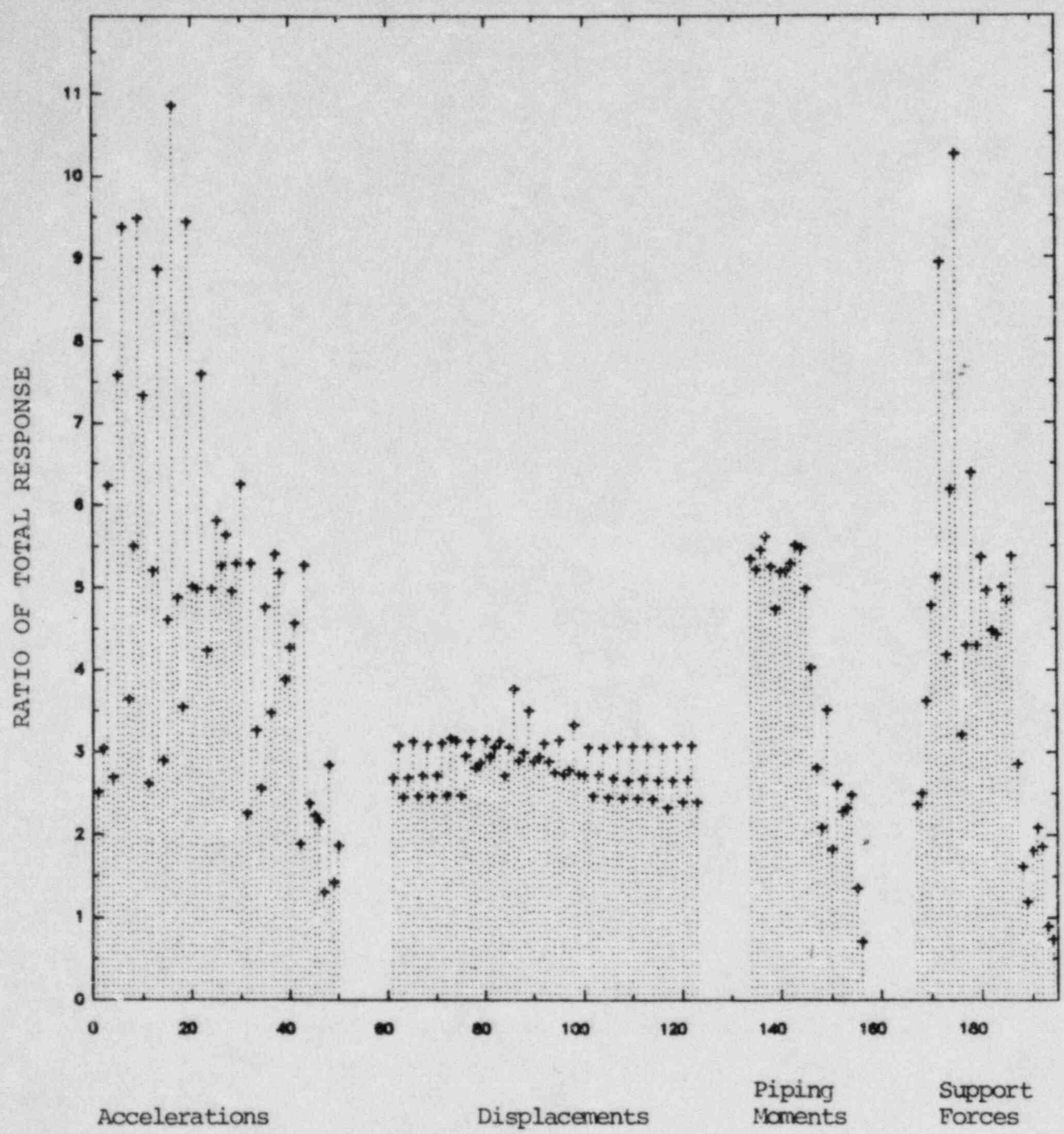


Fig. 14b. Ratios of Total Response Calculated by the SRP Method vs. Best Estimate 84% NEP - AFW Model.

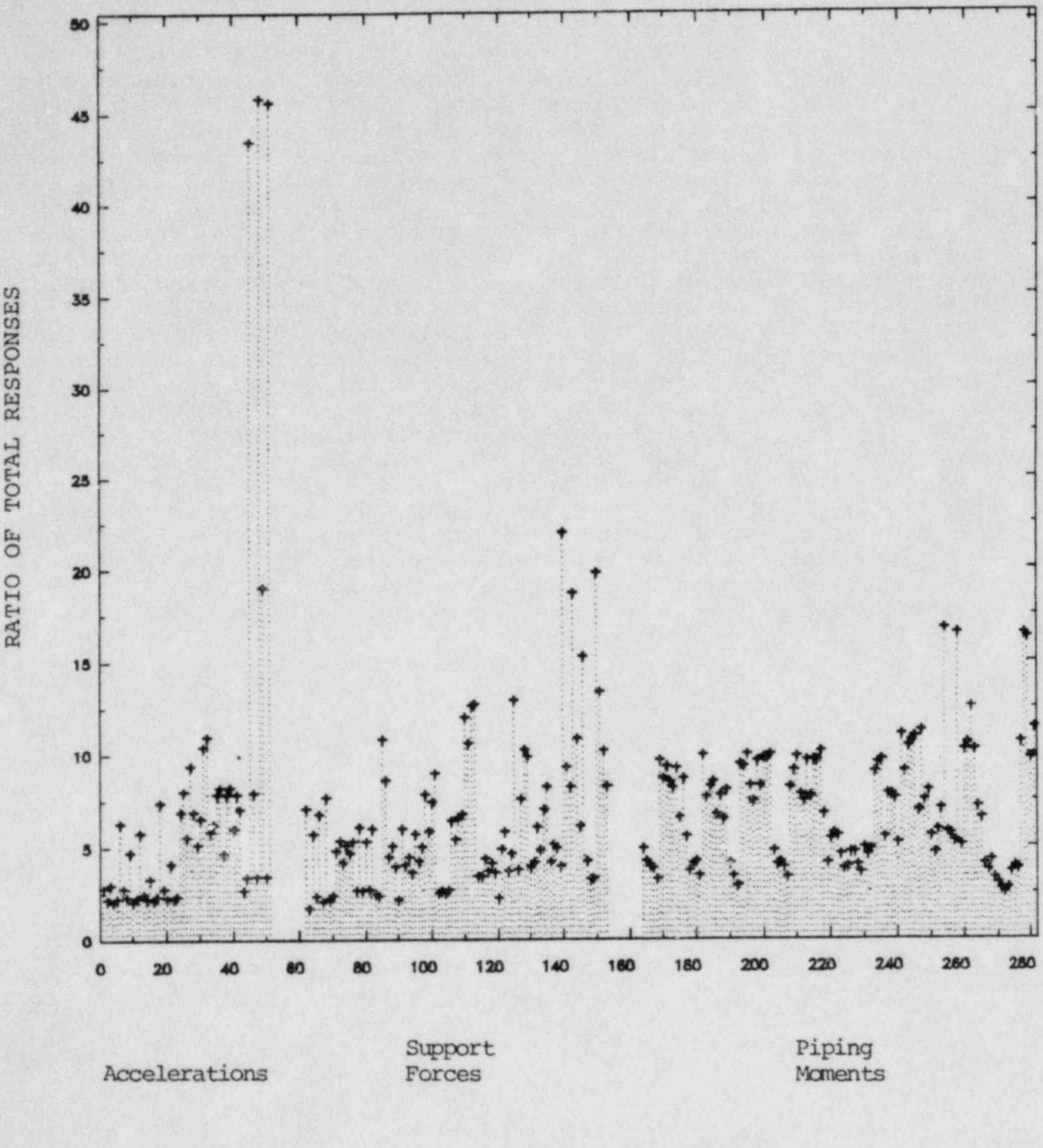


Fig. 14c. Ratios of Total Response Calculated by the SRP Method vs. Best Estimate 84% NEP - RCL Model.

5. CONCLUSIONS

Quantifying the calculational margin associated with a commonly used design analysis approach relative to time history analysis methods was investigated in this study. Several observations regarding the amount and variation of margin associated with the design approach - the SRP response spectrum method - can be made. Large conservatisms result from the analysis of piping systems by the SRP procedures. Despite representing lower bounds, ratios of response calculated by SRP methods versus median and 84% NEP time history values are large. For several reasons, these ratios represent lower bounds. First, not all aspects of the SRP methodology were included in calculating SRP responses. The approach to SSI and structure response for both the best estimate and SRP methods were similar except for treatment of uncertainties. Applying the SRP methodology to the SSI and structure response calculational elements would lead to higher response. Second, the best estimate response values were biased high due to the large variability in input parameters and conservative nominal parameter values for structure and piping system damping. Finally, the pseudostatic responses defined for the SRP method were calculated by time history analysis and were therefore less than that calculated in a static analysis involving worst case support displacements. Lower bound total SRP response values result.

6. REFERENCES

1. Atomic Energy Commission, "Regulatory Guide 1.60, Design Response Spectra for Seismic Design of Nuclear Power Plant," Rev. 1, (1973).

2. Atomic Energy Commission, "Regulatory Guide 1.61, Damping Values for Seismic Design of Nuclear Power Plants," (1973).

3. Nuclear Regulatory Commission, "Regulatory Guide 1.122, Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components," Rev. 1, (1978).

4. Nuclear Regulatory Commission, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," LWR Edition, NUREG-0800, (1981).

5. Nuclear Regulatory Commission, "Regulatory Guide 1.92, Combining Modal Responses and Spatial Components in Seismic Response Analysis," Rev. 1, (1976).

6. Johnson, J. J., Goudreau, G. L., Bumpus, S. E., and Maslenikov, O. R., "SMACS-Seismic Methodology Analysis Chain with Statistics," NUREG/CR-2015, Vol. 9, (1981).

7. Benda, B. J., Johnson, J. J., Lo, T. Y., "Major Structure Response," NUREG/CR-2015, Vol. 5, (1981).

8. Shieh, L. C., Chuang, T. Y., O'Connell, W. J., "Subsystem Response" NUREG/CR-2015, Vol. 6, (1981).

9. Coats, D. W., "Recommended Revisions to Nuclear Regulatory Commission Design Criteria," NUREG/CR-1161, (1979).

APPENDIX A

APPENDIX A

DESCRIPTION OF STRUCTURES AND PIPING SYSTEMS

The Zion nuclear power plant, Zion, Illinois, (Fig. A1) was the subject of the analyses conducted. Two structures, the containment building and the AFT complex house the piping systems of interest in this study. Models for all the structures analyzed here were originally developed for the SSMRP 3, 4 . A brief description of the models is given here.

The computer program SMACS [6] was used to calculate soil-structure interaction (SSI), structure response, and multi-support time history analysis of piping systems. The substructure approach to SSI and structure response applied in SMACS requires the structure's dynamic characteristics to be described by its fixed-base eigensystem. Hence, the modal characteristics of the structures of interest itemized next are fixed-base values.

The containment building (Fig. A2) is comprised of two separate structures on a common basemat -- a prestressed containment shell and a concrete internal structure. The internal structure supports a four loop, pressurized water reactor nuclear steam supply system (NSSS). The containment shell was modeled with a series of beam elements. Masses and rotary inertias were lumped at node points. Rotary inertias affecting bending and torsional response of the shell were included. Thirteen modes defined its dynamic characteristics. The internal structure, including a simplified model of the NSSS was modeled with three-dimensional beam and plate finite elements. Masses were again lumped at selected node points. Sixty fixed-base modes were included in the time history response analyses.

The AFT complex consists of the T-shaped auxiliary building, the turbine building, the fuel handling building and the diesel generator rooms. The complex is assumed to be symmetrical with respect to a dividing line between the two reactor units. A detailed, three-dimensional model of half of the complex containing over 3800 degrees-of-freedom was constructed (Fig. A3). Applying the appropriate boundary conditions along the plane of symmetry, the model was used to extract first the symmetric and then the antisymmetric modes. A combined total of 113 modes were used to define the structure's dynamic characteristics.

Points in the structures supporting the three piping systems considered here were identified. Response at these points in the form of response spectrum and time history records were retained for input to the piping models.

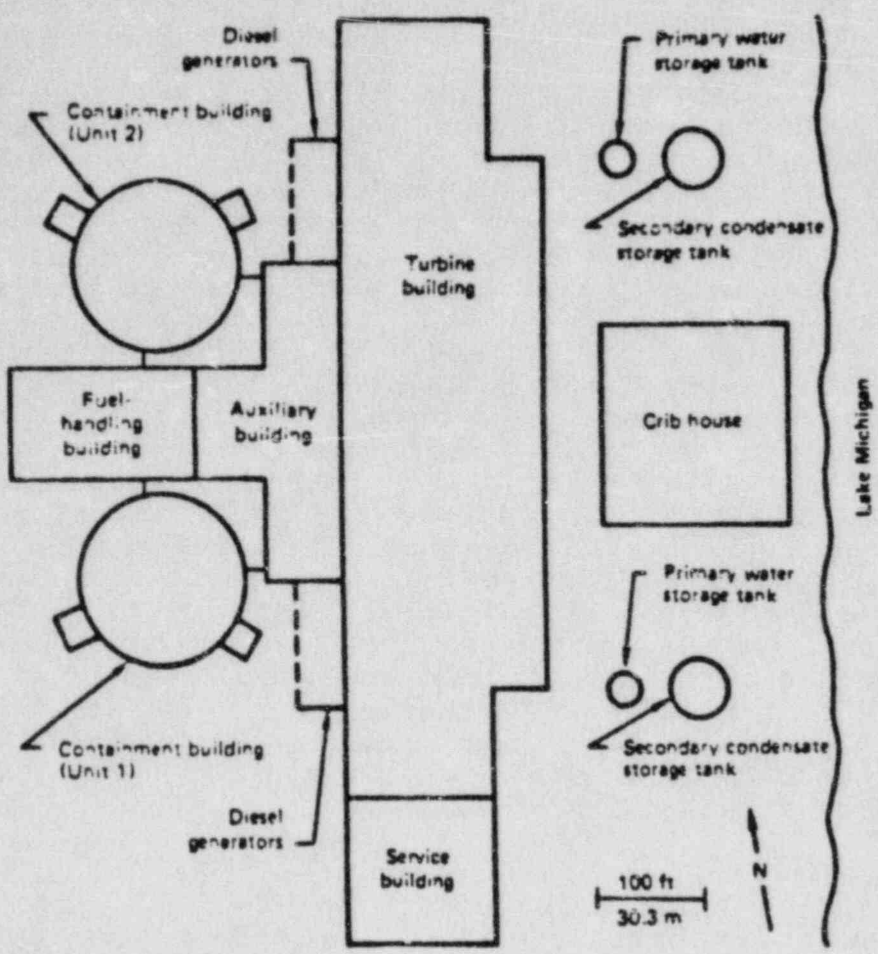


Fig. A1. Site Plan of the Zion Nuclear Power Plant.

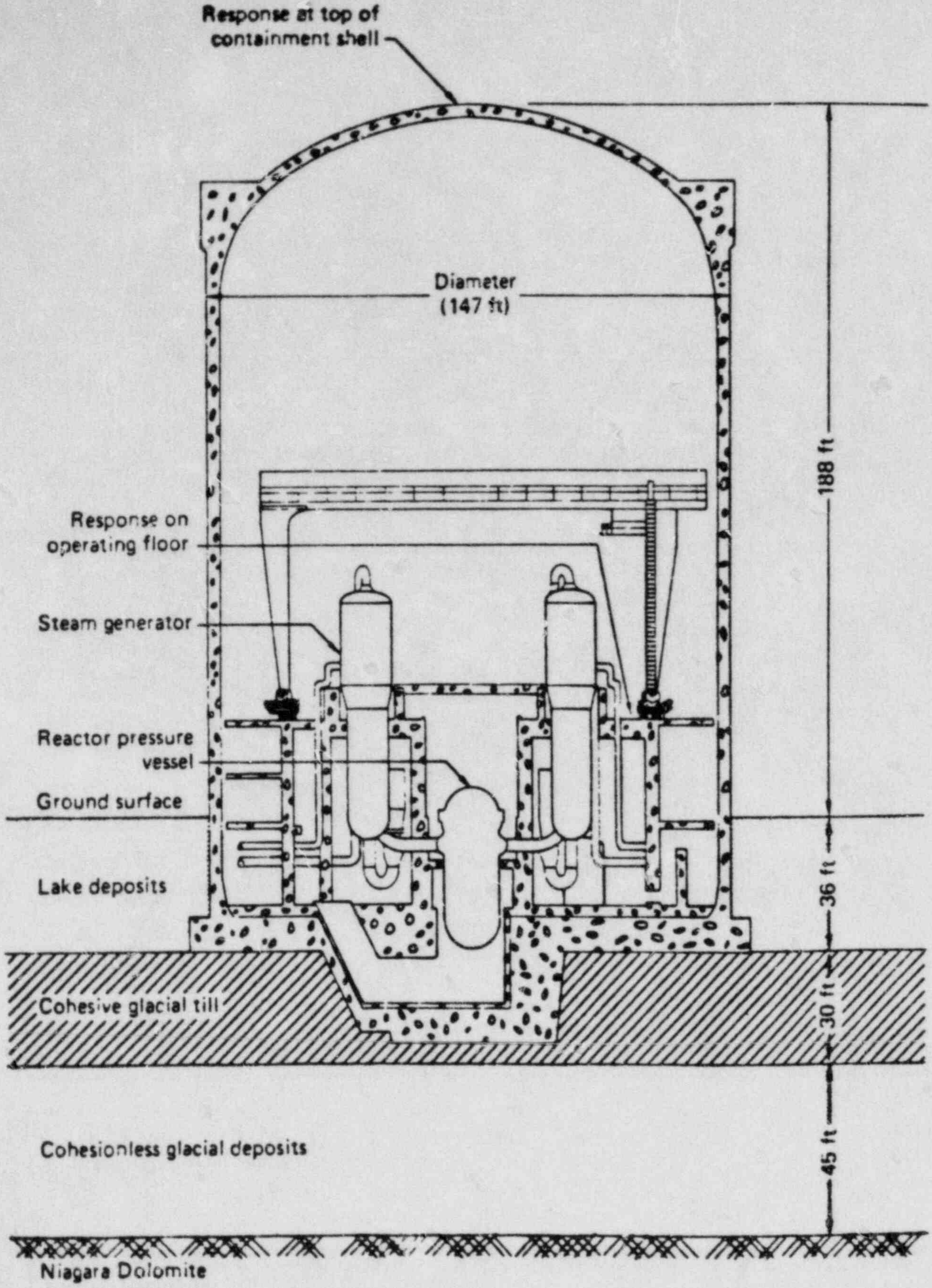


Fig. A2. Cross section of the containment building at Zion.

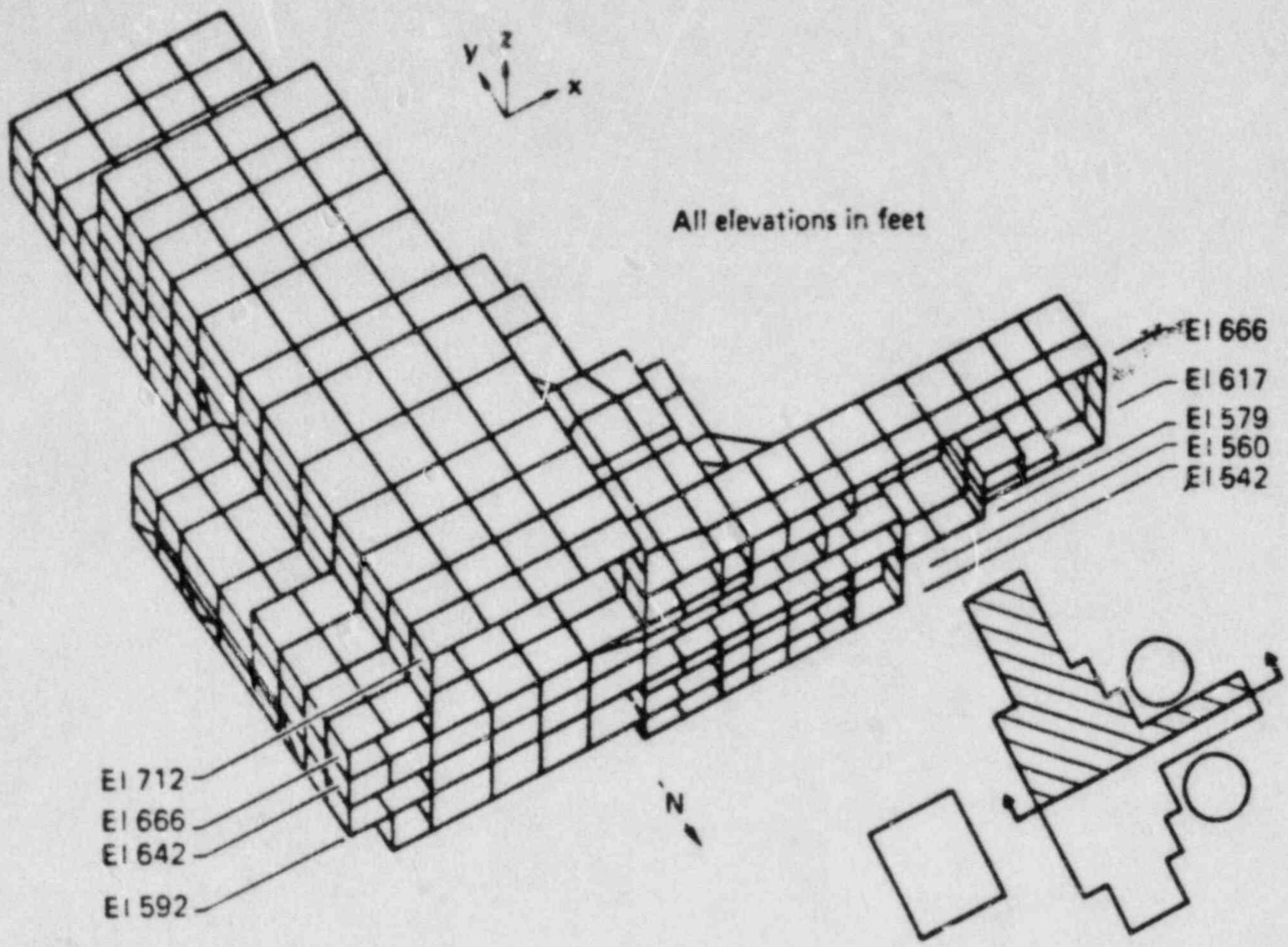


Fig. A3. Finite Element Model of a Portion of the Auxiliary Building.

APPENDIX B

APPENDIX B

PSEUDOSTATIC MODE APPROACH TO MULTI-SUPPORT EXCITATION ANALYSES

Following is a derivation of the pseudostatic mode approach to multisupport excitation analysis which was used to determine piping systems response in the time history analysis method.

The equations of motion for an elastic damped system subjected to zero external loads can be partitioned into active degrees-of-freedom (x_1) and specified support degrees-of-freedom (x_2) and written as

$$\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ P \end{Bmatrix} \tag{1}$$

where x_i, $\dot{x}_i$, and $\ddot{x}_i$ denote absolute displacements, velocities, and accelerations; and M, C, and K denote mass, damping and stiffness matrices, respectively. The vector P denotes support forces. Equation 1 can be rewritten as

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

and

$$[M_2]\{\ddot{x}_2\} + [C_{22}]\{\dot{x}_2\} + [K_{22}]\{x_2\} = -[C_{21}]\{\dot{x}_1\} - [K_{21}]\{x_1\} + \{P\} \tag{2b}$$

Assume the absolute displacement x_1 to be composed of two parts -- a pseudostatic portion x_1^S and a dynamic portion x_1^D:

$$\{x_1\} = \{x_1^S\} + \{x_1^D\} \tag{3}$$

where x is defined by

$$[K_{11}]\{x_1^S\} = -[K_{12}]\{x_2\} \tag{4a}$$

and thus

$$\begin{aligned} \{x_1^S\} &= -[K_{11}]^{-1}[K_{12}]\{x_2\} \\ \{\dot{x}_1^S\} &= -[K_{11}]^{-1}[K_{12}]\{\dot{x}_2\} \\ \{\ddot{x}_1^S\} &= -[K_{11}]^{-1}[K_{12}]\{\ddot{x}_2\} \ . \end{aligned} \tag{4b}$$

The pseudostatic component x_1^S can be interpreted as the response induced in the system due to support motions, excluding inertia effects, whereas the dynamic portion x_1^D can be seen as a perturbation of the pseudostatic response due to inertia effects. The pseudostatic mode method efficiently uses an eigenfunction expansion of x_1^D . Since x_1^D represents motion relative to the supports, a limited number of modes adequately represent its spatial and temporal behavior.

Rewriting Eq. 2a using Eqs. 3 and 4 recognizing, rigid-body motion as a stress-free state of the system, and assuming damping to be proportional to stiffness, leads to

$$[M_1]\{\ddot{x}_1^D\} + [C_{11}]\{\dot{x}_1^D\} + [K_{11}]\{x_1^D\} = [M_1][K_{11}]^{-1}[K_{12}]\{\ddot{x}_2\} \quad . \tag{5}$$

Assume that the displacement x_1^D can be represented by an eigenfunction expansion, i.e., that a linear coordinate transformation exists that diagonalizes the mass, stiffness, and damping matrices ($[M_1]$, $[K_{11}]$, and $[C_{11}]$, respectively). Then

$$[x_1^D] = [\Phi]\{q\} \quad , \tag{6}$$

where $\{q\}$ is of the form $\{e^{i\omega t}\}$ and the columns of $[\Phi]$ are the eigenvectors $\{\Phi_j\}$. The functions q_j are denoted generalized coordinates.

Substituting Eq. 6 into Eq. 5 and applying the assumptions of diagonalization of the mass, stiffness, and damping matrices yields

$$\{\ddot{q}\} + [\,^{\backslash}2\beta_j\omega_j{}_{\backslash}]\{\dot{q}\} + [\,^{\backslash}\omega_j^2{}_{\backslash}]\{q\} = [\hat{\Phi}]^T[M_1][K_{11}]^{-1}[K_{12}]\{\ddot{x}_2\} \tag{7}$$

where ω_j and β_j are the natural frequency and the fraction of critical damping, respectively, of the jth mode. The matrix $[\hat{\Phi}]$ denotes the incomplete eigenfunction expansion of $\{x_1^D\}$, i.e., a reduced set of the complete expansion $[\Phi]$. The right-hand side of Eq. 7 can be simplified to

$$\{\ddot{q}\} + \left[{}^{\backslash}2\beta_j\omega_{j\backslash}\right]\{\dot{q}\} + \left[{}^{\backslash}\omega_{j\backslash}^2\right]\{q\} = \left[{}^{\backslash}\omega_{j\backslash}^2\right]^{-1}\left[\hat{\Phi}\right]^T\left[K_{12}\right]\{\ddot{x}_2\} \quad , \tag{8}$$

which is used to determine the piping system inertial response.

Recovery of response -- accelerations, displacements, and stress -- remains to be discussed. Solution of the equations of motion (Eq. 8) does not require the pseudostatic modes directly; however, response recovery does. Denote by P the pseudostatic modes or influence coefficients relating in-system response to unit support motions. Then,

$$[K_{11}][P] = -[K_{12}] \quad . \tag{9}$$

For displacement or acceleration response, it is a simple matter to show

$$\{x_1\} = [\hat{\Phi}]\{q\} + [P]\{x_2\} \tag{10}$$

where the first term is the inertial response and the second is the pseudostatic response.

For stress response, it is also easily shown that the stress in member m, $\{\sigma_m\}$, can be written as

$$\{\sigma_m\} = \left[\hat{S}_{1m}\right]\{q\} + \left[\hat{S}_{2m}\right]\{x_2\} \quad , \tag{11}$$

where

$$\left[\hat{S}_{1m}\right] = \left[S_{1m}\right]\left[\hat{\Phi}\right]$$

and

$$\left[\hat{S}_{2m}\right] = \left[S_{1m}\right]\left[P\right] + \left[S_{2m}\right]\{x_2\} \quad .$$

The matrices $[S_{1m}]$ and $[S_{2m}]$ are stress-displacement relationships relating stresses in member m to active displacement x_1 and support displacements x_2 , respectively, and provide for the calculation of pipe element forces and moments. As in Eq. 10, the first term is the stress due to inertial response and the second term is the stress due to pseudostatic response.

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The seismic response of piping systems is frequently separated into two parts -- the inertial response and the pseudostatic response. Various analysis procedures have been developed to calculate each portion of the response separately. The analysis procedures used are frequently simplified and, in so doing, introduce significant conservatism. Conservatism in the US NRC SRP response spectrum analysis methodology is quantified here as measured against a multi-support time history analysis procedure. Also, best estimate piping system responses are compared to design values which is valuable to seismic PRA applications.

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