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Quantification of Margins in Piping System Seismic Response: Methodologies and Damping

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ABSTRACT

The conservatism of seismic analysis and design of piping systems due to analysis methodologies and damping values was quantified. Envelope response spectrum analyses, independent support motion response spectrum analyses, and multi-support time history analysis methodologies were evaluated. Constant damping, ranging from 1% to 10%, and PVRC damping were considered. Conservatisms were evaluated with respect to best estimate responses of the entire seismic analysis chain and of the piping system alone.

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FOREWORD

The authors wish to express their appreciation to Mr. D. J. Guzy of the US NRC and Dr. Robert C. Murray of Lawrence Livermore National Laboratory, for their interest, support, and valuable comments during the course of this work. In addition, special thanks to Ms. Elaine M. Brovont for her compilation of the manuscript. This effort was supported by Lawrence Livermore National Laboratory under Subcontract Number 1281903.

EXECUTIVE SUMMARY

The seismic analysis and design of piping systems has been shown to be extremely conservative. This conservatism results from conservative treatment of the piping system itself and from conservatisms introduced in the other elements of the seismic analysis chain, i.e. seismic input, soil-structure interaction (SSI), and structure response. Previous studies have investigated conservatism in calculated piping system responses by two basic approaches -- both are utilized herein. The first approach isolates the piping system dynamic analysis and quantifies the effect on piping system response of changing methodologies and/or parameters in the analysis. In this approach, consistency is maintained through the steps of the seismic analysis chain to the level of piping system analysis. Changing methodologies and/or parameters in the piping system analysis then allows one to quantify their effect on response. The second approach treats the entire seismic analysis chain and seeks to compare "best estimate" or realistic piping response with responses calculated by a design procedure. "Best estimate" refers to realistic seismic input, SSI models and parameters, structure models and parameters, and piping system models and parameters. In addition, best estimate analyses explicitly include uncertainty. Consequently, the end result -- piping system response -- is expressed as a probability distribution.

A major objective of this study was to interpret previously calculated responses in terms of: new results calculated utilizing recently assimilated data on piping system damping; and state-of-the-art best estimate seismic analyses, again utilizing the most recently assimilated data on soil, structure, and piping system dynamic behavior. Hence, only limited re-analyses were performed for this study.

Three piping system models (AFW, RHR, RCL) of the Zion Nuclear Power Plant were the subject of this study. The characteristics in terms of size, stiffness, and complexity represent a range of nuclear piping configurations. The three models were relatively low frequency with their fundamental frequencies below 4 Hz. These three models have been studied extensively in past investigations and previously calculated responses were used extensively herein. Piping response in the form of nodal accelerations and displacements and element forces and moments were compared.

The responses from three types of piping analysis were compared: multi-support time history analysis (MTH), envelope response spectrum analysis (ERS), and independent support motion response spectrum analysis (ISM). Many of the analyses compared here are denoted "R.G. 1.60" due to the seismic input being defined by a single or ensemble of earthquake motions comprised of artificial time histories whose response spectra essentially envelope the design ground response spectra of US NRC Regulatory Guide 1.60. The data sets for comparison purposes were:

Multi-support time history analysis, R.G. 1.60.

All multi-support time history analyses were performed with SMACS -- the probabilistic response analysis program developed for the US NRC Seismic Safety Margins Research Program (SSMRP). Piping system damping differentiated the cases. For the AFW and RHR models, constant damping cases of 1%, 2% 4%, 5% and 10% were considered. For the RCL model, constant damping cases of 2%, 3%, 4%, 5%, and 10% were considered. In addition, PVRC damping was considered for all three models. Thirty earthquake simulations comprised each of these analyses. Median values of response, i.e. median of the thirty earthquake simulations, were the quantities compared here.

Multi-support time history analysis, R.G. 1.60, INEL damping.

This case serves as the basis of comparison for the scenarios of isolating piping system dynamic analyses and quantifying their conservatism. The only difference between this case and those discussed above is in the piping system analysis. Uncertainty in piping system dynamic characteristics is explicitly included. Piping system frequencies were assumed to be uncertain and their variability was described by a lognormal distribution with a coefficient of variation (COV) of 0.3. Piping system damping was likewise assumed uncertain and described by a lognormal distribution with median of 5.67% and a COV of 0.84 -- both values correspond to data assimilated by Idaho National Engineering Laboratory (INEL) for the US NRC; hence, the term INEL damping. Responses for this case are in the form of probability distributions and the results of other analyses are correlated with nonexceedance probabilities (NEPs) of this case.

Envelope response spectrum analysis (ERS).

The envelope response spectrum analysis method corresponds to a US NRC Standard Review Plan (SRP) Sec. 3.9.2 acceptable method for the analysis of multiply supported equipment and components. The procedure is one in which a response spectrum analysis of the piping system is performed -- the excitation being defined by three response spectra (one in each orthogonal horizontal direction and the vertical direction). Each response spectrum is the envelope of all support point response spectra for the direction of interest. Two forms of this design procedure were the basis for responses compared here. The first employed US NRC Regulatory Guide 1.61 damping values of 2% for the AFW, RHR, and RCL models. Three analyses from seismic input through piping system response were performed and the results were averaged to minimize artificial time history induced variations in the response. The second form employed PVRC damping and only a single earthquake was considered. The former is denoted "ERS(2%)" and the latter "ERS(PVRC)" in the subsequent text.

Independent support motion response spectrum analysis (ISM).

The independent support motion response spectrum analysis results compared here were calculated by Brookhaven National Laboratory (BNL). The basic approach is to calculate response of the piping system for each independent support degree-of-freedom separately and combine these responses by an appropriate rule. The R.G. 1.60 analyses through the structure response phase were used in the BNL analyses, i.e. thirty earthquake simulations were considered and the median response value over the thirty was used in the comparisons. Only the AFW and RHR models were considered due to the large size of the RCL model. As in the envelope response spectrum analysis, two cases, differing only by the damping values assumed in the piping system, were considered. The first employed US NRC Regulatory Guide 1.61 damping of 2% for the AFW and RHR models. The second employed PVRC damping for the RHR model only. In the subsequent text, the former is denoted "ISM/SRSS(2%)" and the latter "ISM/SRSS(PVRC)." The "SRSS" is included to identify the method of support group combination.

Multi-support time history analysis, best estimate.

Best estimate analyses were performed with SMACS for the AFW, RHR, and RCL models. Each element in the seismic analysis chain was treated as best estimate and explicitly included uncertainty. Probability distributions of piping responses were calculated. Hence, the nonexceedance probability of each piping response, conditional on an earthquake occurring of specified peak ground acceleration, was estimated. The approach taken here was to compare "design responses" with the distribution of best estimate values quantifying their conservatism. For these comparisons to have meaning, consistency between the elements of the models (design vs. best estimate) must be maintained. For the seismic input, an ensemble of thirty earthquake motions (three components each -- two horizontal and the vertical) were developed. The peak ground acceleration of the time histories corresponded to 0.18g - identical to the R.G. 1.60 data set. The frequency characteristics of the time histories was such that their 84% NEP response spectra approximated the R.G. 1.60 design ground response spectra. Hence, this best estimate data set corresponds to the original R.G. 1.60 data set and the philosophy employed to arrive at the design ground response spectra. The SSI, structure, and piping system models were identical to those of the R.G. 1.60 analyses with two exceptions: higher, more realistic damping characteristics were assumed for the structures; and random variability in soil, structure, and piping system parameters was modeled. When variability was included in the R.G. 1.60 analyses, it represented total uncertainty.

Response Comparisons -- R.G. 1.60 Design Analyses vs. R.G. 1.60 INEL Damping

The approximate range of NEPs for each of the R.G. 1.60 design analyses vs. the R.G. 1.60 INEL damping case is shown below. This set of results focuses on the conservatism in the piping system analysis methodologies and the effect of damping assumptions. The values represent the range of NEPs calculated for nodal accelerations and element forces and moments. Slightly lower NEP values were calculated for nodal displacements. The range includes all three piping models -- no apparent differences occurred for the different models.

Analysis/ Damping	Range of NEPs (%) R.G. 1.60 INEL Damping
MTH/1%	83-94
MTH/2%	71-85
MTH/3%	60-65
MTH/4%	54-65
MTH/5%	49-55
MTH/PVRC	51-62
MTH/10%	32-43
ERS(2%)	>99.7
ERS(PVRC)	>96.4
ISM/SRSS(2%)	>93.6
ISM/SRSS(PVRC)	>92.7

These results quantify the conservatism in the piping system analysis procedures and in the piping system damping values. For example, performing a piping system dynamic analysis by the envelope response spectrum analysis technique and applying R.G. 1.61 damping values (2%) leads to calculated responses which exceed the 99.7% NEP when treating the piping system analysis itself in a best estimate manner. Similarly, significant conservatism remains in the process when the envelope response spectrum analysis approach is applied with PVRC damping. Note, the multi-support time history analysis with PVRC damping leads to responses with NEPs slightly higher than the median. The effect of other damping values on the NEPs is apparent from the table.

Response Comparisons -- R.G. 1.60 Design Analyses vs. Best Estimate

The approximate range of NEPs for each of the R.G. 1.60 design analyses vs. the best estimate results is shown below. This set focuses on the conservatism introduced throughout the seismic methodology chain. Again, these values represent the range of NEPs calculated for nodal accelerations and element forces and moments. Slightly lower NEPs were calculated for nodal displacements. The range includes all three piping models.

Analysis/ Damping	Range of NEPs (%) Best Estimate
MTH/1%	>97
MTH/2%	93-99.5
MTH/3%	91-99
MTH/4%	87-98
MTH/5%	83-97
MTH/PVRC	85-97
MTH/INEL	75-96
MTH/10%	67-89
ERS(2%)	>99.9
ERS(PVRC)	>99.9
ISM/SRSS(2%)	>99.8
ISM/SRSS(PVRC)	>98.6

These results quantify the conservatism in piping system response introduced through the entire seismic methodology chain. One readily observes the high NEPs for all of the cases studied. Note, in particular, that the multi-support time history analysis with PVRC damping leads to responses with NEPs of 85-97%. Hence, applying a methodology which is considered best estimate (multi-support time history analysis) and applying damping to the piping system which approximates median values (PVRC damping), conservatism in the remaining elements of the seismic methodology chain still leads to design responses with nonexceedance probabilities greater than 85%. Further, if one established a performance specification such as: seismic analysis procedures and parameter values of the analysis shall be selected such that if an earthquake occurred with peak ground acceleration equal to the design earthquake, the probability of exceeding the response levels determined in the seismic analysis and used in the seismic design would be about 10-15%. Then, the design analysis procedures employed here for seismic input, SSI, and structure response in conjunction with multi-support time history analysis and PVRC damping and for independent support motion with SRSS of support group responses utilizing PVRC damping satisfy this criteria.

The conclusions drawn here are generic in the sense that consistent soil-structure-piping system models were analyzed in all cases with differences only in parameter values. For the case of comparisons with RG 1.60, INEL damping, seismic input and soil-structure system models and parameters were identical up to piping system response calculations. Then, the piping system analysis methodologies and parameters were varied to quantify their effects. For the case of comparisons with best estimate values, the soil-structure models were identical with changes in parameter values only. Additional potential conservatisms, such as SSI embedment effects, were not included in one case and excluded from another.

1.0 INTRODUCTION

1.1 BACKGROUND

The seismic response of piping systems is frequently separated into two parts -- the inertial or vibratory response and the pseudostatic response due to relative motions of the piping system supports. Several analysis procedures have been developed to calculate each portion of the response separately. This study focuses on inertial response. The US Nuclear Regulatory Commission (NRC) in the Standard Review Plan (SRP), Regulatory Guides, and other licensing documents specifies acceptable methods of analysis of multiply - supported equipment and components with distinct inputs. Along with methods of analysis, parameter values, such as damping, are specified. The present study evaluates methods of analysis of piping systems and the important parameter damping.

The seismic analysis and design of piping systems has been shown to be extremely conservative [1-3]. This conservatism results from conservative treatment of the piping system itself and from conservatisms introduced in the other elements of the seismic analysis chain, i.e. seismic input, soil-structure interaction (SSI), and structure response. Previous studies have investigated conservatism in calculated piping system responses by two basic approaches. The first approach isolates the piping system dynamic analysis and quantifies the effect on piping system response of changing methodologies and/or parameters in the analysis. In this approach, consistency is maintained through the seismic analysis chain to the level of piping system analysis, i.e. the same seismic input, soil-structure interaction (SSI) models and parameters, and structure models and parameters are used. Then, given consistent input to the piping systems, the effects of changing methodologies and/or parameters on piping system response are investigated.

Examples of using this approach are contained in Refs. 1-5 and are summarized here. Most of these comparisons were performed for three piping system models (AFW, RHR, RCL) of the Zion Nuclear Power Plant. The characteristics of these models, in terms of size, stiffness, and complexity represent a range of nuclear piping configurations. The three models were relatively low frequency with their fundamental frequencies below 4 Hz. These three models were the subject of the current study also and are described in detail in Sec. 2.

- Benda and Johnson [1] performed multi-support time history analysis of the three piping system models (AFW, RHR, RCL) for varying assumptions of piping system damping. The methodology of SMACS, to be described in Sec. 3, was used for each case. Also, all elements of the analysis were identical from definition of the seismic input to the input to the piping system models. Various damping assumptions were then made to quantify the effect of damping on piping system response. For the study, PVRC damping was incorporated into the multi-support time history analysis procedure of SMACS. PVRC damping denotes the recommendation of the Technical Committee on Piping Systems of the Pressure Vessel Research Committee (PVRC). These recommended damping values are a function of the piping system frequencies--5% damping for frequencies below 10 Hz, 2% damping for frequencies greater then 20 Hz, and a linear variation from 5% to 2% for intermediate frequencies. For the RHR and AFW models, damping values of 1%, 2%, 4%, 5%, 10%, and PVRC damping were considered. For the RCL model, 2%, 3%, 4%, 5%, 10%, and PVRC damping were considered. Comparisons of responses (nodal accelerations and displacements, element forces and moments) quantified the effects of various damping assumptions on response.

- Chuang et al. [2] evaluated the impact of the PVRC damping proposal and a PVRC proposed alternative to peak broadening of in-structure response spectra, namely spectrum peak shifting, on piping system response. Envelope response spectrum analysis (ERS) was the principal analysis technique employed. The basic procedure for the ERS is to calculate in-structure response spectra at piping support locations. Peak broaden these spectra when this procedure is applied. Envelope the resulting spectra in each of three orthogonal directions (two horizontal and the vertical) and use these envelopes for the response spectrum analysis of the piping system. The three piping models AFW, RHR, and RCL of the Zion Nuclear Power Plant were studied. For this study, the base case was the ERS technique with US NRC Regulatory Guide (RG) 1.61 damping and spectrum peak broadening according to US NRC RG 1.122. Three additional response spectrum analyses were performed: one using PVRC damping instead of RG 1.61 values; a second using peak shifting instead of peak broadening; and the third using the combination of PVRC damping and peak shifting. When RG 1.61 was applied, OBE level damping was assumed because the OBE typically governs piping system design. Also, PVRC damping values correspond to OBE level stresses [8]. For the RHR and AFW models, 1% constant damping was used. For the RCL model, 2% constant damping was used. Responses were compared and the effect of each item quantified. In addition to this quantification based on applying the ERS technique, two other studies were performed. One was a comparison of the ERS responses with those calculated applying multi-support time history analysis techniques with constant damping of 1% and 2% for the RHR and AFW models and 2% for the RCL model. This comparison showed that substantial conservatism remained for the ERS technique with PVRC damping when compared with responses calculated by the multi-support time history analysis technique. The second study investigated the hardware effects (snubbers and restraints) of using PVRC damping and the alternative to peak broadening with ERS. It was demonstrated for the AFW model that both snubbers and 7 of the 10 horizontal restraints would be unnecessary. Hence, significant conservatism was retained and hardware changes could be implemented. Johnson et al. [3] performed similar comparisons for the base case, i.e. ERS with RG 1.61 damping and RG 1.122 peak broadening, and multi-support time history analysis results. Their study set the ground work for Chuang et al. [2]. In addition, Johnson et al. introduced the concept and application of best estimate responses and their comparison with design results to quantify conservatism. This approach is discussed below.

- Subudhi et al. [5] investigated independent support motion (ISM) response spectrum analysis techniques applied to six piping system models [4], two of which were the AFW and RHR of the Zion Nuclear Power Plant. The basic objective of this study was to investigate and quantify the conservatism in various ISM procedures compared to each other and multi-support time history analysis results. Variations in ISM procedures were with combination procedures (rules and sequence) for support groups, modes, and directions--fourteen different combination rules were considered. Comparisons between the fourteen and multi-support time history results were made. Also, uniform or envelope response spectrum analyses (ERS) were performed. The study concludes that using the ISM procedure, the sequence of combination between modes, directions, and groups has a small effect on results. The combination procedure used to sum group contributions has a far greater effect. Algebraic combination was found to yield results similar to those predicted by the ERS. Absolute combination provided very conservative estimates of response while SRSS combination provided an estimate of response which was statistically equivalent to those developed with the ERS method. This study also investigated pseudostatic response calculational procedures and combination of inertial and pseudostatic responses. The inertial response aspect used RG 1.61 damping values. A follow-up to this study [18] repeated these analyses for PVRC damping. Selected results from Ref. 18 are compared here.

The second approach treats the entire seismic analysis chain and seeks to compare a "best estimate" or realistic piping response with responses calculated by a design procedure. The concept of "best estimate" calculations as they pertain to seismic responses was introduced by Johnson et al. [11] for seismic probabilistic risk assessments (PRAs). One element of a seismic PRA methodology is predicting median responses and their dispersion conditional on the occurrence of an earthquake characterized by its peak ground acceleration or other descriptor. One way of predicting median response and its dispersion is calculationally. The computer program SMACS was developed to do so and is described in Sec. 3. SMACS has been applied in numerous situations to predict structure, component, and piping system response distributions, e.g. Bohn et al. [14]. "Best estimate" as used here refers to each element in the seismic analysis chain being treated as "best estimate" and explicitly including uncertainty, i.e. realistic seismic input, soil-structure interaction models and parameters, structure models and parameters, and piping system models and parameters. For illustration purposes, consider the following procedure. SMACS performs repeated analyses, each analysis simulating an earthquake occurrence. Each analysis can have a different seismic input and different values of parameters describing the soil, structure, and piping system dynamic characteristics. Assume thirty simulations were performed. The result of the thirty simulations is thirty values of peak response at points of interest in the structures, components, and piping systems. Consider a typical piping system response as shown in Fig. 1-1--a support force in the RHR piping model. The thirty values of peak response are plotted as discrete points. From the thirty values, the two parameters necessary to define a lognormal distribution are calculated--median and lognormal standard deviation. Figure 1-1 itemizes the two parameters for this case--a median value of 188.7 lbs. and a lognormal standard deviation of 0.27. Using these two parameters, the lognormal distribution function is shown as a segmented curve in Fig. 1-1. Based on the derived distribution function, statements can be made concerning the probability of exceedance or nonexceedance of a particular response value. For example, the probability of exceedance and nonexceedance of the median value (188.7 lbs.) is 50%. The probability of a force (in the specific RHR support represented in Fig. 1-1) exceeding 250 lbs. is about 15%. Inversely, the probability of a force not exceeding 250 lbs. is about 85%. This latter quantity is denoted nonexceedance probability (NEP) and is used extensively herein. Johnson et al. [3] introduced a second application of these best estimate response distributions. Given a response value calculated by a design procedure and using design parameter values such as damping, to what nonexceedance probability does it correspond? The higher the nonexceedance probability, the more calculational conservatism exists in the procedure. These types of comparisons are presented in subsequent sections. The results of this type of comparison as presented by Johnson et al. [3] showed large conservatisms in the design calculated responses versus the "best estimate" median or 84% NEP values. The "best estimate" seismic input, SSI, structure, and piping aspects were "best estimate" given the state of knowledge at the time.

Table 1.1 summarizes many of these analyses.

The present study utilizes both approaches in investigating calculational margins in piping system response.

1.2 OBJECTIVES AND SCOPE

A major objective of this study was to re-establish the "best estimate" baseline used in previous evaluations of piping system analysis methodologies and parameter values. The original baseline was developed by Johnson et al. [3] and reflected then current state-of-the-art knowledge. Over the past 8 years, the state-of-the-art has evolved. The particular scenario analyzed by Johnson et al. [3] corresponded to the US NRC Seismic Safety Margins Research Program (SSMRP) Phase I analysis--a demonstration calculation. In the ensuing time, changes were made to the methodology and parameter values. For example, the SSMRP Phase II response analyses (Bohn et al. [14]) used revised models for seismic input and SSI, and revised parameter values for soil, structure, and piping systems. Revisions reflected additional data, changes in the manner in which particular phenomena were treated (local site amplification, structure-to-structure interaction, etc.) and treatment of uncertainty. Johnson et al. [3] and the SSMRP Phase I analyses combined random and modeling uncertainty, whereas SSMRP Phase II treated the two separately. The present study focuses on random uncertainty.

The key differences between the "best estimate" analyses done to date are:

- Seismic input. Johnson et al. [3] used an ensemble of ninety earthquakes whose peak ground accelerations (PGAs) ranged from

0.15g to 0.30g with a median value of 0.18g. The frequency characteristics of the ensemble were those of a deep soil site and represented a realistic or "best estimate" seismic input for this case. Bohn et al. [14] used several ensembles of earthquake motions--each representing the hazard over a portion of the seismic hazard curve. Hence, PGAs varied depending on the hazard curve interval. The frequency characteristics of the motions included local site amplification to account for the shallow soil layers at the Zion site. These were considered "best estimate" including local site amplification effects. The present study utilizes an ensemble of thirty earthquakes--each earthquake comprised of three components of motion (two horizontal and the vertical). This ensemble was derived to represent the philosophy of US NRC RG 1.60. Horizontal and vertical components are anchored to 0.18g PGA. The frequency characteristics are such that the mean-plus-one-standard-deviation response spectra approximates the design response spectra of RG 1.60. The mean response spectra approximate the mean of the records which were the basis for RG 1.60. Hence, this ensemble represents closely the data base, including its variability, which led to the development of RG 1.60 and its mean-plus-one-standard-deviation or 84% NEP response spectra match RG 1.60; this aspect is important to subsequent comparisons.

- Soil-Structure Interaction. The SSI models in terms of phenomena explicitly included are identical for Johnson et al. [3] and the present study. Some differences in soil properties, in particular, soil material damping was introduced based on the revised analyses performed for SSMRP Phase II (Bohn et al. [14]). Median values of soil material damping were increased slightly. The Zion site was discretized into four layers for analysis purposes--the third layer being denoted the reference layer. References 3 and 11 assigned a median value of material damping of 2.5% in this layer; whereas Ref. 14 and the present study assigned a median value of 4.4% based on additional analyses. Median values of soil shear modulus remained essentially the same.

- Structure and Piping Models. The structure and piping models were identical for all studies, i.e. Refs. 3,13,14 and the present study. Some changes in best estimate material properties, i.e. damping, were made. References 3 and 13 assigned median values of structure damping of 2% and piping system damping of 2% which are unrealistically low for the excitation level considered (PGA of 0.18g) and in light of data assimilated in recent years. For the present study, a median value of structure damping of 10% was assumed based on recent test results for concrete shear wall structures. A median value of piping system damping of 7.5% [12] was used in the present study.
- Treatment of Uncertainty. Johnson et al. [3] and the SSMRP Phase I analyses combined random and modeling uncertainty and treated them simultaneously. Consequently, the coefficients of variation (COVs) of input parameters were relatively large--soil shear modulus, COV=0.7; soil material damping, COV=1.0; structure and piping frequency, COV=0.5; structure and piping damping, COV=0.7. Bohn et al. [14] treated random and modeling uncertainty separately. In the present study, only random uncertainty was included in the "best estimate" analyses and the variability assigned to randomness reflected recent information on structures [7] and piping systems [8]. The COVs are itemized in Sec. 3.

Given this revised "best estimate" baseline, previously calculated responses are reinterpreted quantifying the conservatism in their values. The form of the quantification is as discussed in Sec. 1.1--in terms of nonexceedance probabilities.

A second major objective of this study was to isolate the piping system analysis and quantify the effects of various piping system analysis methodologies and piping system damping values on response. Many cases have been analyzed and compared previously, e.g. Benda and Johnson [1]. The present report presents an additional comparison based on a second "best estimate" baseline, i.e. best estimate treatment of the piping system only. Design procedures are maintained through the structure response stage, i.e. seismic input (RG 1.60), SSI, and structure response. Piping system analysis is then treated in a best estimate fashion--best estimate methodology (multi-support time history analysis), best estimate parameter values (for this study, a distribution of piping system damping was assumed based on Ref. 8), and explicitly including uncertainty in piping system frequencies and damping (for this study, based on Refs. 7 and 8). The result is a distribution on piping system response from which NEPs can be estimated corresponding to the various design procedures considered.

This report is organized as follows. Section 2 describes the three piping models of the Zion Nuclear Power Plant which formed the basis of this study. Section 3 describes the methods of analyses, analyses performed, and analyses compared herein. Section 4 presents numerical results. Section 5 draws conclusions from the results.

Table 1.1a

COMPARISON OF RESPONSE ANALYSIS METHODS FOR THE AFW AND THE RHR PIPING SYSTEM

Analysis Case	Seismic Input	Variability SSI/Structure	Piping Method of Analysis	Damping Nominal(%)	Var	Piping Response	Reference	Comments
1	BE (90 EQ)	Yes	MTH	2	Yes	50%, 84% NEP	[3]	-
2	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[3]	-
3	RG 1.60 (3 EQ)	No	ERS	2	No	Avg of 3	[3]	-
4	RG 1.60 (30 EQ)	Yes	MTH	1	No	50% NEP	[2]	-
5	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[2]	Same as Case 2
6	RG 1.60 (1 EQ)	No	ERS	1	No	-	[2]	-
7	RG 1.60 (1 EQ)	RG Broad	ERS	PVRC Damp	-	-	[2]	-
8	RG 1.60 (1 EQ)	PVRC Broad	ERS	RG Damp	No	-	[2]	-
9	RG 1.60 (1 EQ)	PVRC Broad	ERS	PVRC Damp	-	-	[2]	-
10	RG 1.60 (30 EQ)	Yes	MTH	1	No	50% NEP	[1]	Same as Case 4
11	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[1]	Same as Case 2
12	RG 1.60 (30 EQ)	Yes	MTH	5	No	50% NEP	[1]	-
13	RG 1.60 (30 EQ)	Yes	MTH	PVRC Damp	-	50% NEP	[1]	-
14	RG 1.60 (30 EQ)	Yes	MTH	4	No	50% NEP	[1]	-
15	RG 1.60 (30 EQ)	Yes	MTH	10	No	50% NEP	[1]	-
16	RG 1.60 (33 EQ)	Yes	ISM	2	No	50% NEP	[5]	-
17	RG 1.60 (30 EQ)	Yes	ISM	PVRC	No	50% NEP	[7]	(RHR only)
18	RG 1.60 (30 EQ)	Yes	MTH	INEL	Yes	NEP	*	-
19	BE (30 EQ)	Yes	MTH	INEL	Yes	NEP	*	-

For the AFW system, an additional series of analyses were conducted by Chuang, et al. using the methodology of cases 6 and 9 above. These analyses investigated alternative support configurations of the AFW model.

Notes

MTH = Multi-support time history analysis
ERS = Envelope Response spectrum analysis
ISM = Independent support motion response spectrum analysis
INEL = Best estimate piping system damping
* = Current Study

Table 1.1b

COMPARISON OF RESPONSE ANALYSIS METHODS FOR THE RCL PIPING SYSTEM

Analysis Case	Seismic Input	Variability SSI/Structure	Piping Method of Analysis	Damping Nominal(%)	Damping Var	Piping Response	Reference	Comments
1	BE (90 EQ)	Yes	MTH	2	Yes	50%, 84% NEP	[3]	-
2	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[3]	-
3	RG 1.60 (3 EQ)	No	ERS	2	No	Avg of 3	[3]	-
4	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[2]	-
5	RG 1.60 (1 EQ)	No	ERS	2	No	-	[2]	Same as Case 2
6	RG 1.60 (1 EQ)	RG Broad	ERS	PVRC Damp	No	-	[2]	-
7	RG 1.60 (1 EQ)	PVRC Broad	ERS	RG Damp	No	-	[2]	-
8	RG 1.60 (1 EQ)	PVRC Broad	ERS	PVRC Damp	No	-	[2]	-
9	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[1]	-
10	RG 1.60 (30 EQ)	Yes	MTH	3	No	50% NEP	[1]	Same as Case 4
11	RG 1.60 (30 EQ)	Yes	MTH	5	No	50% NEP	[1]	-
12	RG 1.60 (30 EQ)	Yes	MTH	PVRC Damp	-	50% NEP	[1]	-
13	RG 1.60 (30 EQ)	Yes	MTH	4	No	50% NEP	[1]	-
14	RG 1.60 (30 EQ)	Yes	MTH	10	No	50% NEP	[1]	-
15	RG 1.60 (30EQ)	Yes	MTH	INEL	Yes	NEP	*	-
16	BE (30EQ)	Yes	MTH	INEL	Yes	NEP	*	-

Notes

MTH = Multi-support time history analysis

ERS = Envelope response spectrum analysis

ISM = Independent support motion response spectrum analysis

INEL = Best estimate piping system damping

* = Current Study

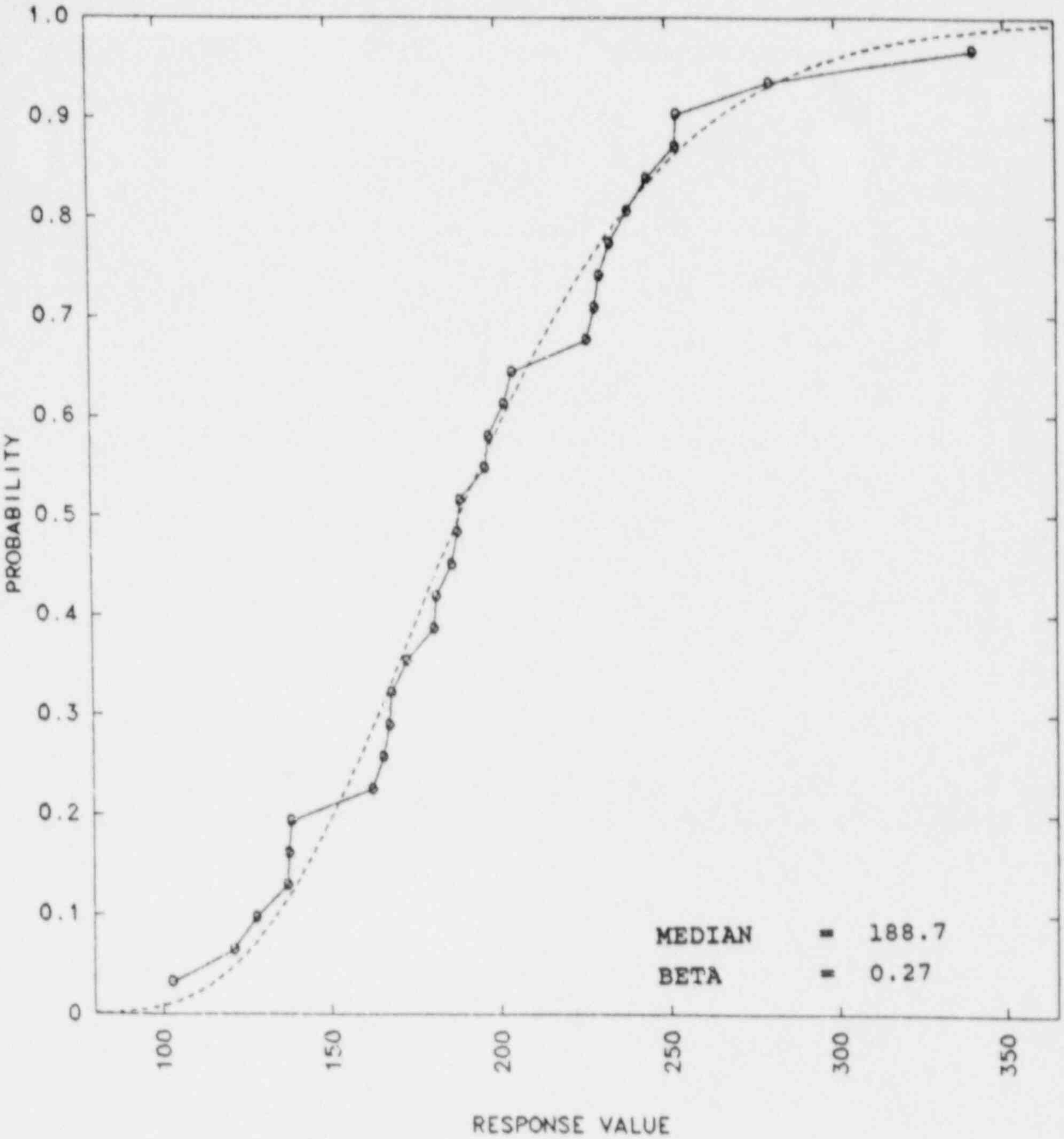

Fig. 1-1 Distribution of a Typical Support Force in the RHR Mode, Best Estimate

2.0 DESCRIPTION OF PIPING MODELS

2.1 INTRODUCTION

Three Zion Nuclear Power Plant piping systems were the subject of this study. In this section, the structures housing the piping systems, the three piping models, and their key parameters are described.

2.2 ZION STRUCTURES

Figure 2-1 illustrates the arrangement of buildings at the Zion plant. The piping systems of interest are housed in two structures, the containment building and the auxiliary, fuel-handling, turbine building (AFT) complex. The AFT complex consists of connected buildings housing the turbines, fuel-handling equipment, diesel generators, etc. Models of these structures were originally developed for the NRC-sponsored Seismic Safety Margins Research Program (SSMRP) [9].

Containment Building. The containment building has two separate structures, the containment shell and an internal structure, on a common basemat (Fig. 2-2).

The pre-stressed concrete containment shell is modeled with beam elements. The model includes rotational inertias that model bending and torsion of the shell. Masses and rotational inertias are lumped at node points. The first 13 fixed-base modes were included in the dynamic analysis. These modes cover all the structure's natural modes below 33 Hz.

Inside the containment shell, a separate concrete internal structure (Fig. 2-2) supports a four-loop pressurized-water reactor (PWR) Westinghouse nuclear steam-supply system (NSSS). The internal structure, including an appropriate representation of the NSSS, is modeled with three-dimensional finite elements (Fig. 2-3). The elements are beams, trusses, plates, straight and curved pipes, etc. Masses are lumped at selected node points. The first 60 fixed-base modes were included in the analysis which defined the structure's natural modes below 33 Hz.

AFT Complex. The T-shaped AFT complex is treated as being symmetrical about a vertical east-west plane between the two containment buildings. A three-dimensional finite-element model of half of the complex containing over 3800 degrees-of-freedom was constructed (Fig. 2-4). Applying appropriate boundary conditions along the plane of symmetry and extracting symmetrical and anti-symmetrical modes led to the description of the dynamic characteristics of the structure. One hundred and thirteen fixed-base modes were included in the dynamic analyses.

2.3 PIPING MODELS

Three piping models were considered in this study: a model of a portion of the auxiliary feedwater system (AFWS), a model of a portion of the residual heat-removal (RHR) and safety injection system (SIS), and a model of a portion of the reactor coolant system (RCS). We refer to these as the AFW, the RHR, and the RCL models. The mathematical models used in this study were previously developed [10].

AFW Model. The AFWS is for emergency cooling if the main feedwater system fails. Only part of the AFWS, the piping from steam generator 1A to containment penetrations was considered (Fig. 2-5). The AFW model consists of a 16-inch main feedwater (MFW) line from the steam generator nozzle to a containment penetration and a 3-inch auxiliary feedwater line branched from the 16-inch MFW line to a containment penetration.

RHR Model. The RHR system removes residual heat from the core and reduces the temperature of the reactor coolant system. The SIS cools the core and limits the metal-water interaction. One part of the RHR/SIS, the piping inside the AFT complex and a small portion inside the containment shell (Fig. 2-6) were the subject of this study. The RHR model consists of a 12-inch line from a wall anchor at the internal structure of the containment building to an anchor in the AFT complex, and an 8-inch line from the refueling water storage tank (RWST) nozzle to the 12-inch line.

RCL Model. The RCS transfers heat generated in the core to the steam generators which produce the steam to drive the turbines. A portion of the RCS was modeled, namely, all four reactor coolant loops (RCL), six branch lines of the loops, and all major NSSS equipment, including the reactor pressure vessel (RPV), four steam generators (SG), four reactor coolant pumps (RCP), and a pressurizer (Fig. 2-7). Each of the four reactor coolant loops consists of a 29-inch hot leg from the nozzle of RPV to SG, one 31-inch crossover leg from the nozzle of SG to RCP, and a 27.5-inch cold leg from the nozzle of RCP to RPV.

The six branch lines are:

- The 14-inch pressurizer surge line from the pressurizer to the hot leg of the RCL No. 4.
- The 14-inch line from the hot leg of RCL No. 1 to the RHRS.
- The 8-inch SI line to the cold leg of RCL No. 1.
- The 8-inch bypass line from the hot leg to the cold leg of RCL No. 1
- The two 4-inch pressurizer spray lines from the cold leg of RCL Nos. 3 and 4 to the pressurizer.

Basis for Selection. These piping models were selected to cover a wide range of parameters. As can be seen in Table 2.1, the piping systems vary considerably in size and complexity. In terms of the number of support motions and modes considered, the RHR model is smallest and least complex, the RCL model is the largest and most complex, and the AFW model is intermediate. Table 2.2 lists the first ten natural frequencies of each piping system.

Features of the Models. The models had several features in common:

- Piping was assumed to be linearly elastic.
- Appropriate stiffnesses were incorporated for piping supports (including rigid hangers, lateral restraints, and snubbers), except those of the RHR model, where the piping supports were assumed to be rigid.
- Constant and variable spring hangers were not included because their small stiffnesses were negligible compared to the stiffness of piping and other types of restraints (snubbers, etc.).
- The stiffness formulation of curved pipe (elbow or bend) elements included the effect of internal pressure on the flexibility of curved pipes.

Response of Models. For each piping model, responses at selected nodes and elements were calculated. Response locations were the same as those selected in previous studies where emphasis was placed on determining response at locations of high stress, i.e., elbows, tees, reducers, etc. Nodal accelerations and displacements, reaction forces in supports, and pipe resultant moments--the amplitude of the vector sum of the two orthogonal bending moments and the torsional moment -- were calculated. In all, the following responses were determined:

- 50 accelerations, 63 displacements, 28 support reactions, and 23 pipe resultant moments for the AFW model.
- 28 accelerations, 51 displacements, 15 support reactions, and 22 pipe resultant moments for the RHR model.
- 51 accelerations, 94 support reactions, and 118 pipe resultant moments for the RCL model.

Table 2.1

KEY PARAMETERS OF THE THREE PIPING MODELS

Piping Model	No. of Nodes	No. of Equations	No. of Support Motions	No. of Modes Considered
AFW	263	945	45	36
RHR	96	423	21	18
RCL	760	2941	127	130

Table 2.2

PIPING SYSTEM FREQUENCIES (HZ)

Mode	AFW	RHR	RCL
1	2.86	3.86	1.43
2	3.76	8.11	2.41
3	4.48	9.35	3.26
4	4.89	10.89	3.47
5	7.27	12.22	4.39
6	7.56	13.83	4.84
7	7.86	14.88	5.25
8	8.01	16.82	5.99
9	9.05	19.95	6.03
10	9.63	21.74	6.40

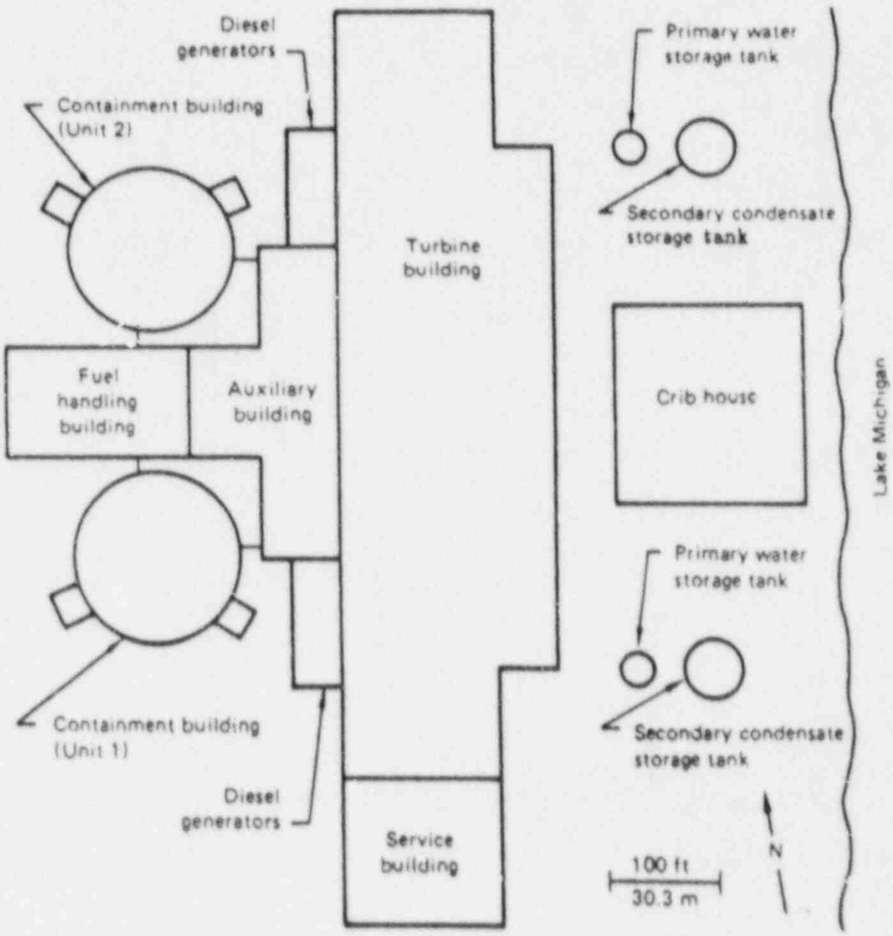

Fig. 2-1 General Arrangement of Structures at the Zion Nuclear Power Plant

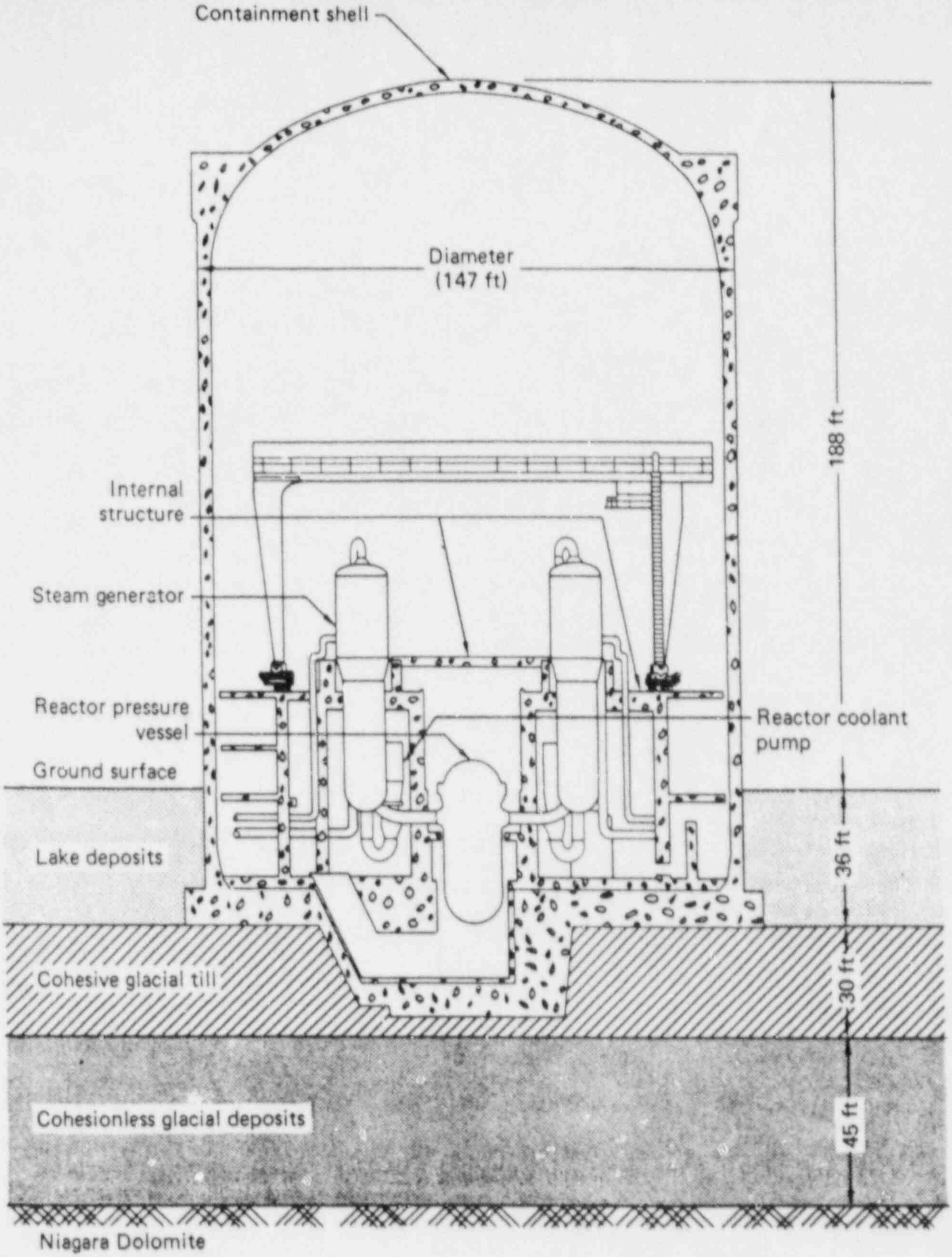

Fig. 2-2 Cross Section of the Zion Containment Building.

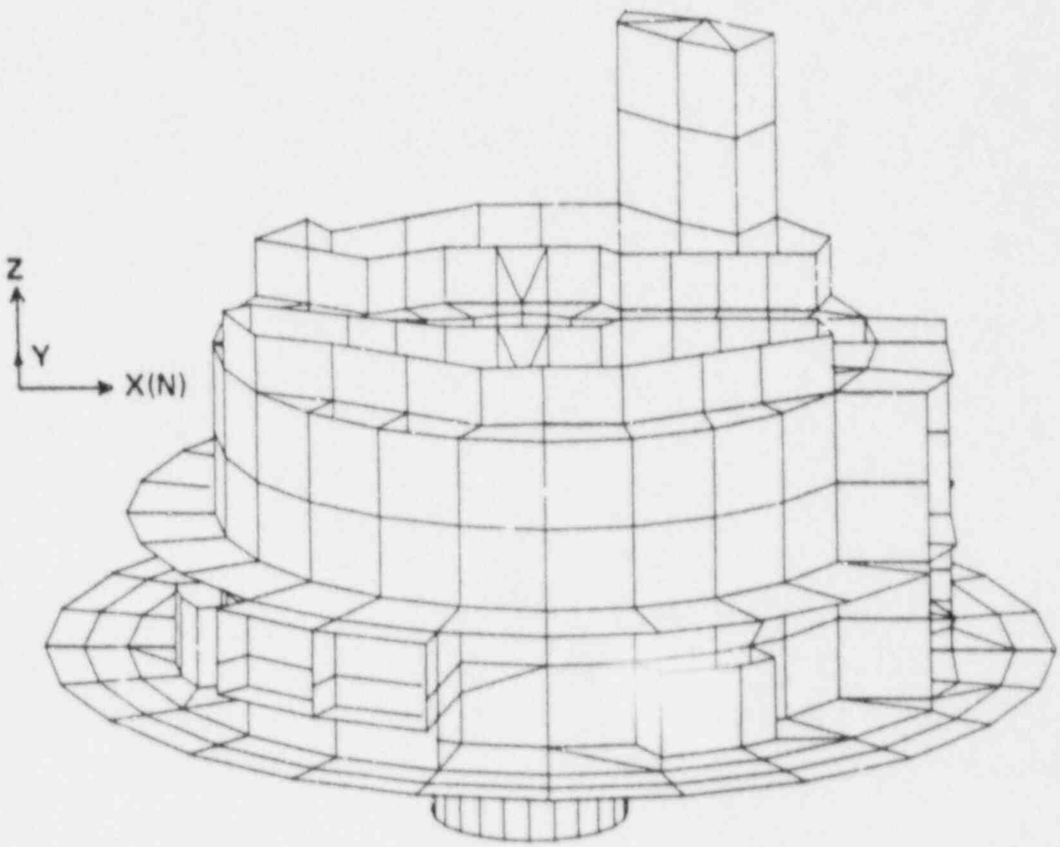

Fig. 2-3 A Perspective View of the Three-Dimensional Finite Element Model for the Internal Structure Within the Containment Building at Zion.

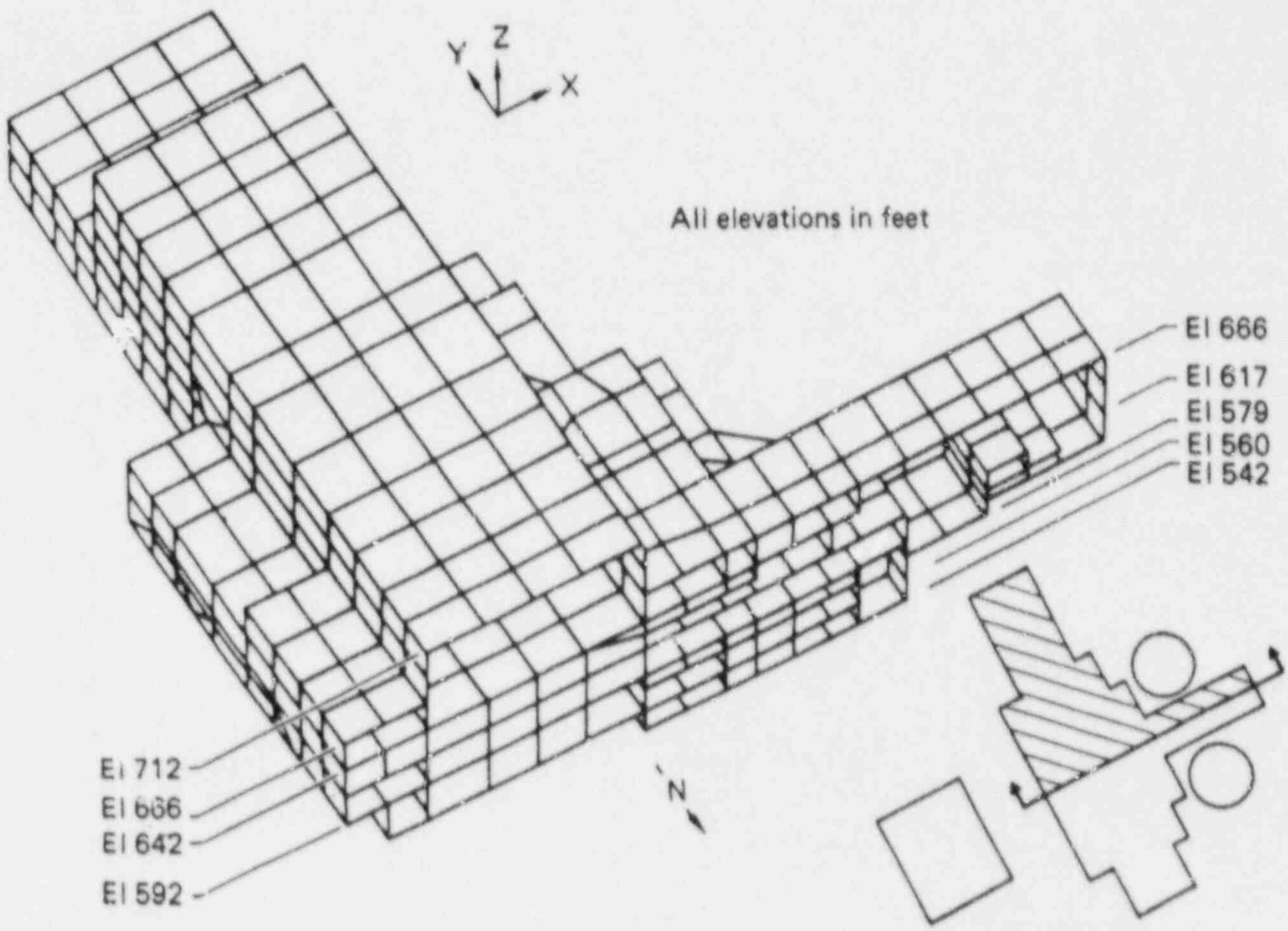

Fig. 2-4 Finite Element Half-Structure Model of the AFT Complex; Shaded Area of the Inset Sketch Shows the Portion of the Structure Modeled.

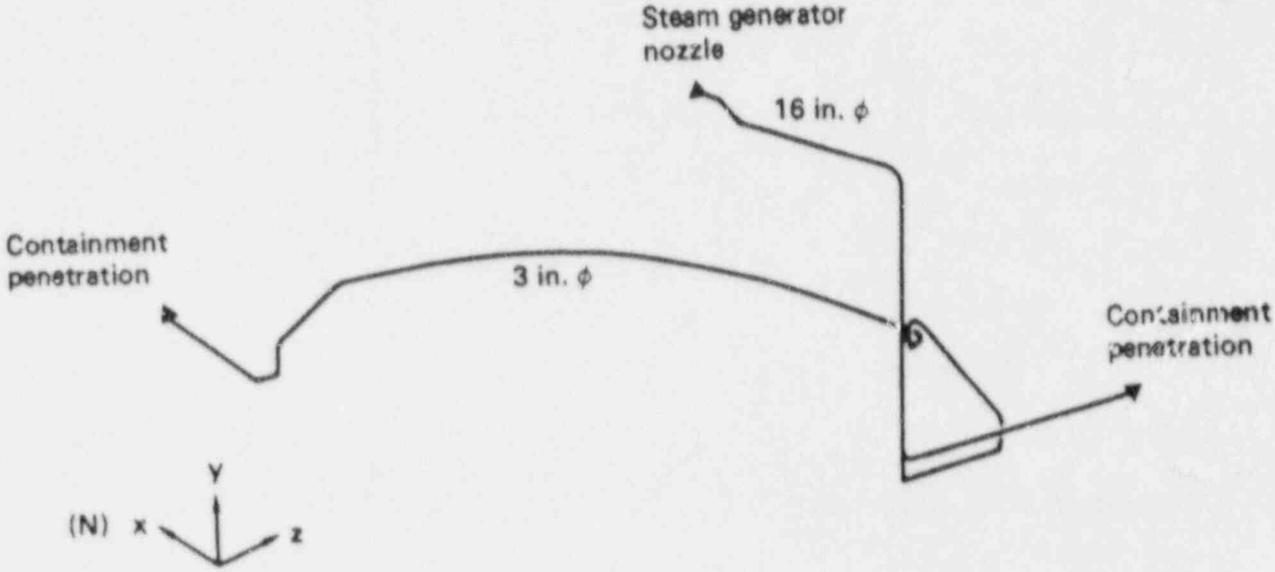

Fig. 2-5 Schematic of the AFW Piping Model.

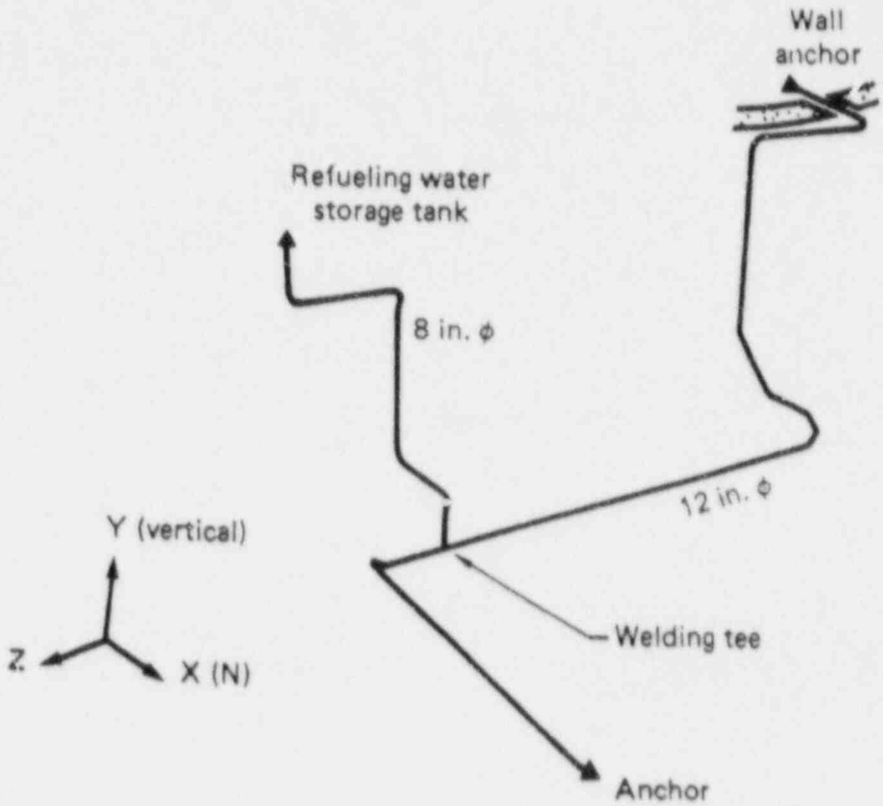

Fig. 2-6 Schematic of the RHR Piping Model.

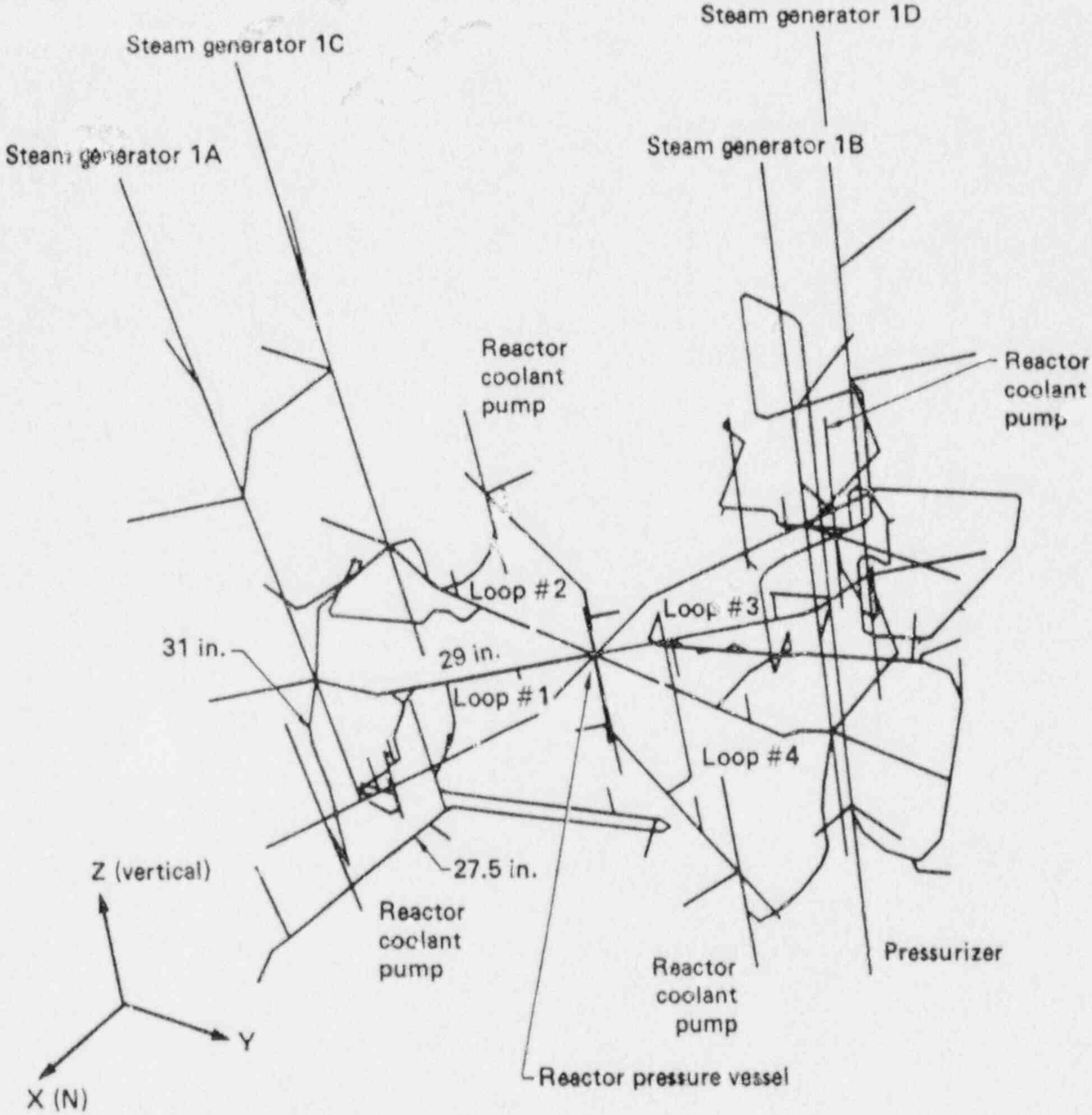

Fig. 2-7 Schematic of the RCL Model.

3.0 METHODS OF ANALYSIS AND ANALYSES PERFORMED

3.1 OVERVIEW

For this study, the results of several sets of analyses are compared. They reflect different piping system analyses and parameters; and different treatment of the seismic analysis chain. There are several objectives of the present study; all of which are based on comparing amplitudes of calculated response for different analysis assumptions and parameter values. One set of comparisons is between results broadly classified as design analyses. A second set is between design analysis results and responses calculated assuming design procedures up to the piping system analysis stage and then treating piping system response, itself, in a best estimate fashion, i.e. best estimate methodology (multi-support time history analysis), best estimate parameter values (damping), and explicitly including uncertainty in piping system frequencies and damping. A third set of comparisons is between design analysis results and responses denoted best estimate, i.e. where each element in the seismic analysis chain is treated in a best estimate manner (seismic input, soil-structure models and parameters, and piping system models and parameters). In addition, uncertainty in each element is modeled explicitly. The end results of the best estimate analyses are distributions of response from which approximate nonexceedance probabilities (NEP) can be obtained for each of the design analysis results. Before proceeding to a detailed description, an overview of the cases and the comparisons is presented.

The set of analyses broadly classified as design analyses are characterized by the seismic input being defined by US Nuclear Regulatory Commission (NRC) Regulatory Guide 1.60 (R.G. 1.60) design ground response spectra. Either a single set of earthquake time histories (three components) or an ensemble of motions each satisfying the NRC criteria of enveloping R.G. 1.60 design ground response spectra were used. For these design analyses, three piping system analysis procedures were considered; multi-support time history analysis, envelope response spectrum analysis, and independent support motion response spectrum analysis.

The multi-support time history analysis procedure used in this study was developed for the SSMRP and is contained in the computer program SMACS [11]. The procedure is described in detail in Sec. 3.2. Several multi-support time history analyses were performed and are denoted "R.G. 1.60" -- the difference between them being the amount of damping assumed in the piping system. Constant (independent of piping system frequency) damping cases were 1%, 2% 4%, 5%, and 10% for the RHR and AFW systems and 2%, 3%, 4%, 5%, and 10% for the RCL system. Two additional damping cases were analyzed for the three piping systems -- PVRC damping and INEL damping. PVRC damping denotes the recommendation of the Technical Committee on Piping Systems of the Pressure Vessel Research Committee (PVRC). The recommended damping values are a function of the piping system frequencies -- 5% damping for frequencies below 10 Hz, 2% damping for frequencies greater than 20 Hz and a linear variation from 5% to 2% for intermediate frequencies. This PVRC damping proposal is ASME Code Case N-411, Alternative Damping Values for Seismic Analysis of Classes 1, 2, and 3 Piping Sections, Section III, Division 1. The case denoted "INEL damping" is intended to represent realistic best estimate damping in the piping system as supported by data [8] and its extrapolation [12] to higher excitation levels. The probability distribution for piping system damping for the three models was assumed to be lognormal and characterized by a median value of 5.67% and a logarithmic standard deviation of 0.84. The median and lognormal standard deviation were taken from Ref. 8. These damping values are constant for all piping system frequencies, i.e., they are not frequency dependent. They represent a "best estimate" at OBE level stresses. In addition to uncertainty in piping system damping, uncertainty in piping system frequencies was explicitly treated by assigning a probability distribution to a multiplicative function applied to the calculated piping system frequencies; the distribution is assumed to be lognormal with a median value of 1.0 and a logarithmic standard deviation of 0.3 [7].

The envelope response spectrum analysis procedure conforms to one of the specified procedures in the US NRC Standard Review Plan (SRP) Sec. 3.9.2. In general, the procedure is one in which a response spectrum analysis of the piping system is performed -- the excitation being defined by three response spectra (one in each orthogonal horizontal direction and one in the vertical direction). Each response spectrum is the envelope of all support point response spectra for the direction of interest. For this case, design procedures such as spectrum peak broadening, spectrum smoothing, and US NRC Regulatory Guide 1.92 modal and directional combination rules applied. Responses for this SRP envelope response spectrum analysis case were those reported in Ref. 3. Two damping cases were considered: constant damping of 2% for the AFW, RHR, and RCL models; and PVRC damping.

The independent support motion response spectrum analysis results compared here were calculated by Brookhaven National Laboratory (BNL) and reported in Ref. 18. The basic approach is to calculate response of the piping system for each independent support degree-of-freedom separately and combine these responses by an appropriate rule. The RHR model was analyzed for the thirty earthquake R.G. 1.60 data set. Note, the individual responses for each of thirty-three earthquakes were provided by BNL. This study utilized the subset of thirty earthquakes corresponding to those described earlier. Hence, the median response over the thirty simulations was calculated and used. Reference 18 contains many comparisons of results based on different response combination rules. The SRSS support group response combination followed by RG 1.92 modal and directional combination was compared here.

Table 1.1 is repeated here as Table 3.1 and it summarizes the many analyses of the AFW, RHR, and RCL piping systems that have been performed in the past and for the present study.

Table 3.1a

COMPARISON OF RESPONSE ANALYSIS METHODS FOR THE AFW AND THE RHR PIPING SYSTEM

Analysis Case	Seismic Input	Variability SSI/Structure	Piping Method of Analysis	Damping Nominal(%)	Var	Piping Response	Reference	Comments
1	BE (90 EQ)	Yes	MTH	2	Yes	50%, 84% NEP	[3]	-
2	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[3]	-
3	RG 1.60 (3 EQ)	No	ERS	2	No	Avg of 3	[3]	-
4	RG 1.60 (30 EQ)	Yes	MTH	1	No	50% NEP	[2]	-
5	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[2]	Same as Case 2
6	RG 1.60 (1 EQ)	No	ERS	1	No	-	[2]	-
7	RG 1.60 (1 EQ)	RG Broad	ERS	PVRC Damp	-	-	[2]	-
8	RG 1.60 (1 EQ)	PVRC Broad	ERS	RG Damp	No	-	[2]	-
9	RG 1.60 (1 EQ)	PVRC Broad	ERS	PVRC Damp	-	-	[2]	-
10	RG 1.60 (30 EQ)	Yes	MTH	1	No	50% NEP	[1]	Same as Case 4
11	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[1]	Same as Case 2
12	RG 1.60 (30 EQ)	Yes	MTH	5	No	50% NEP	[1]	-
13	RG 1.60 (30 EQ)	Yes	MTH	PVRC Damp	-	50% NEP	[1]	-
14	RG 1.60 (30 EQ)	Yes	MTH	4	No	50% NEP	[1]	-
15	RG 1.60 (30 EQ)	Yes	MTH	10	No	50% NEP	[1]	-
16	RG 1.60 (30 EQ)	Yes	ISM	2	No	50% NEP	[7]	-
17	RG 1.60 (30 EQ)	Yes	ISM	PVRC	No	50% NEP	-	Personal Communication
18	RG 1.60 (30 EQ)	Yes	MTH	INEL	Yes	NEP	*	-
19	BE (30 EQ)	Yes	MTH	INEL	Yes	NEP	*	-

For the AFW system, an additional series of analyses were conducted by Chuang, et al. using the methodology of cases 6 and 9 above. These analyses investigated alternative support configurations of the AFW model.

Notes

MTH = Multi-support time history analysis
ERS = Envelope Response spectrum analysis
ISM = Independent support motion response spectrum analysis
INEL = Best estimate piping system damping
* = Current Study

Table 3.1b

COMPARISON OF RESPONSE ANALYSIS METHODS FOR THE RCL PIPING SYSTEM

Analysis Case	Seismic Input	Variability SSI/Structure	Piping Method of Analysis	Damping Nominal(%)	Var	Piping Response	Reference	Comments
1	BE (90 EQ)	Yes	MTH	2	Yes	50%, 84% NEP	[3]	-
2	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[3]	-
3	RG 1.60 (3 EQ)	No	ERS	2	No	Avg of 3	[3]	-
4	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[2]	-
5	RG 1.60 (1 EQ)	No	ERS	2	No	-	[2]	Same as Case 2
6	RG 1.60 (1 EQ)	RG Broad	ERS	PVRC Damp	No	-	[2]	-
7	RG 1.60 (1 EQ)	PVRC Broad	ERS	- RG Damp	No	-	[2]	-
8	RG 1.60 (1 EQ)	PVRC Broad	ERS	PVRC Damp	No	-	[2]	-
9	RG 1.60 (30 EQ)	Yes	MTH	2	No	50% NEP	[1]	-
10	RG 1.60 (30 EQ)	Yes	MTH	3	No	50% NEP	[1]	Same as Case 4
11	RG 1.60 (30 EQ)	Yes	MTH	5	No	50% NEP	[1]	-
12	RG 1.60 (30 EQ)	Yes	MTH	PVRC Damp	-	50% NEP	[1]	-
13	RG 1.60 (30 EQ)	Yes	MTH	4	No	50% NEP	[1]	-
14	RG 1.60 (30 EQ)	Yes	MTH	10	No	50% NEP	[1]	-
15	RG 1.60 (30EQ)	Yes	MTH	INEL	Yes	NEP	*	-
16	BE (30EQ)	Yes	MTH	INEL	Yes	NEP	*	-

Notes

MTH = Multi-support time history analysis

ERS = Envelope response spectrum analysis

ISM = Independent support motion response spectrum analysis

INEL = Best estimate piping system damping

* = Current Study

3.2 MULTI - SUPPORT TIME HISTORY ANALYSIS

The multi - support time history analysis procedure used in this study was developed for the SSMRP [11]. 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, the uncertainty inherent in deterministic analysis is taken into account. Uncertainty is 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 [11]. This design efficiently spans the parameter spaces.

The responses from two broad types of multi-support time history analyses are compared here: the first is denoted "best estimate" and is characterized by "best estimate" definitions of seismic input, and the physical parameters of the soil-structure-piping system; the second type is denoted "R.G. 1.60" reflecting the definition of seismic input as being artificial time histories whose response spectra essentially envelope the design ground response spectra of Regulatory Guide 1.60. Both types of analyses were introduced in Sec. 3.1 and are next discussed in detail.

3.2.1 Best Estimate Time History Analysis

To perform a probabilistic response analysis with SMACS, 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:

<u>Free-field motion.</u> An ensemble of thirty sets of three components of acceleration time histories (two horizontal and the vertical) defined the seismic input. The ensemble of acceleration time histories was developed such that the 84% NEP of the resulting response spectra approximate the US NRC Regulatory Guide 1.60 design ground response spectra. This approach follows the intent of the development of US NRC Regulatory Guide 1.60. Figure 3-1 shows the mean and the 84% NEP response spectra compared to Regulatory Guide 1.60 spectra (horizontal and vertical). All of the horizontal time histories were scaled to a peak ground acceleration of 0.18g; the vertical time histories similarly were scaled to 0.18g to match the design ground response spectrum. Statistical independence of the three components for each of the thirty earthquakes was verified; correlation coefficients less than 0.16. The original data set that was used as a basis for developing RG 1.60 response spectra formed the basis for generation of the artificial time histories. This original data set, however, was not explicitly used herein for a number of reasons. First, the mean-plus-one-standard-deviation response spectra of the original data set do not closely

approximate RG 1.60 spectra in all frequency ranges. Second, each recorded earthquake does not in general, contain three components of motion and three components are required for the analysis. Third, the recorded motions differ in time step and duration and such differences create logistic problems with the multiple analyses. The calculated response spectra from the recorded motions comprised the ensemble of target spectra used to generate the artificial time histories. Hence, the frequency characteristics of the ensemble closely approximate the recorded data except in those frequency ranges where additional amplification was necessary.

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. 9, 10, and 13. 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 and taking into account the most recent data. Soil properties corresponding to a free-field excitation of 0.18g peak acceleration were used [14]. Structure stiffness properties correspond to best estimate values as presented in Ref. 9. Nominal values of structural damping of 10% of critical were selected for the analysis. Finally, piping system modeling corresponded to that of SSMRP and as described in Sec. 2. Nominal piping system damping corresponding to SSE level excitations was assumed based on Refs. 8 and 12; a nominal value of 7.5% was used for each piping system.

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 random uncertainty. This assumption corresponds to the SSMRP Phase 2 study. The coefficients of variation (COVs) used in the present study are shown in Table 3.2

Experimental design. The SMACS analysis uses a Latin hypercube experimental design to efficiently sample the parameter spaces for a limited number of simulations. For the best estimate analysis, 30 earthquake simulations were performed. Hence 30 sets of three components of motion (90 time histories) were selected. Next, the distribution of each variable input parameter was divided into 30 equal-probability intervals. A value was randomly selected from each interval, and the 30 values for each variable were rearranged randomly. The 30 sets of time histories and the permuted values of the variable parameters were then grouped to give 30 combinations of input values for the dynamic analyses. Therefore, in a series of 30 analyses, each time history set is used once, and a parameter value was selected once from each of the 30 intervals in each of the parameter distributions. The set of 30 input combinations is called a Latin hypercube sampling set.

The 30 "best estimate" analyses performed gave 30 values for every piping system response request. Figure 3-2 shows the data points from the 30 analyses and the lognormal distribution of response constructed from the data for a typical component. From such a curve, response values corresponding to the median (50% NEP) or other NEP response values can be determined.

3.2.2 R.G. 1.60 Analysis

The second set of multi-support time history analyses is denoted "R.G. 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 R.G. 1.60 analysis. This data set was obtained from the nuclear industry. The three components 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 3-3 shows mean and 84% NEP response spectra for the R.G. 1.60 data set. Note, the relatively small variation in spectral acceleration due to the fact that each time history was generated to the same target response spectra.

The SSI, structure, and piping system models used in the R.G. 1.60 analyses were identical to those used in the best estimate analyses. Nominal values of input parameters for stiffness characteristics were identical. However, nominal values of structural damping corresponded to SSMRP Phase 1 values and the data available at that time. Nominal damping of 2% in the structures was assumed. This corresponds to all previous "R.G. 1.60 analyses."

An additional difference between the best estimate analyses and the R.G. 1.60 analyses is the variation assumed for the input parameters. Variability in soil and structure parameters was intended to represent total uncertainty. This again corresponds to all previous studies and, in fact, the identical experimental designs were used for soil and structure properties for all "R.G. 1.60 analyses." Since the principal comparisons made here are between median values of response from the R. G. 1.60 analyses, the impact of including total uncertainty instead of random uncertainty only is negligible. Table 3.3 itemizes coefficients of variation for the R. G. 1.60 analyses.

Table 3.2

COEFFICIENTS OF VARIATION (COVs) OF INPUT PARAMETERS
FOR THE BEST ESTIMATE ANALYSIS

Parameter	COV
Soil shear modulus	0.35
Soil damping	0.5
Structure frequency	0.25
Structure damping	0.35
Piping system frequency	0.3
Piping System damping	0.84

Table 3.3

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
Piping system frequency	No variation *
Piping system damping	No variation *

*For the INEL damping case, a COV of 0.3 on piping system frequency and 0.84 on piping system damping was assumed.

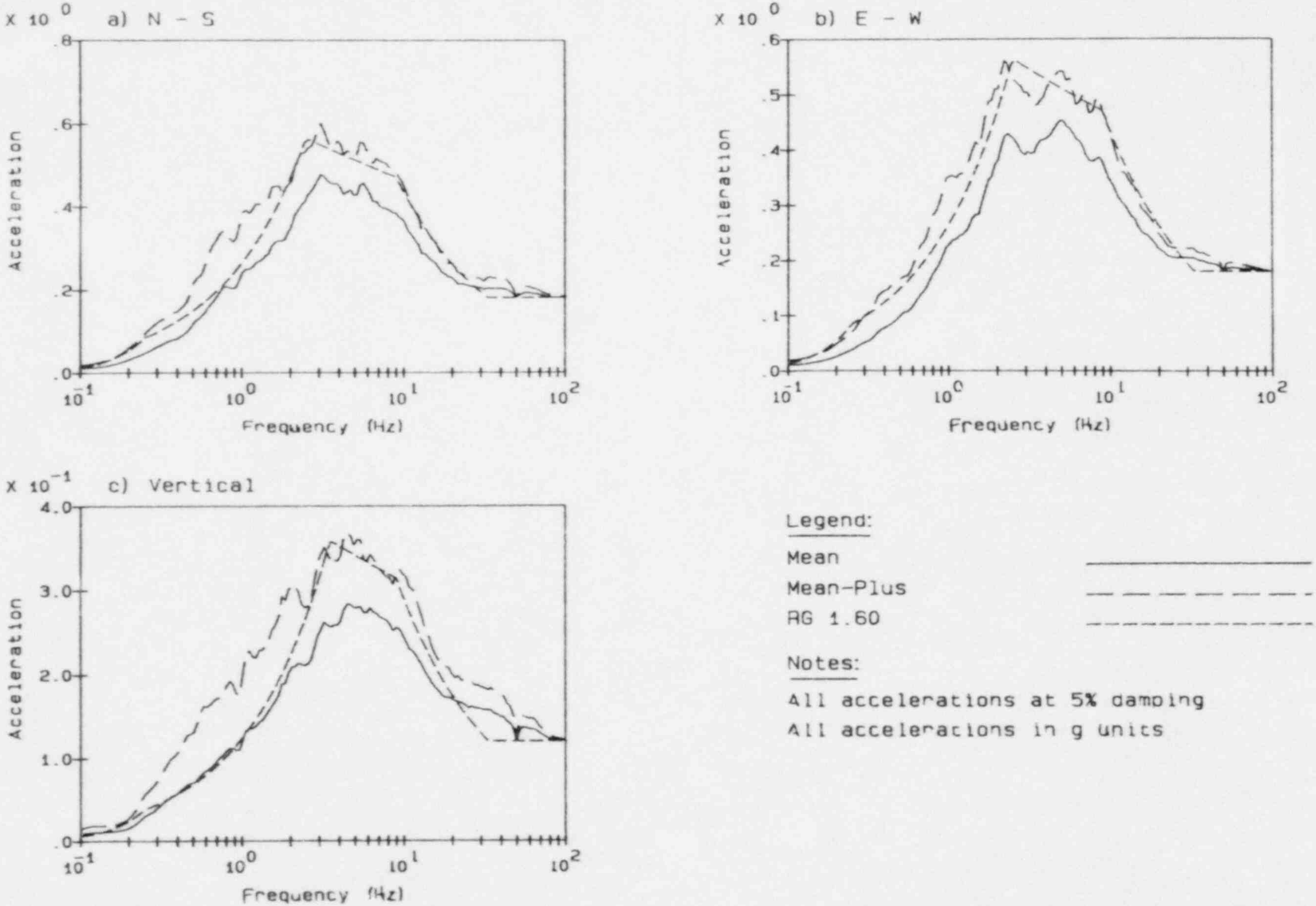

Fig. 3-1 Mean and Mean-Plus One Standard Deviation Best Estimate and RG 1.60 Response Spectra

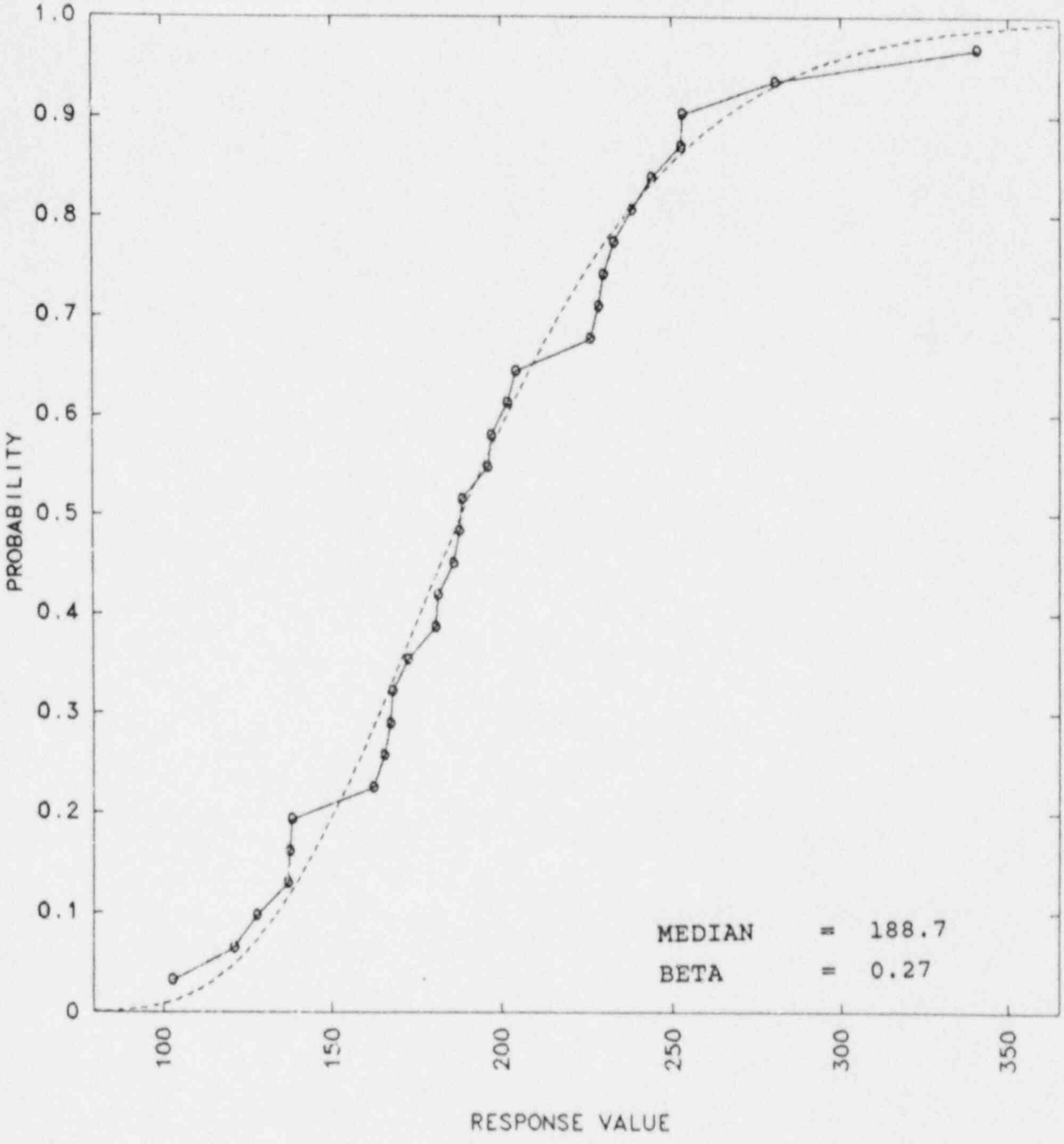

Fig. 3-2 Distribution of a Typical Support Force in the RHR Model, Best Estimate

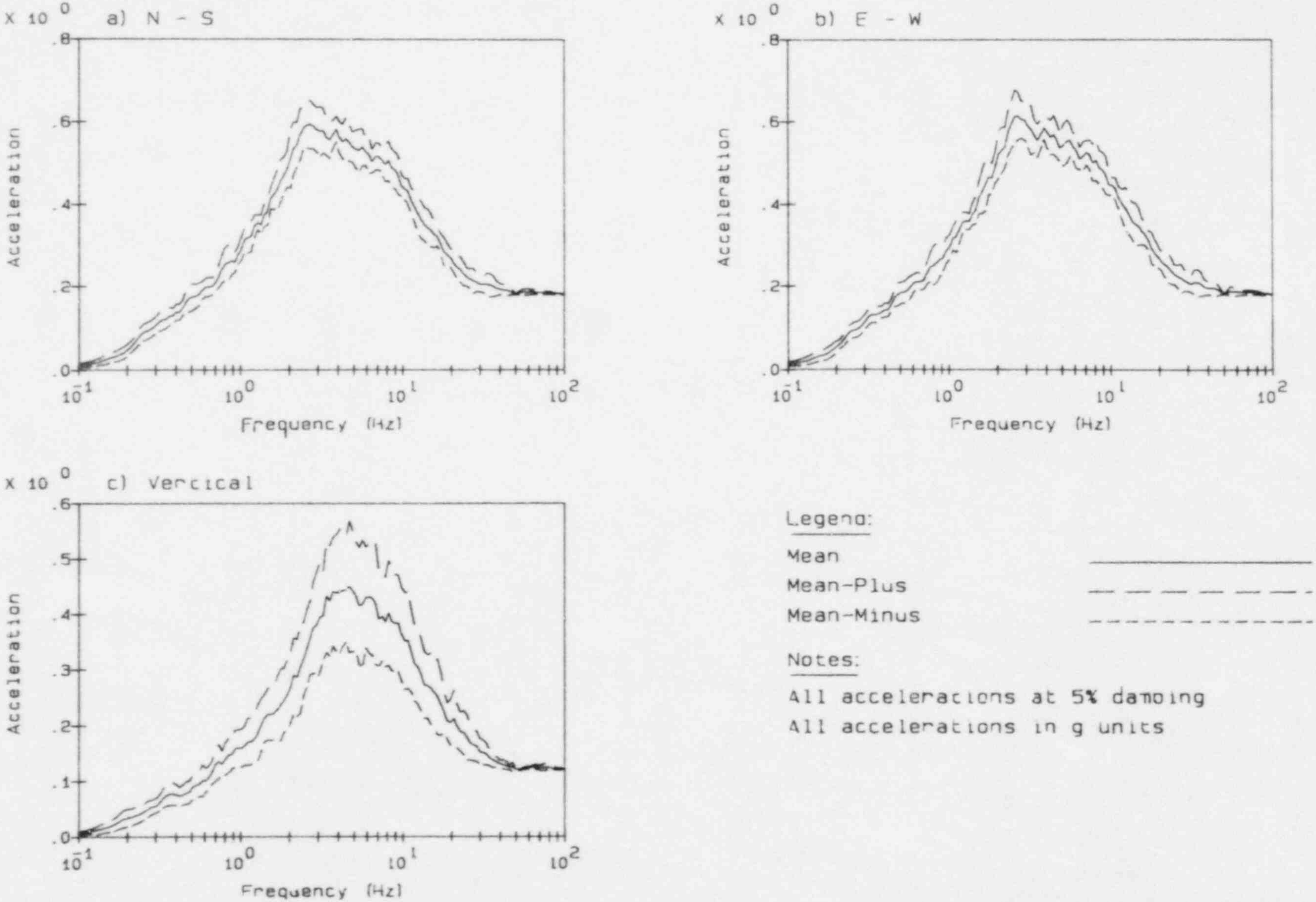

Fig. 3-3 Mean, Mean-Plus, and Mean-Minus One Standard Deviation Response Spectra of the RG 1.60 Data Set

3.3 US NRC SRP RESPONSE SPECTRUM ANALYSIS

In the US NRC Standard Review Plan (SRP) 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 SRP envelope response spectrum analysis results compared here are those reported in Refs. 2 and 3. A review of the methodology employed follows.

Two cases are compared here and the methodology differs slightly for the two -- constant 2% piping system damping and PVRC piping system damping.

Constant 2% Damping [3].

Three sets of acceleration time histories were selected at random from the group of 30 used in the R.G. 1.60 analysis and three complete analyses performed--the results then averaged to minimize the variations due to the time histories. 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. 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.

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 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. These response quantities for the SRP method were defined as the average of the results given by the three analyses to minimize variations due to time history characteristics.

PVRC Damping [2].

For the PVRC damping case, the same procedure was applied with the exception that only a single earthquake was considered due to the limited resources available at the time. Hence, no averaging of individual artificial time history effects occurred.

3.4 INDEPENDENT SUPPORT MOTION RESPONSE SPECTRUM ANALYSIS

The independent support motion response spectrum analysis procedure used by Brookhaven National Laboratory (BNL) is described in Refs. 5 and 18. The basic approach is to derive modal participation factors for each individual support (or group of supports) in each direction of excitation. Piping system response due to each support excitation is obtained by multiplying the participation factors by the corresponding response spectral ordinates. Hence, one obtains response for every combination of modes, supports, and directions. The question which then remains is the combination rule to be applied for responses due to modes, supports, and directions and the order of combination. Reference 5 investigated fourteen different rules and quantified their effects. The present evaluation selected one of the fourteen for assessment purposes -- Case 4 which is SRSS of support group responses followed by US NRC Regulatory Guide 1.92 modal and directional combination. The responses compared were the median values over thirty R.G. 1.60 earthquakes -- the thirty earthquakes discussed in Sec. 3.2.2. Two damping cases were considered -- constant 2% damping denoted "ISM/SRSS (2%)" and PVRC damping denoted "ISM/SRSS(PVRC)."

4.0 NUMERICAL RESULTS AND INTERPRETATION

The major objective of this study and others [1-4, 5-7] was to quantify the relationship between piping system responses calculated by different analysis techniques and for different parameter values, specifically damping. Most previous studies quantified these relationships by determining ratios of response; in some instances, averaged over response types and components. Reference 1, for example, quantified through ratios the relationship between responses calculated assuming constant damping (1%, 2%, 3%, 4%, 5%, and 10%) and responses calculated assuming PVRC damping. All cases utilized the multi-support time history analysis procedure of SMACS for piping system dynamic analysis. The form of a typical result was a mean ratio and its coefficient of variation. For example, the AFW model nodal accelerations, 1% damping vs. PVRC damping, a mean ratio of 1.84 with a COV of 0.08 was calculated. These results are not repeated here.

An alternative method of comparing responses and interpreting the results is presented here. The concept is one of quantifying conservatism by estimating the nonexceedance probabilities of each analysis case compared to the R.G. 1.60 INEL damping case and the best estimate case. Consider Figs. 4-1. Figure 4-1a shows a cumulative distribution function for a typical response in the RHR model. Thirty data points are plotted -- each one representing the response for an earthquake simulation. Superimposed on the data is a lognormal distribution function fit to the data and plotted as a segmented curve. The two parameters (median, lognormal standard deviation) which define the distribution are shown. The median values of support force for each analysis case to be compared herein are sketched on the figure. This permits one to visualize the comparisons and the nonexceedance probabilities reported herein. Figure 4-1b is a similar figure for the same RHR model support force but for the best estimate case. For the individual response shown in Fig. 4-1, the nonexceedance probabilities by analysis case are approximately:

NONEXCEEDANCE PROBABILITIES (%)
TYPICAL RHR SUPPORT FORCE

	R.G. 1.60 INEL Damping	Best Estimate
MTH/1%	89.	100.
MTH/2%	77.	97.
MTH/4%	59.	90.
MTH/5%	49.	83
MTH/PVRC	56.	89.
MTH/INEL	*	86.
MTH/10%	37.	72.
ERS(2%)	100.	100.
ERS(PVRC)	99.	100.
ISM/SRSS(2%)	97.	100.
ISM/SRSS(PVRC)	85.	99.

* The median MTH/INEL is the 50% NEP value for the R.G. 1.60, INEL damping case.

As described in Sec. 2, the number of responses for each piping model is large. Hence, there is the need to view the data in a summary form. Figure 4-2 is an example summary plot which displays nonexceedance probabilities for all responses for a particular piping model and for a specific analysis case. Figure 4-2a displays nonexceedance probabilities for the R.G. 1.60 multi-support time history analysis case with PVRC damping vs. R.G. 1.60, INEL damping for the AFW model. Figure 4-2b shows the comparable data but for the best estimate case. Similar plots for all of the comparisons and for the three piping models are contained in Appendix A (R.G. 1.60, INEL damping) and Appendix B (Best Estimate).

A further summary of the data is contained in Tables 4.1 and 4.2. Table 4.1 shows nonexceedance probabilities for each analysis case vs. R.G. 1.60, INEL damping. Table 4.1a is for the AFW model; Table 4.1b is for the RHR model; and Table 4.1c is for the RCL Model. Response quantities are grouped in the tables according to type -- accelerations, displacements, pipe resultant moments, and support forces. The nonexceedance probabilities itemized are mean values over the number of responses in each category. A measure of variability in the nonexceedance probabilities is not contained in the tables. However, coefficients of variation were calculated and were typically less than 0.1 and, in many cases, much less. Hence, a large variability in the nonexceedance probabilities within a response category did not occur. This is also apparent from the summary figures (Fig. 4-2 and Appendices A and B).

Response Comparisons -- R.G. 1.60 Design Analyses vs. R.G. 1.60 INEL Damping

The approximate range of NEPs for each of the R.G. 1.60 design analyses vs. the R.G. 1.60 INEL damping case is shown below. This set of results focuses on the conservatism in the piping system analysis methodologies and the effect of damping assumptions. The values represent the range of NEPs calculated for nodal accelerations and element forces and moments. Slightly lower NEP values were calculated for nodal displacements. The range includes all three piping models -- no apparent differences occurred for the different models.

Analysis/ Damping	Range of NEPs (%) R.G. 1.60 INEL Damping
MTH/1%	83-94
MTH/2%	71-85
MTH/3%	60-65
MTH/4%	54-65
MTH/5%	49-55
MTH/PVRC	51-62
MTH/10%	32-43
ERS(2%)	>99.7
ERS(PVRC)	>96.4
ISM/SRSS(2%)	>93.6
ISM/SRSS(PVRC)	>92.7

These results quantify the conservatism in the piping system analysis procedures and in the piping system damping values. For example, performing a piping system dynamic analysis by the envelope response spectrum analysis technique and applying R.G. 1.61 damping values (2%) leads to calculated responses which exceed the 99.7% NEP when treating the piping system analysis itself in a best estimate manner. Similarly, significant conservatism remains in the process when the envelope response spectrum analysis approach is applied with PVRC damping.

Note, the multi-support time history analysis with PVRC damping leads to responses with NEPs slightly higher than the median. The effect of other damping values on the NEPs is apparent from the table.

Table 4.2 shows identical data for the best estimate case.

<u>Response Comparisons -- R.G. 1.60 Design Analyses vs. Best Estimate</u>

The approximate range of NEPs for each of the R.G. 1.60 design analyses vs. the best estimate results is shown below. This set focuses on the conservatism introduced throughout the seismic methodology chain. Again, these values represent the range of NEPs calculated for nodal accelerations and element forces and moments. Slightly lower NEPs were calculated for nodal displacements. The range includes all three piping models.

Analysis/ Damping	Range of NEPs (%) Best Estimate
MTH/1%	>97
MTH/2%	93-99.5
MTH/3%	91-99
MTH/4%	87-98
MTH/5%	83-97
MTH/PVRC	85-97
MTH/INEL	75-96
MTH/10%	67-89
ERS(2%)	>99.9
ERS(PVRC)	>99.9
ISM/SRSS(2%)	>99.8
ISM/SRSS(PVRC)	>98.6

These results quantify the conservatism in piping system response introduced through the entire seismic methodology chain. One readily observes the high NEPs for all of the cases studied. Note, in particular, that the multi-support time history analysis with PVRC damping leads to responses with NEPs of 85-97%. Hence, applying a methodology which is considered best estimate (multi-support time history analysis) and applying damping to the piping system which approximates median values (PVRC damping), conservatism in the remaining elements of the seismic methodology chain still leads to design responses with nonexceedance probabilities greater than 85%. Further, if one established a performance specification such as: seismic analysis procedures and parameter values of the analysis shall be selected such that if an earthquake occurred with peak ground acceleration equal to the design earthquake, the probability of exceeding the response levels determined in the seismic analysis and used in the seismic design would be about 10-15%. Then, the design analysis procedure employed here for seismic input, SSI, and structure response in conjunction with multi-support time history analysis and PVRC damping satisfies this criteria.

Table 4.1

COMPARISON OF DESIGN ANALYSIS RESULTS
WITH INEL DAMPING PIPING SYSTEM ANALYSIS
(NONEXCEEDANCE PROBABILITIES)
(a) AFW MODEL

	Damping Parameter	Nonexceedance Probability (NEP)(%)
Accelerations	1%	83.7
	2%	73.6
	4%	59.4
	5%	54.5
	PVRC	56.6
	10%	37.6
	ERS(2%)	100.
	ERS(PVRC)	100.
	ISM/SRSS(2%)	96.5
Displacements	1%	70.5
	2%	62.4
	4%	53.7
	5%	50.5
	PVRC	51.3
	10%	42.7
	ERS(2%)	98.6
	ERS(PVRC)	91.7
	ISM/SRSS(2%)	79.4
Pipe Resultant Moments	1%	85.7
	2%	74.4
	4%	59.1
	5%	53.1
	PVRC	54.0
	10%	37.0
	ERS(2%)	100.
	ERS(PVRC)	99.3
	ISM/SRSS(2%)	95.9
Support Forces	1%	84.5
	2%	71.7
	4%	55.9
	5%	49.0
	PVRC	51.9
	10%	35.5
	ERS(2%)	100.
	ERS(PVRC)	99.2
	ISM/SRSS(2%)	93.6

Table 4.1 (Continued)

COMPARISON OF DESIGN ANALYSIS RESULTS WITH INEL DAMPING PIPING SYSTEM ANALYSIS (NONEXCEEDANCE PROBABILITIES)
(b) RHR MODEL

	Damping Parameters	Nonexceedance Probability (NEP)(%)
Accelerations	1%	86.2
	2%	77.6
	4%	64.7
	5%	59.6
	PVRC	61.3
	10%	42.2
	ERS(2%)	99.3
	ERS(PVRC)	96.4
	ISM/SRSS(2%)	97.4
	ISM/SRSS(PVRC)	95.1
Displacements	1%	75.9
	2%	67.5
	4%	57.5
	5%	53.5
	PVRC	54.7
	10%	44.1
	ERS(2%)	92.1
	ERS(PVRC)	78.0
	ISM/SRSS(2%)	89.7
	ISM/SRSS(PVRC)	82.4
Pipe Resultant Moments	1%	94.0
	2%	84.3
	4%	64.6
	5%	54.5
	PVRC	57.9
	10%	32.4
	ERS(2%)	100.
	ERS(PVRC)	98.5
	ISM/SRSS(2%)	98.7
	ISM/SRSS(PVRC)	97.1
Support Forces	1%	90.2
	2%	81.1
	4%	63.5
	5%	54.8
	PVRC	55.3
	10%	35.3
	ERS(2%)	99.9
	ERS(PVRC)	96.4
	ISM/SRSS(2%)	95.8
	ISM/SRSS(PVRC)	92.7

Table 4.1 (Continued)

COMPARISON OF DESIGN ANALYSIS RESULTS
WITH INEL DAMPING PIPING SYSTEM ANALYSIS
(NONEXCEEDANCE PROBABILITIES)
(c) RCL MODEL

	Damping Parameter	Nonexceedance Probability (NEP)(%)
Accelerations	2%	70.0
	3%	61.7
	4%	55.6
	5%	50.8
	PVRC	54.0
	10%	36.6
	ERS(2%)	99.9
	ERS(PVRC)	99.8
Support Forces	2%	69.6
	3%	60.8
	4%	54.5
	5%	49.7
	PVRC	51.3
	10%	36.4
	ERS(2%)	99.7
	ERS(PVRC)	98.9
Pipe Resultant Moments	2%	75.1
	3%	64.7
	4%	56.6
	5%	50.2
	PVRC	51.5
	10%	32.6
	ERS(2%)	100.
	ERS(PVRC)	99.7

Table 4.2

COMPARISON OF DESIGN ANALYSIS RESULTS
WITH BEST ESTIMATE PIPING SYSTEM RESPONSE
(NONEXCEEDANCE PROBABILITIES)
(a) AFW MODEL

	Damping Parameter	Nonexceedance Probability (NEP)(%)
Accelerations	1%	98.0
	2%	95.4
	4%	89.0
	5%	86.0
	PVRC	87.4
	INEL	82.6
	10%	71.1
	ERS(2%)	100.
	ERS(PVRC)	100.
	ISM/SRSS(2%)	99.8
Displacements	1%	88.9
	2%	83.6
	4%	76.9
	5%	74.0
	PVRC	74.8
	INEL	73.5
	10%	66.5
	ERS(2%)	99.9
	ERS(PVRC)	98.2
	ISM/SRSS(2%)	99.9
Pipe Resultant Moments	1%	98.9
	2%	96.8
	4%	91.7
	5%	88.9
	PVRC	89.3
	INEL	86.4
	10%	77.4
	ERS(2%)	100.
	ERS(PVRC)	100.
	ISM/SRSS(2%)	99.9
Support Forces	1%	99.3
	2%	97.7
	4%	93.6
	5%	91.0
	PVRC	92.0
	INEL	90.6
	10%	82.3
	ERS(2%)	100.
	ERS(PVRC)	100.
	ISM/SRSS(2%)	99.9

Table 4.2 (Continued)

COMPARISON OF DESIGN ANALYSIS RESULTS WITH BEST ESTIMATE PIPING SYSTEM RESPONSE (NONEXCEEDANCE PROBABILITIES)
(b) RHR MODEL

	Damping Parameter	Nonexceedance Probability (NEP)(%)
Accelerations	1%	97.0
	2%	93.9
	4%	87.3
	5%	83.8
	PVRC	85.5
	INEL	75.7
	10%	67.4
	ERS(2%)	100.
	ERS(PVRC)	99.9
	ISM/SRSS(2%)	99.8
	ISM/SRSS(PVRC)	99.5
Displacements	1%	92.0
	2%	87.0
	4%	79.3
	5%	75.5
	PVRC	76.7
	INEL	72.0
	10%	65.2
	ERS(2%)	98.5
	ERS(PVRC)	94.2
	ISM/SRSS(2%)	96.5
	ISM/SRSS(PVRC)	93.7
Pipe Resultant Moments	1%	99.8
	2%	99.5
	4%	97.9
	5%	95.4
	PVRC	96.8
	INEL	94.7
	10%	83.0
	ERS(2%)	100.
	ERS(PVRC)	100.
	ISM/SRSS(2%)	100.
	ISM/SRSS(PVRC)	99.9
Support Forces	1%	98.6
	2%	98.1
	4%	95.8
	5%	93.4
	PVRC	93.9
	INEL	92.1
	10%	83.7
	ERS(2%)	100.
	ERS(PVRC)	99.9
	ISM/SRSS(2%)	99.0
	ISM/SRSS(PVRC)	98.6

Table 4.2 (Continued)

COMPARISON OF DESIGN ANALYSIS RESULTS WITH BEST ESTIMATE PIPING SYSTEM RESPONSE (NONEXCEEDANCE PROBABILITIES)
(c) RCL MODEL

	Damping Parameters	Nonexceedance Probability (NEP)(%)
Accelerations	2%	94.9
	3%	91.9
	4%	88.9
	5%	86.1
	PVRC	88.2
	INEL	85.5
	10%	74.6
	ERS(2%)	100.
	ERS(PVRC)	100.
Support Forces	2%	99.1
	3%	98.2
	4%	97.0
	5%	95.7
	PVRC	96.3
	INEL	95.6
	10%	88.6
	ERS(2%)	100.
	ERS(PVRC)	100.
Pipe Resultant Moment	2%	99.3
	3%	98.6
	4%	97.5
	5%	96.1
	PVRC	96.4
	INEL	95.6
	10%	86.4
	ERS(2%)	100.
	ERS(PVRC)	100.

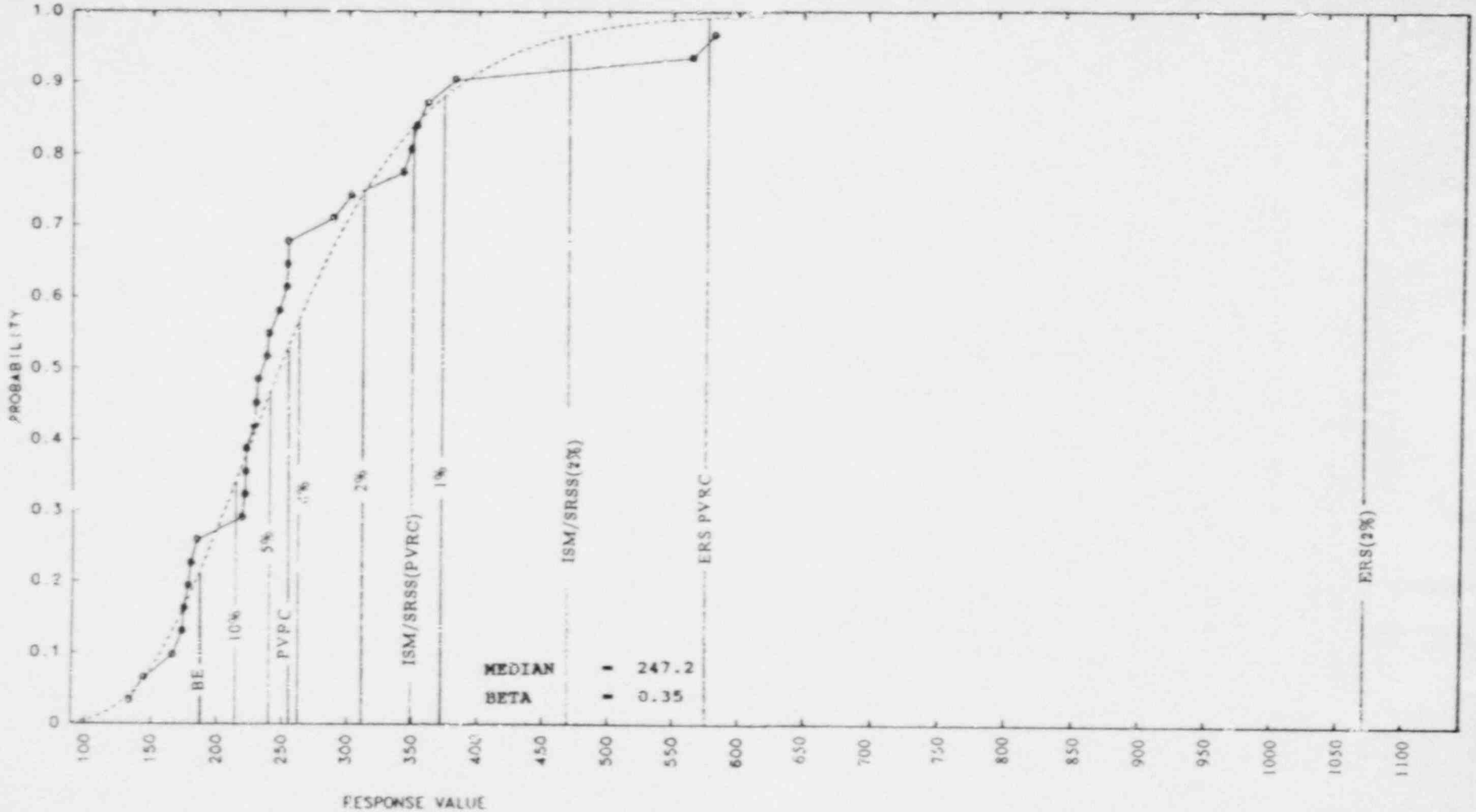

Fig. 4-1 Distribution of a Typical Support Force in the RHR Model with Design Analysis Responses Superposed

(a) R.G. 1.60, INEL Damping

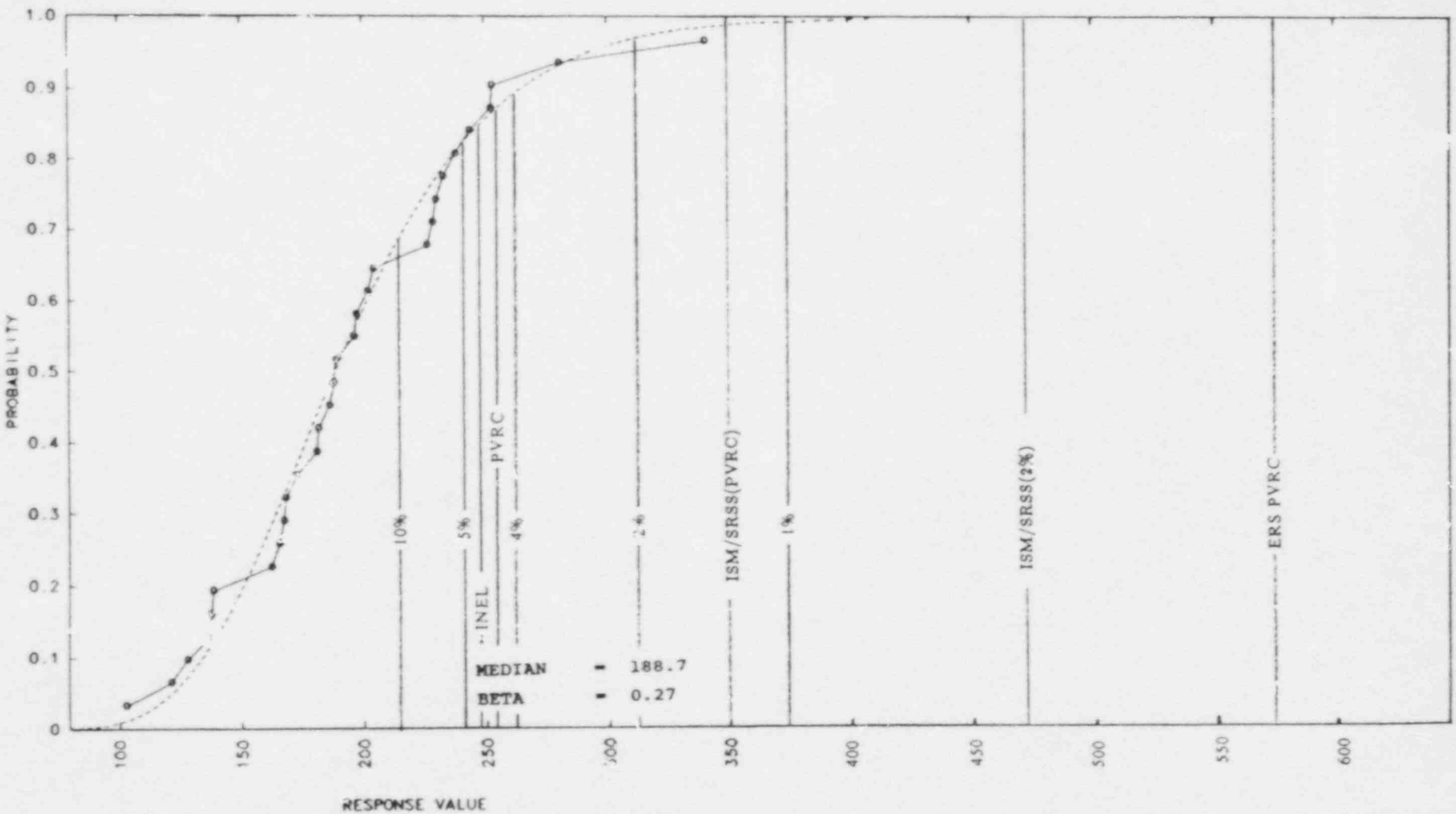

Fig. 4-1 Distribution of a Typical Support Force in the RHR Model with Design Analysis Responses Superposed

(b) Best Estimate

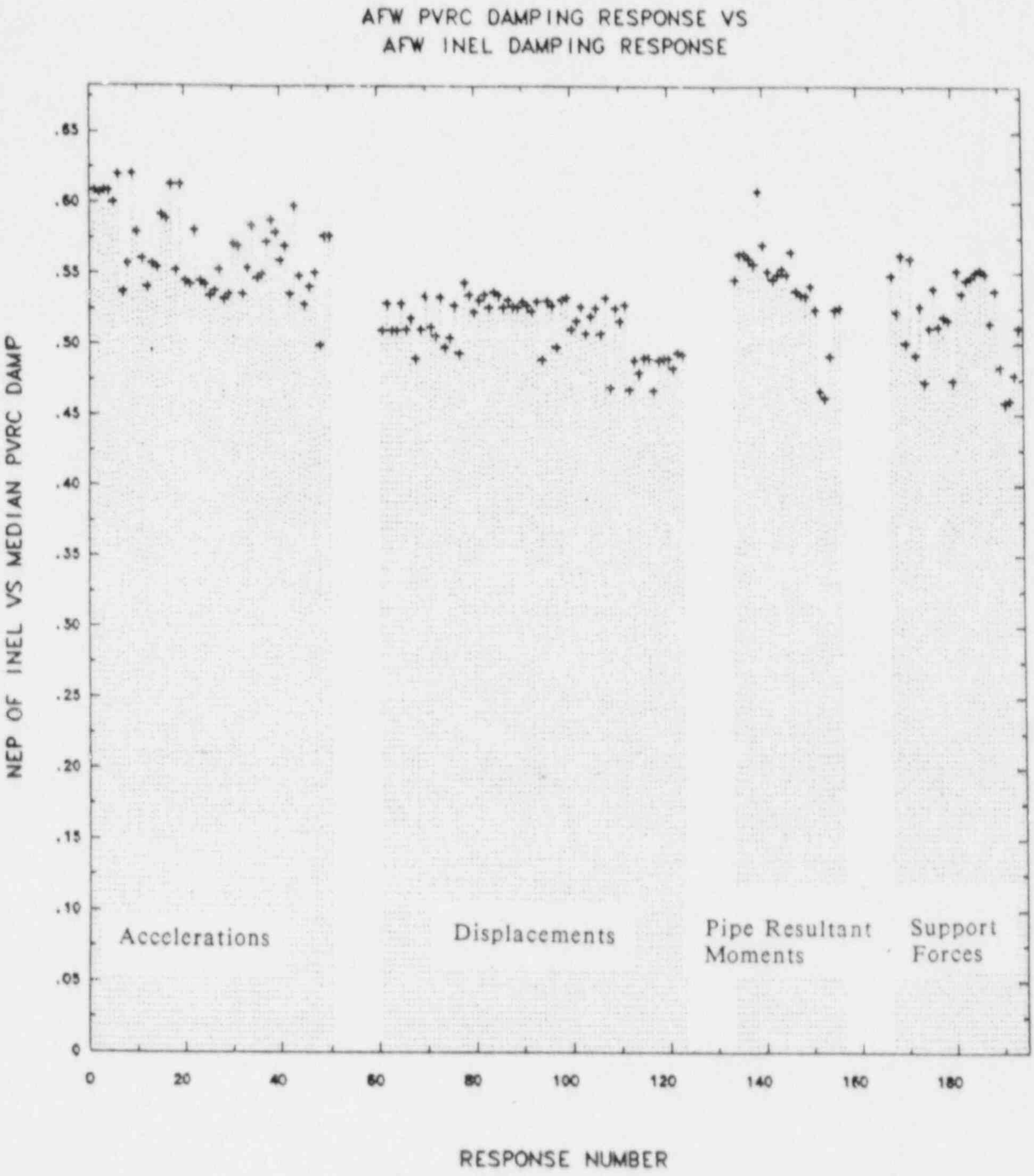

Fig. 4-2a Nonexceedance Probabilities for the AFW Model, R.G. 1.60 PVRC Damping vs. R.G. 1.60 INEL Damping

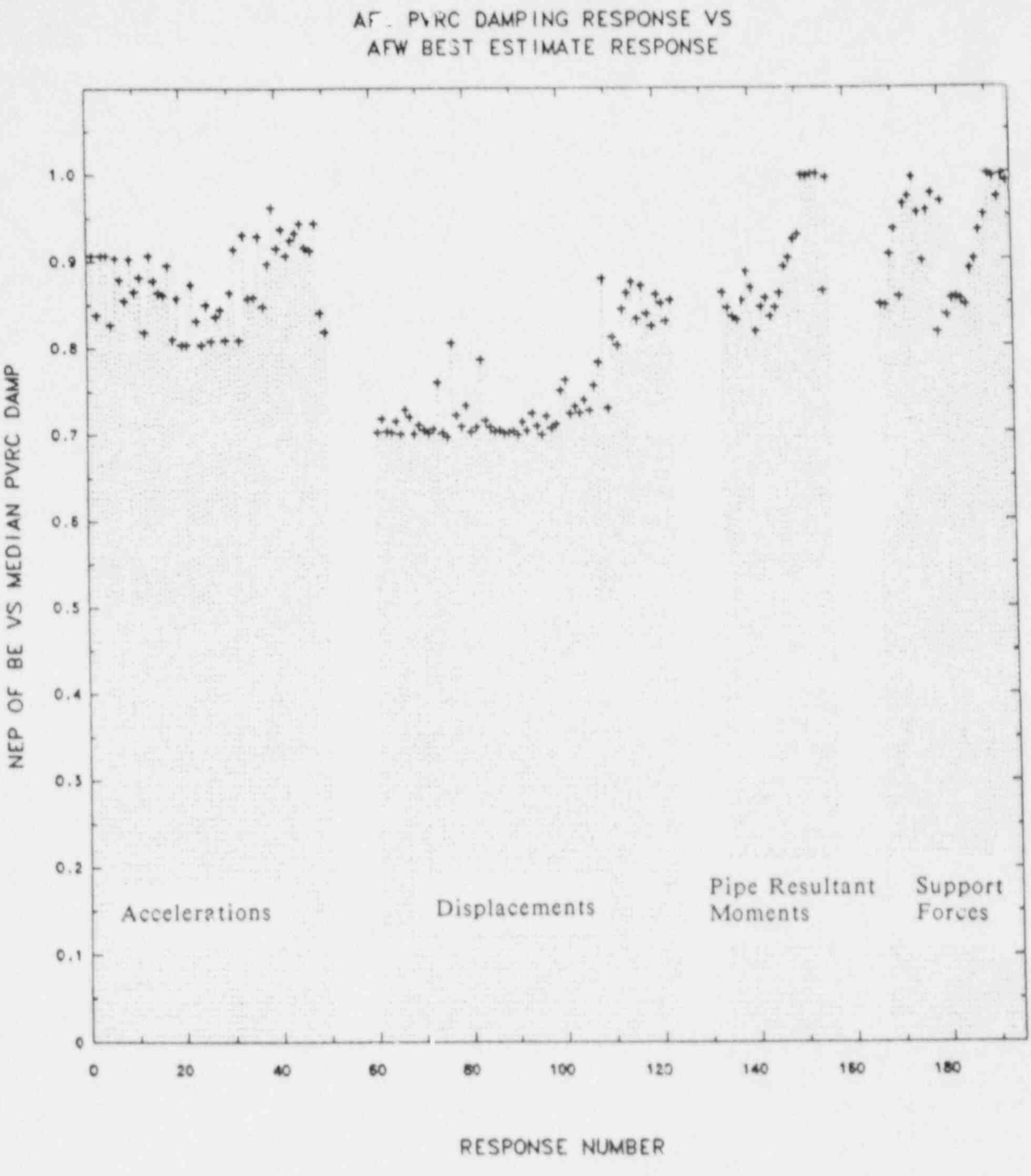

Fig. 4-2b Nonexceedance Probabilities for the AFW Model, R.G. 1.60 PVRC Damping vs. Best Estimate

5.0 CONCLUSIONS

The results presented here confirm that significant conservatism exists in the calculational procedures typically applied for piping system analysis and design. This conservatism is due to treatment of the piping system itself and due to conservatisms introduced throughout the seismic analysis chain (seismic input, SSI, and structure response). The present study quantified this conservatism in terms of nonexceedance probabilities of response. First, using as a basis a best estimate treatment of the piping system only (denoted R.G. 1.60, INEL damping); and second, using as a basis a best estimate treatment of the entire seismic analysis chain.

In an attempt to reduce excess conservatism in the piping system response element, the Technical Committee on Piping Systems of the Pressure Vessel Research Committee recommended piping system damping values which are frequency dependent and higher, in general, than those currently used. Interpreting the results presented here in light of this proposal is appropriate.

First, consider the case isolating the piping system analysis and parameters, and treating it as best estimate. With the R.G. 1.60, INEL damping case as the basis of comparison, the following conclusions can be drawn:

- PVRC damping used in conjunction with the multi-support time history analysis procedure leads to responses which slightly exceed median values.
- PVRC damping used in conjunction with the envelope response spectrum analysis procedure leads to responses with very high nonexceedance probabilities, i.e. >99.9% for design quantities of interest.
- PVRC damping used in conjunction with the independent support motion response spectrum analysis with SRSS combination of support group responses leads to responses with high nonexceedance probabilities, i.e. >92%.

Second, consider the case of treating the entire seismic methodology chain as best estimate. With this best estimate case as the basis of comparison, the following conclusions can be drawn:

- PVRC damping used in conjunction with the multi-support time history analysis procedure leads to responses with nonexceedance probabilities greater than 85% for design quantities of interest.
- PVRC damping used in conjunction with the envelope response spectrum analysis procedure leads to responses with nonexceedance probabilities greater than 99.99%.
- PVRC damping used in conjunction with the independent support motion response spectrum analysis with SRSS combination of support group responses leads to responses with nonexceedance probabilities greater than 98%.

These results may be viewed in an additional perspective. Many forums have recommended [14, 15] and investigated [16] establishing a seismic analysis performance specification in lieu of prescribing analysis techniques and parameter values. In particular, Refs. 14 and 15 recommend (in paraphrased form) that seismic analysis procedures and parameter values of the analysis shall be selected such that if an earthquake occurred with peak ground acceleration equal to that of the design earthquake, the probability of exceeding the response levels determined in the seismic analysis and used in the seismic design would be about 10 - 15%. The design analysis procedure employed here for seismic input, SSI, and structure response in conjunction with the multi-support time history analysis of piping systems utilizing PVRC damping and the case of independent support motion with SRSS of support group responses utilizing PVRC damping satisfy this criteria.

The conclusions drawn here are generic in the sense that consistent soil-structure-piping system models were analyzed in all cases with differences only in parameter values. For the case of comparisons with RG 1.60, INEL damping, the seismic input and soil-structure system models and parameters were identical up to piping system response calculations. Then, the piping system analysis methodologies and parameters were varied to quantify their effects. For the case of comparisons with best estimate values, the soil-structure models were identical with changes in parameter values only. In no case were additional potential conservatisms such as SSI embedment effects included in one case and not another.

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Appendix A

Plots of Nonexceedance Probabilities for the Distribution of INEL Damping Responses

Appendix A contains plots that graphically illustrate the nonexceedance probabilities for all response quantities for each of the three piping systems considered in the study. In this Appendix, the basis for comparison is the distribution of INEL damping time history responses. For a given response quantity, e.g., a nodal acceleration, and a given analysis method, e.g., constant 1% damping time history analysis, the plotted value is the probability that an INEL damping response will not exceed the median response of the alternate analysis method.

For the AFW and RHR piping system models, nonexceedance probabilities for the following analysis methods are given:

- envelope response spectrum analysis using 2% damping
- envelope response spectrum analysis using PVRC damping
- independent support motion response spectrum analysis using 2% damping
- independent support motion response spectrum analysis using PVRC damping (RHR only)
- multi-support time history analysis using constant 1% damping
- multi-support time history analysis using constant 2% damping
- multi-support time history analysis using 4% constant damping
- multi-support time history analysis using 5% constant damping
- multi-support time history analysis using 10% constant damping
- multi-support time history analysis using PVRC damping

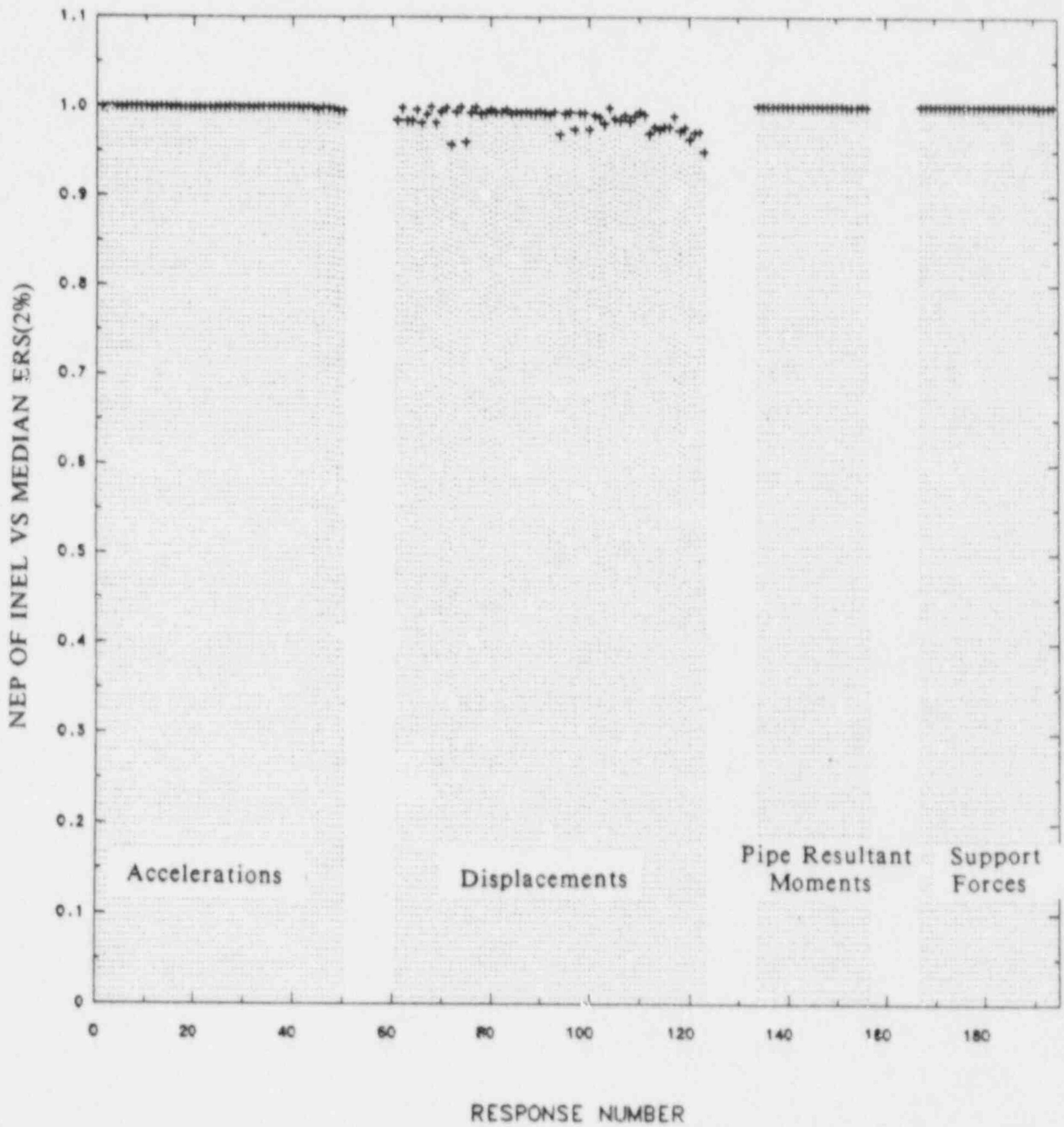
For the RCL piping system model, plots are given for the following analyses:

- envelope response spectrum analysis using 2% damping
- envelope response spectrum analysis using PVRC damping
- multi-support time history analysis using constant 2% damping
- multi-support time history analysis using constant 3% damping
- multi-support time history analysis using 4% constant damping
- multi-support time history analysis using 5% constant damping
- multi-support time history analysis using 10% constant damping
- multi-support time history analysis using PVRC damping

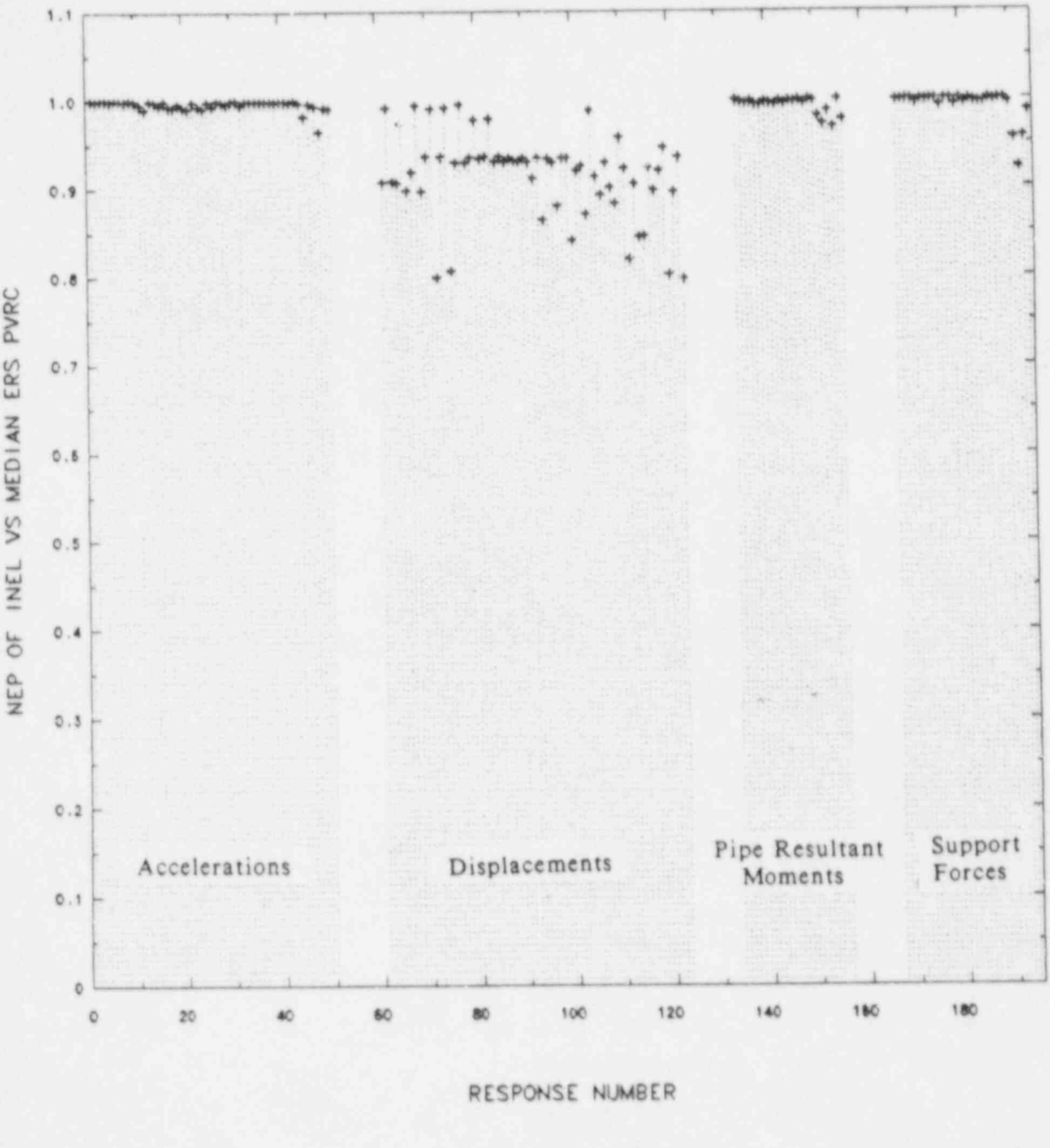
The data is presented in a format that has been used in previous reports. Each plot shows the data for all response quantities calculated for a piping system model by a given analysis method. The response quantities for the AFW and RHR piping system models and the order in which they appear on a plot are nodal accelerations, nodal displacements, piping element resultant moments, support forces. For the RCL piping system model, the order of response quantities is nodal accelerations, support forces, piping element resultant moments.

AFW Piping System Model

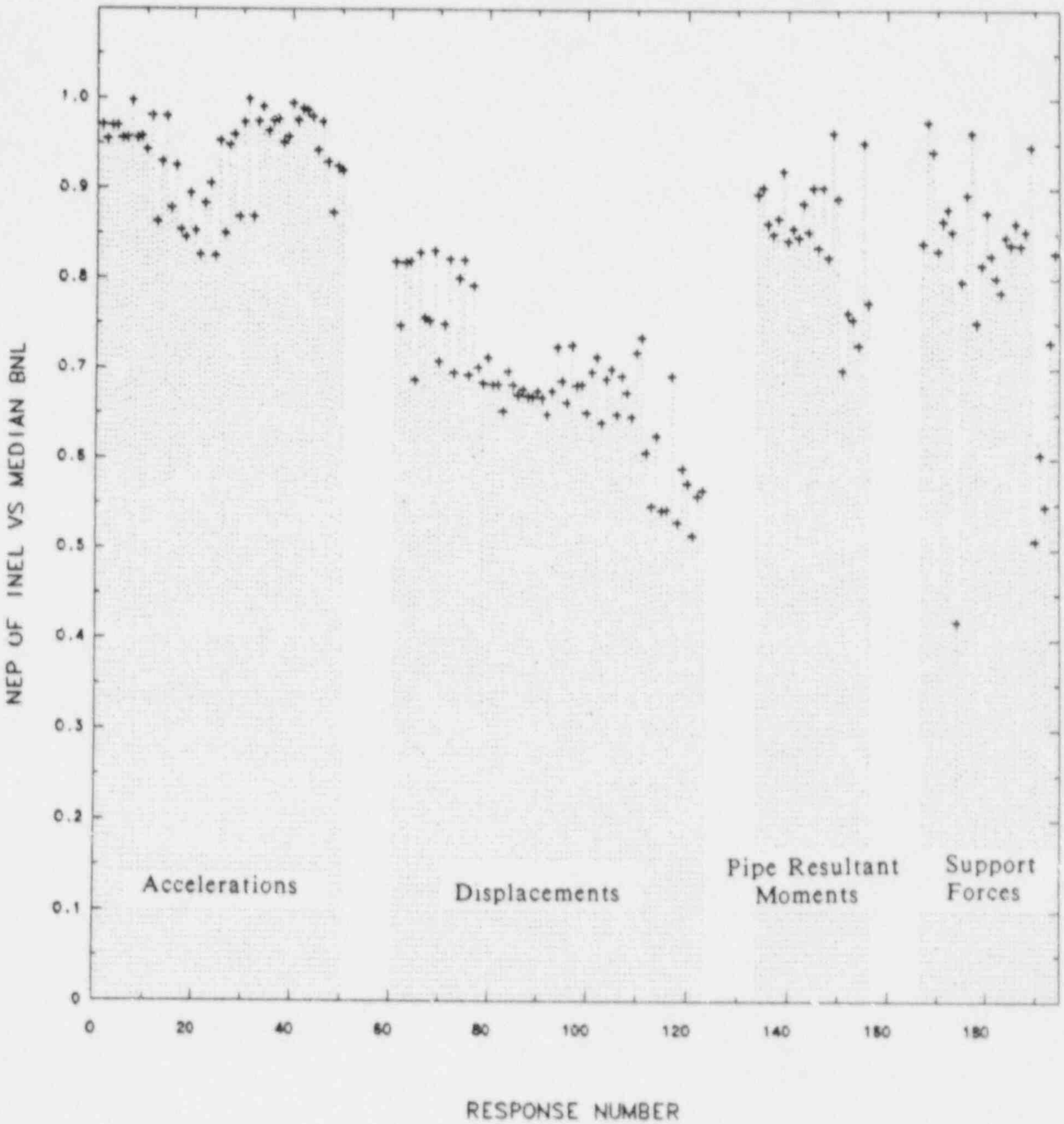
AFW ERS(2%) SPECTRA VS
AFW INEL DAMPING RESPONSE

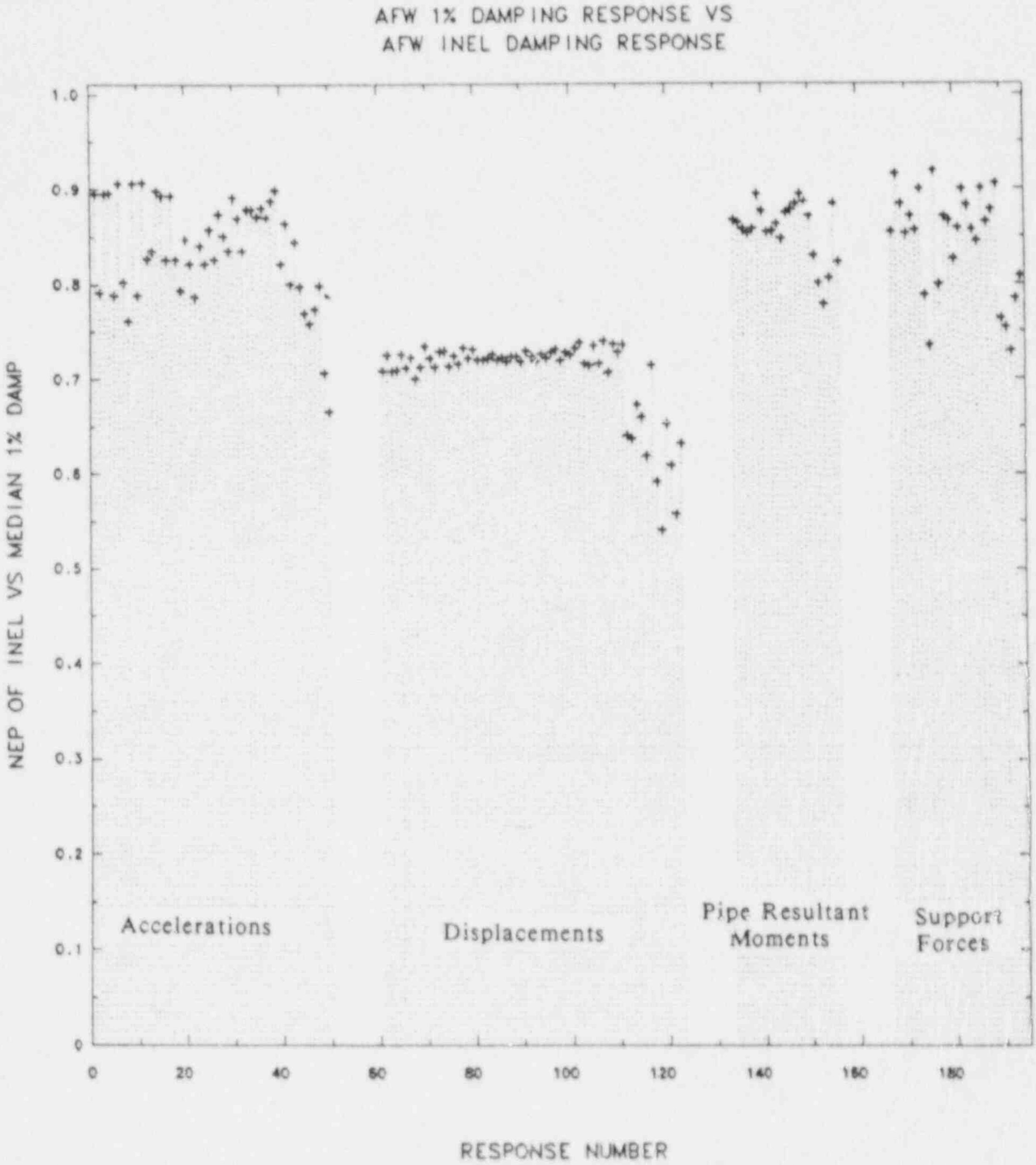


AFW ERS PVRC SPECTRA VS
AFW INEL DAMPING RESPONSE

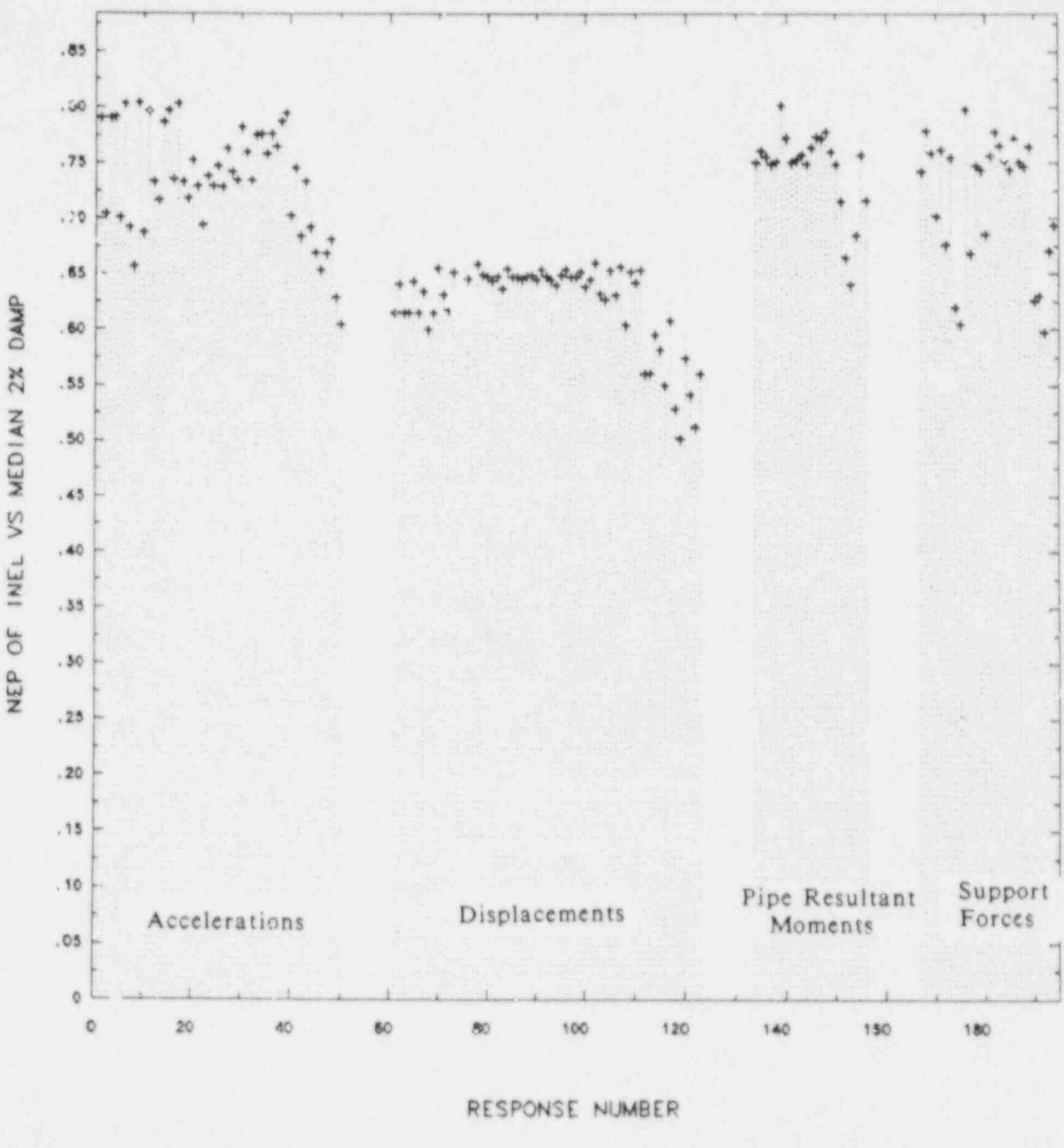


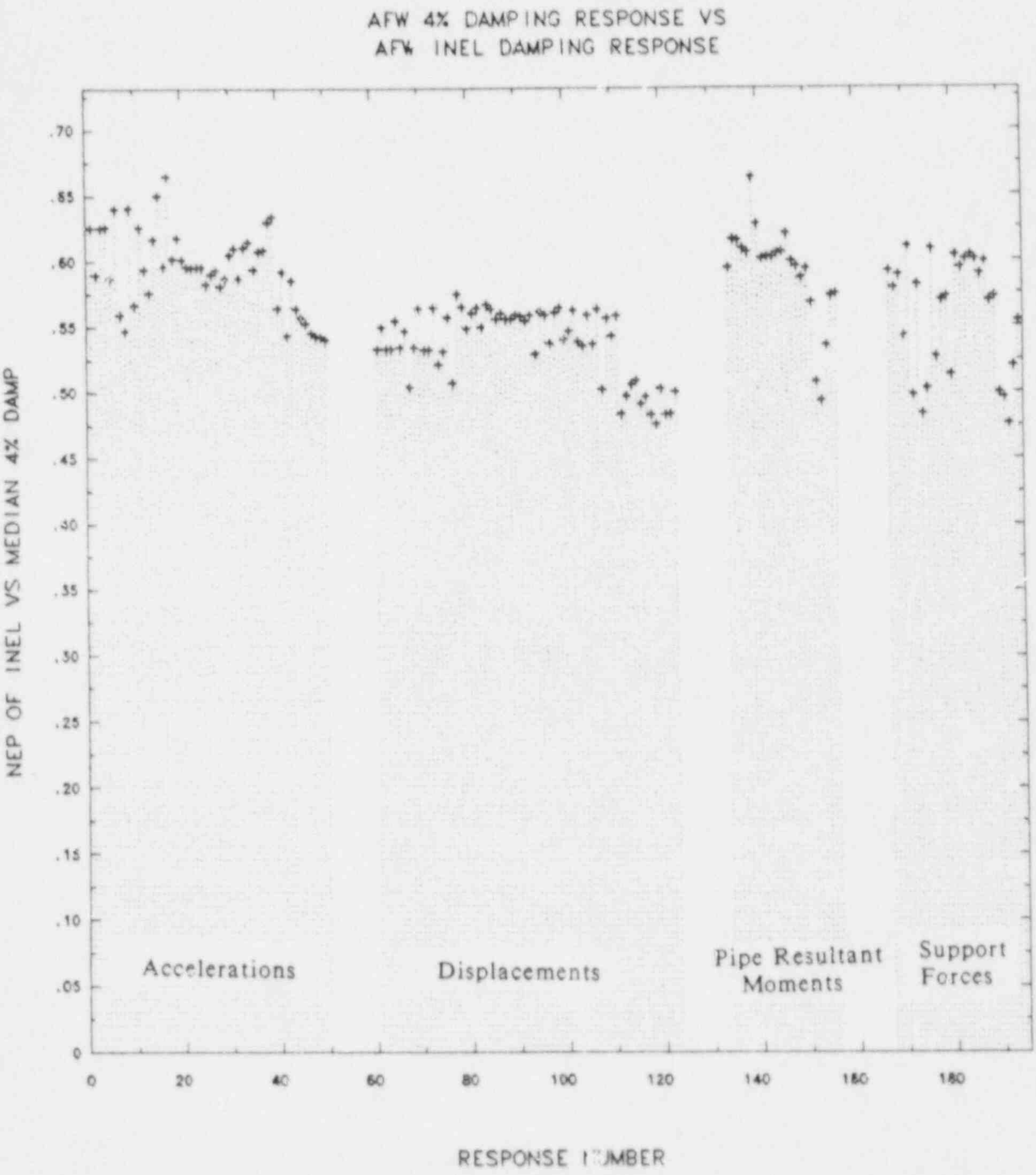
AFW BNL ISM/SRSS(PVRC) VS
AFW INEL DAMPING RESPONSE

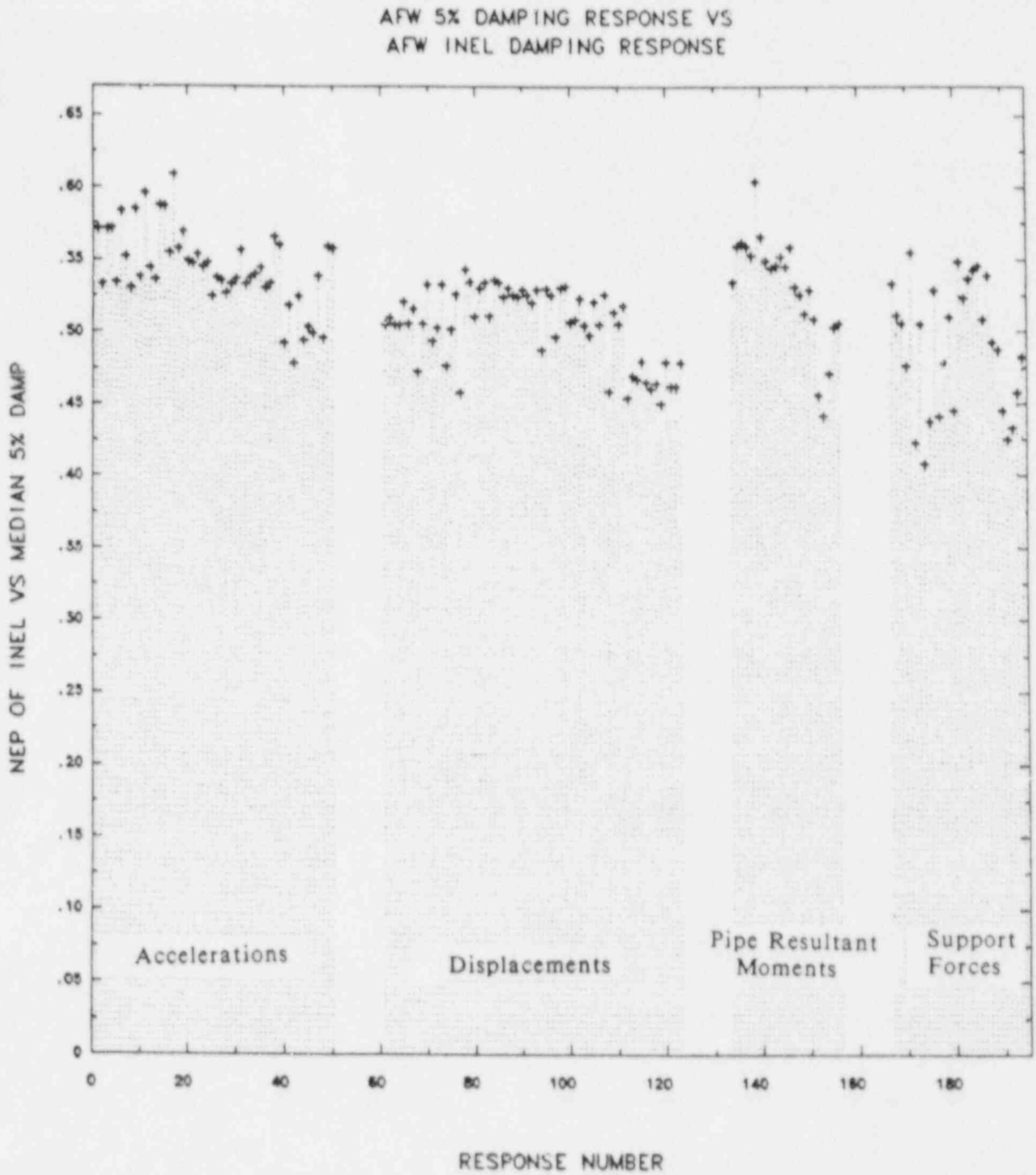


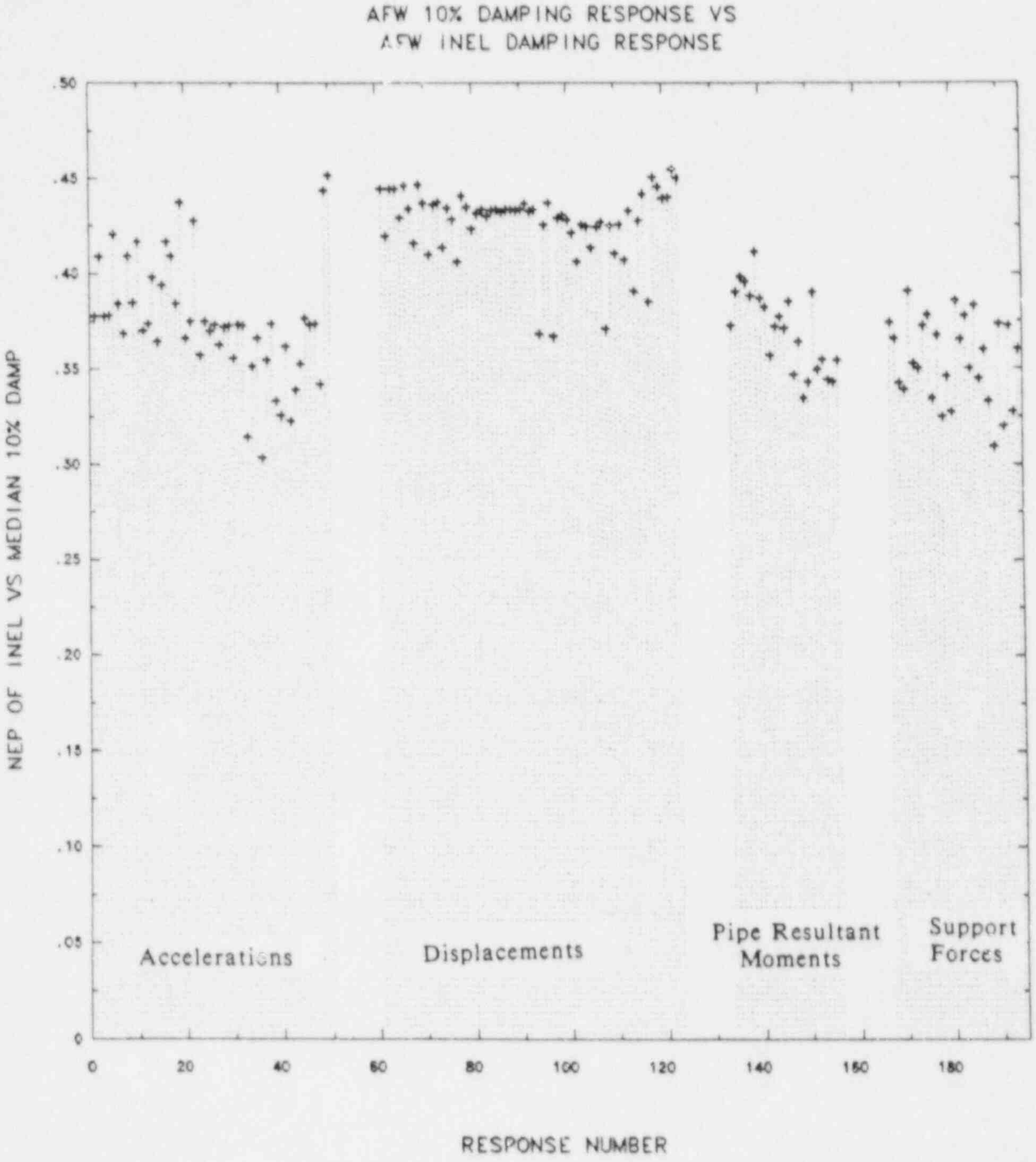

AFW 1% DAMPING RESPONSE VS
AFW INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 1% DAMP
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
180
Accelerations
Displacements
Pipe Resultant
Moments
Support
Forces
RESPONSE NUMBER

AFW 2% DAMPING RESPONSE VS
AFW INEL DAMPING RESPONSE

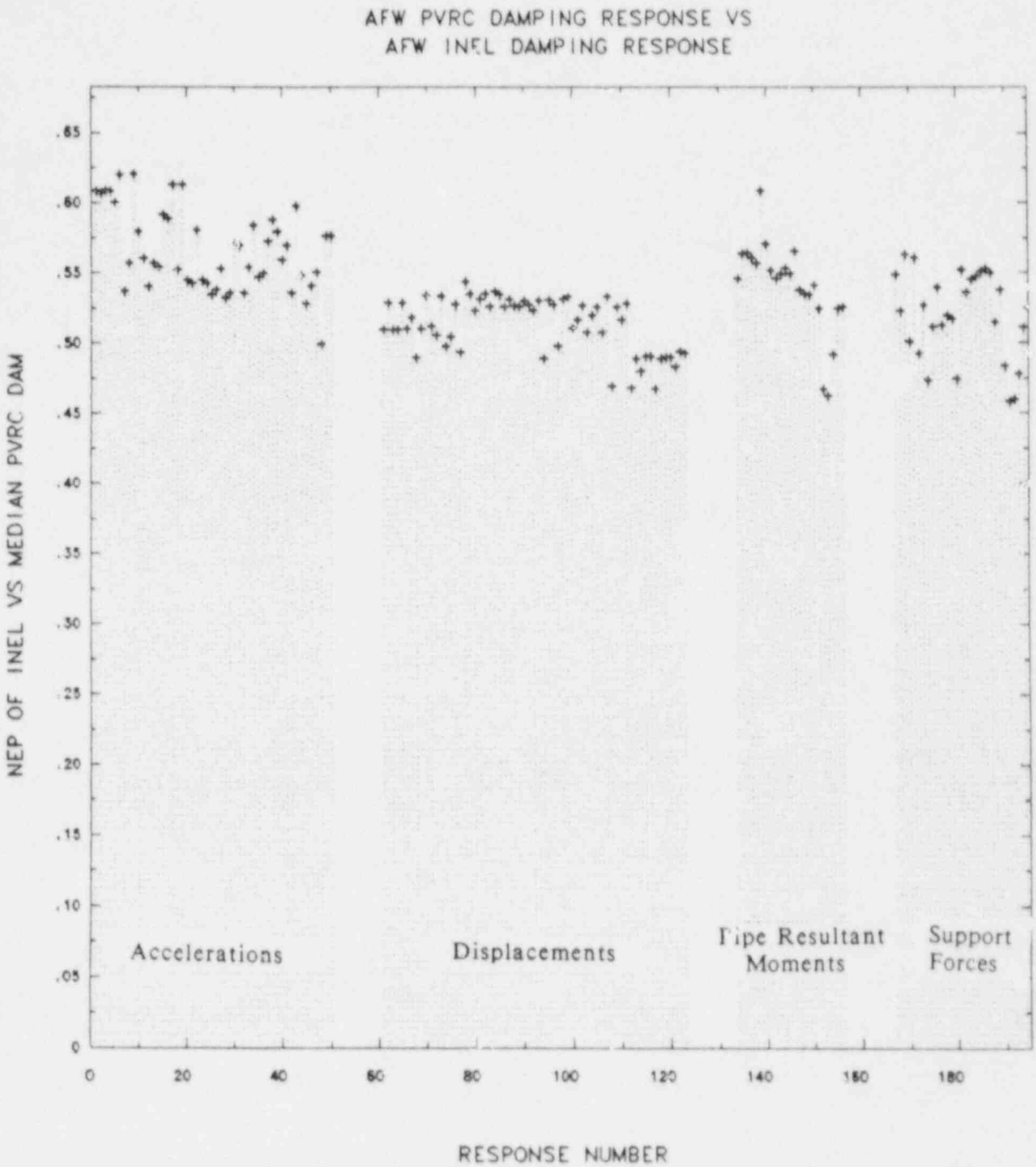



AFW 4% DAMPING RESPONSE VS
AFW INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 4% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces


AFW 5% DAMPING RESPONSE VS
AFW INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 5% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces

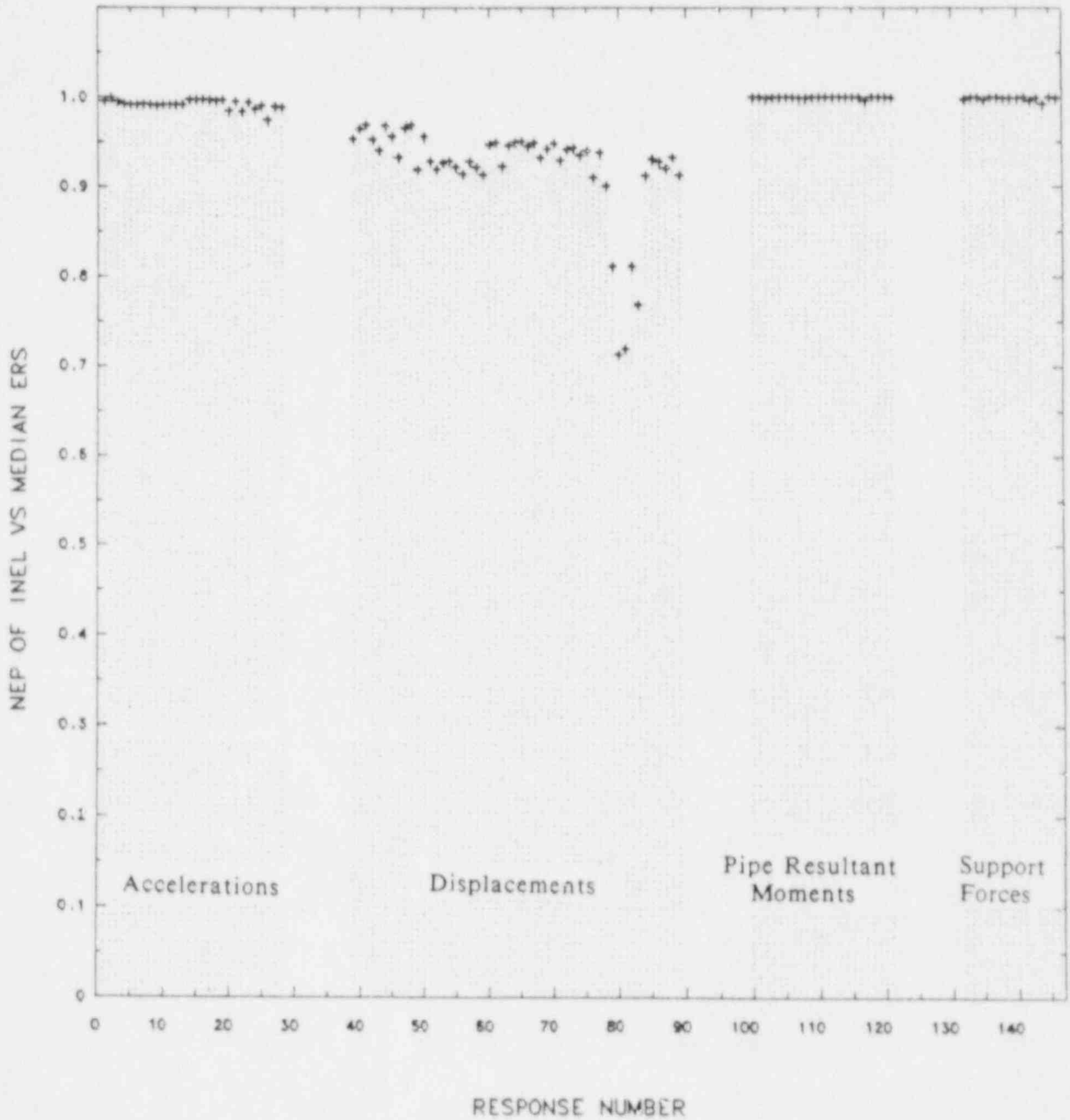


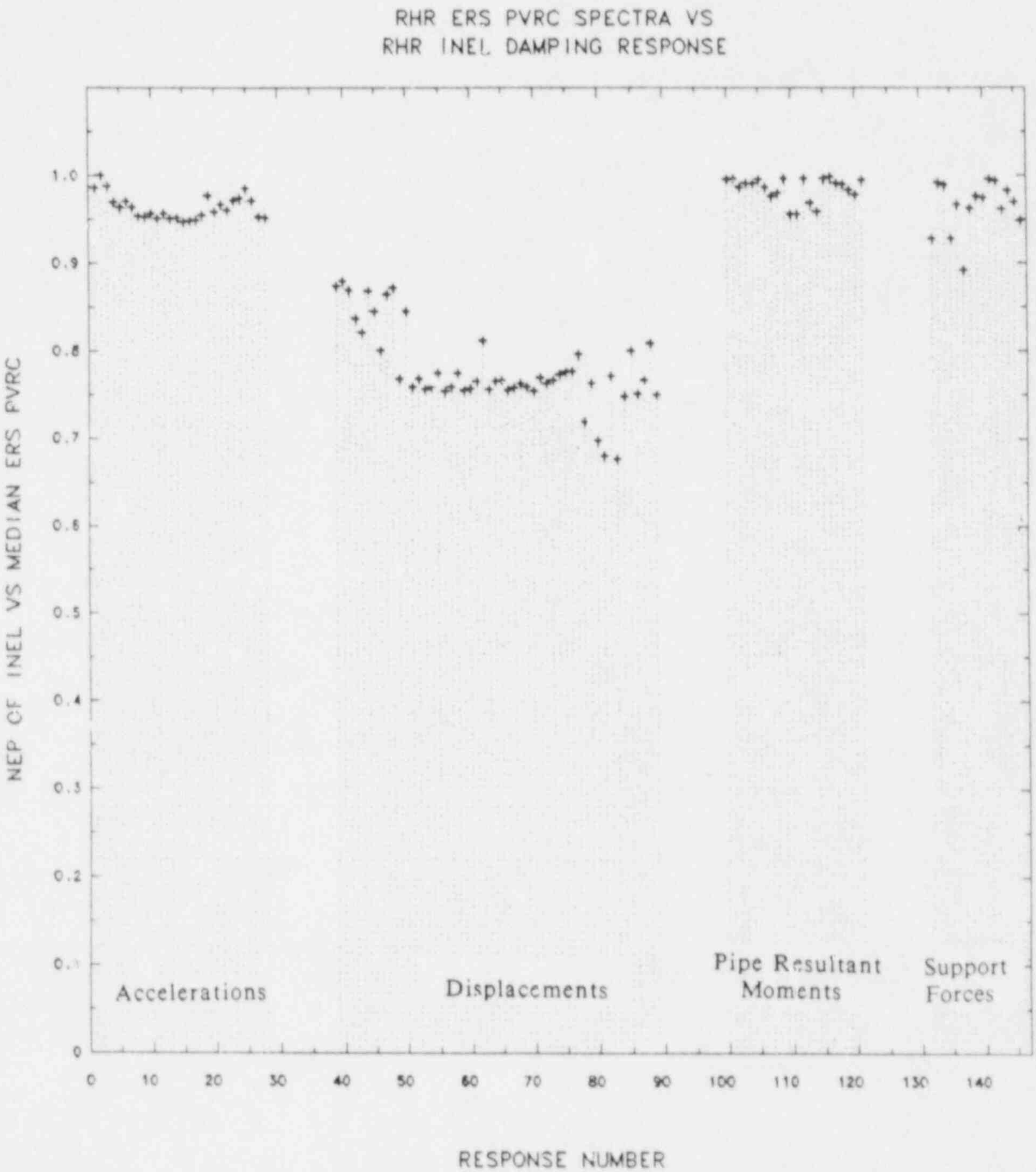
AFW 10% DAMPING RESPONSE VS
AFW INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 10% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces


AFW PVRC DAMPING RESPONSE VS
AFW INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN PVRC DAM
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces

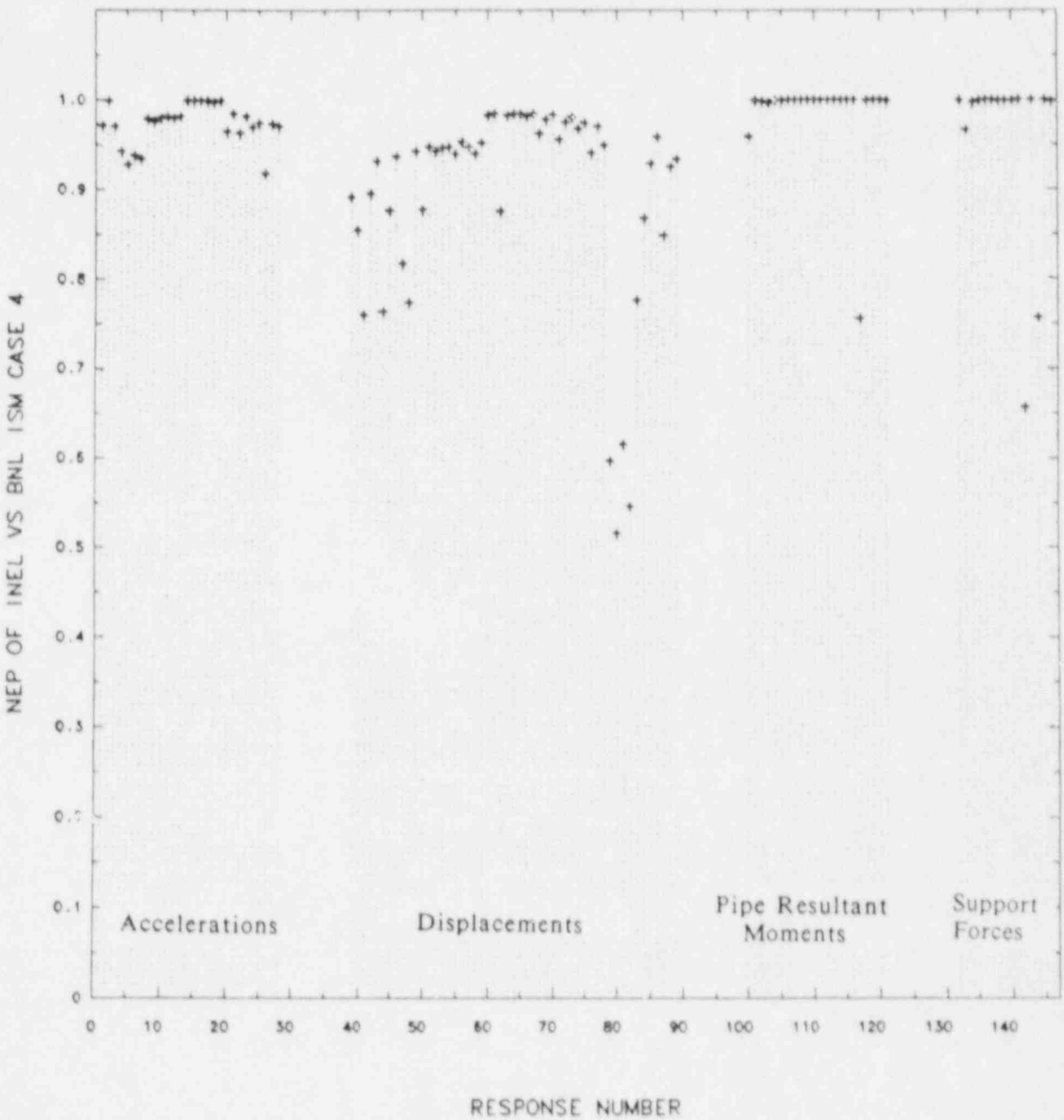
RHR Piping System Model

RHR ERS(2%) VS
RHR INEL DAMPING RESPONSE

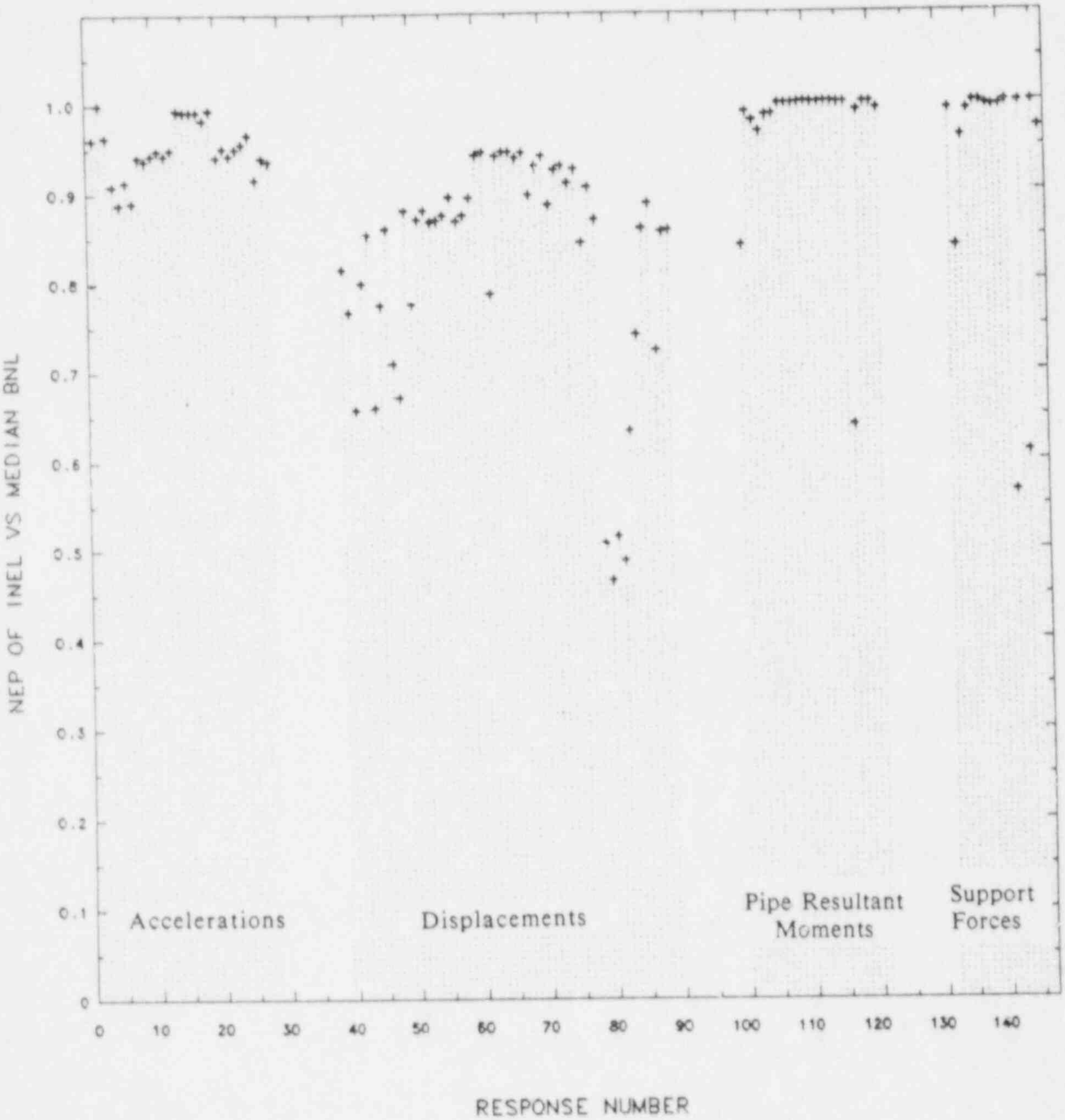


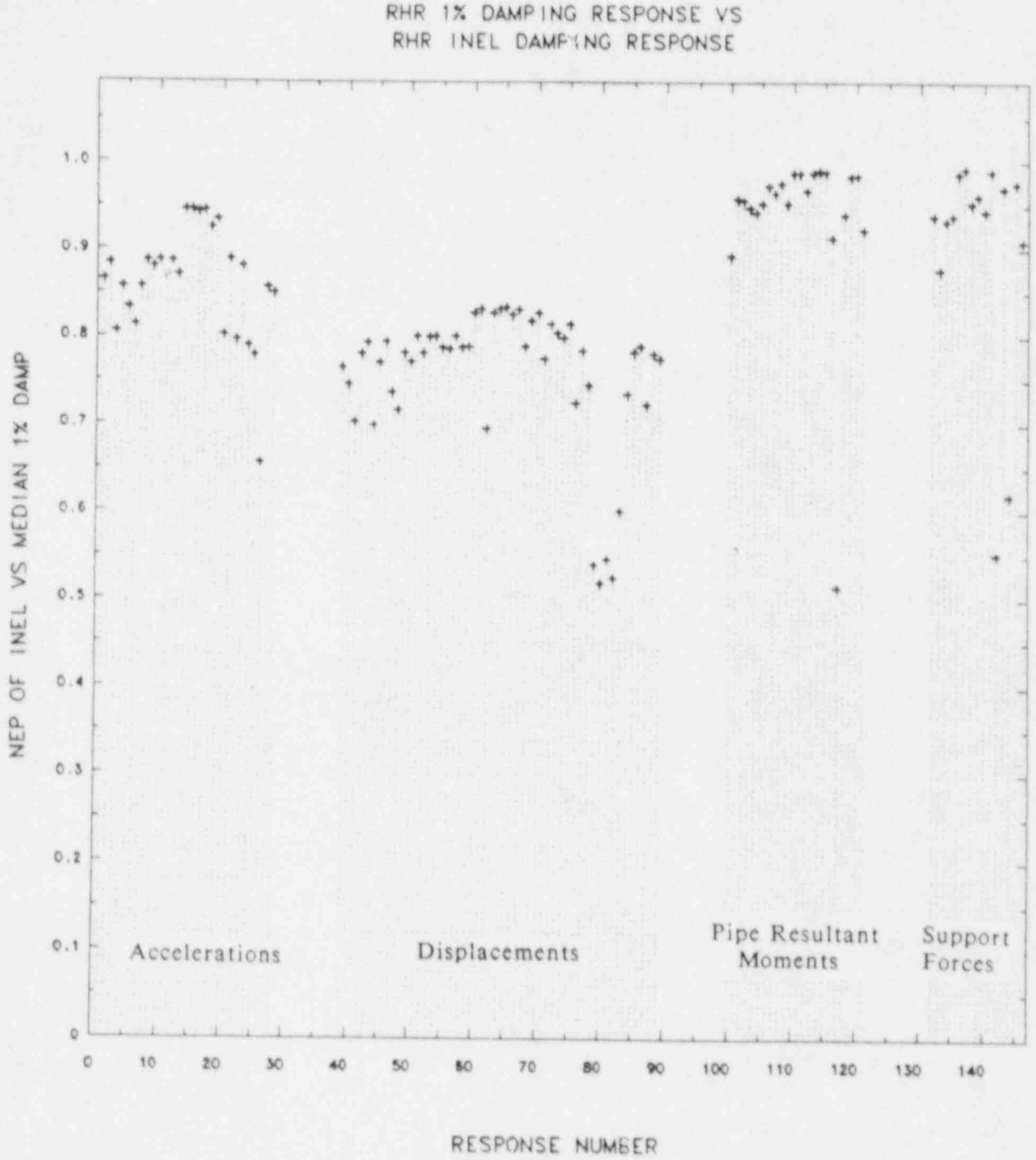

RHR ERS PVRC SPECTRA VS
RHR INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN ERS PVRC
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

BNL ISM/SRSS(2%) RESPONSE VS
RHR INEL DAMPING RESPONSE

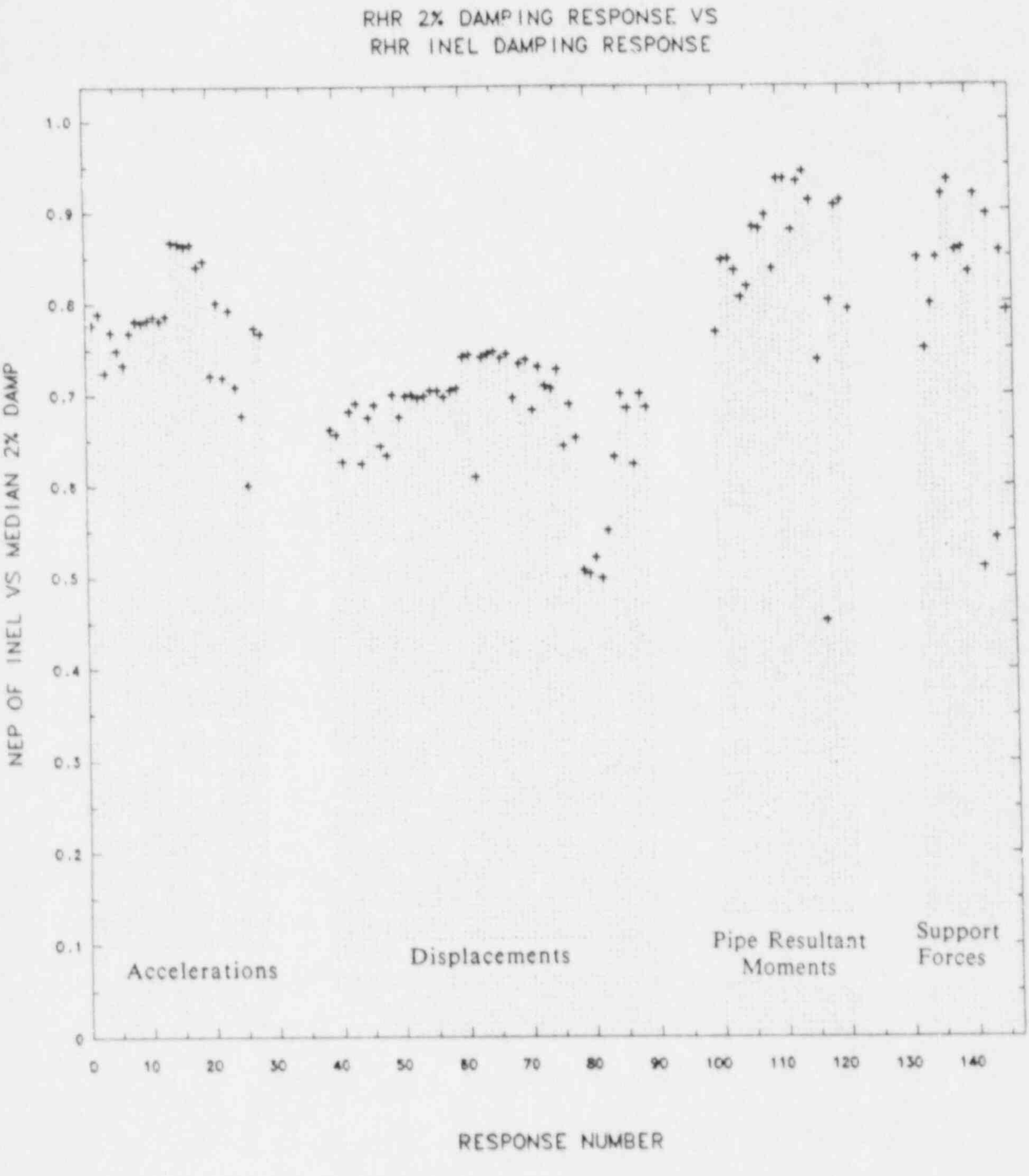


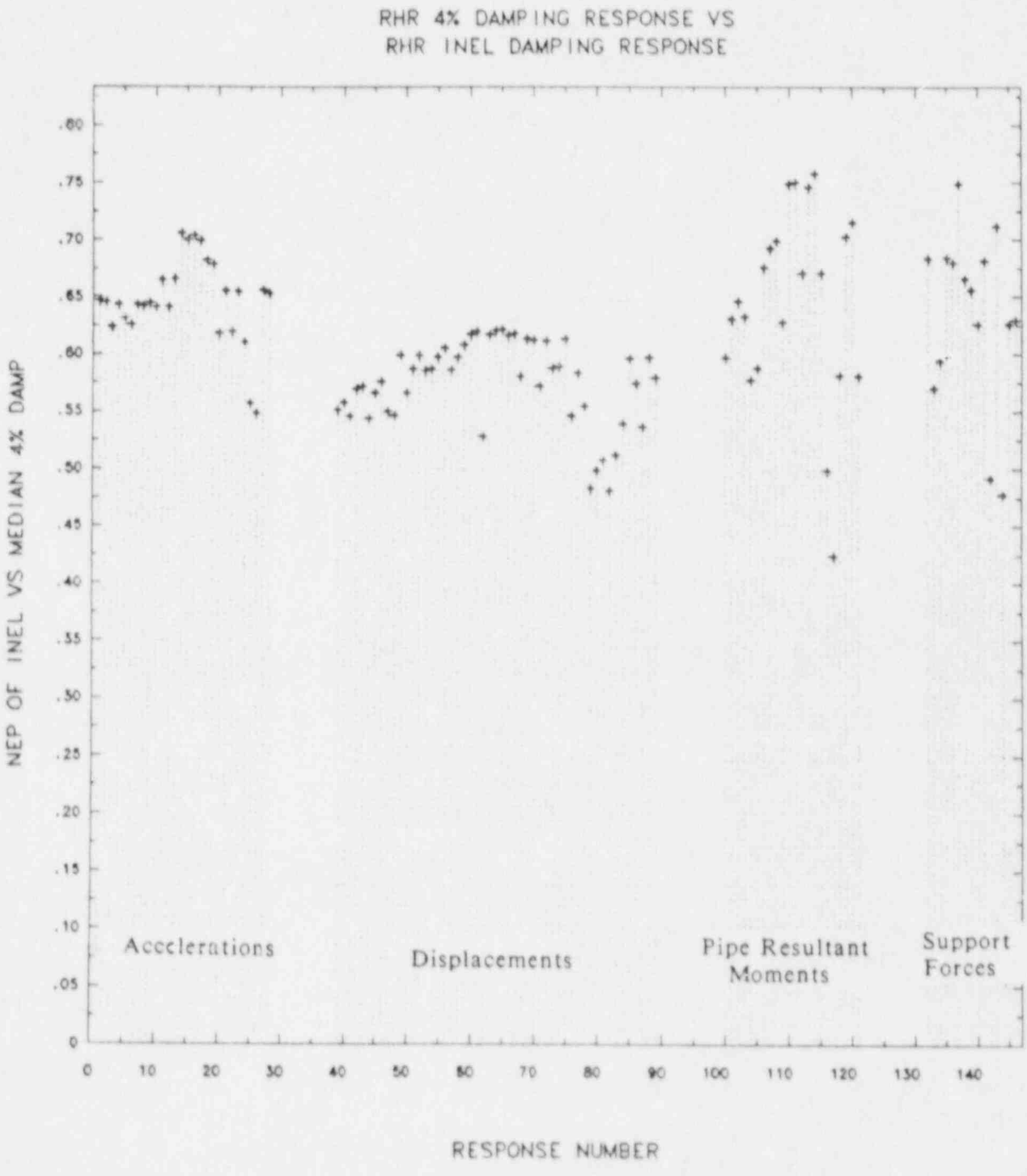
RHR BNL ISM/SRSS(PVRC) VS
RHR INEL DAMPING RESPONSE

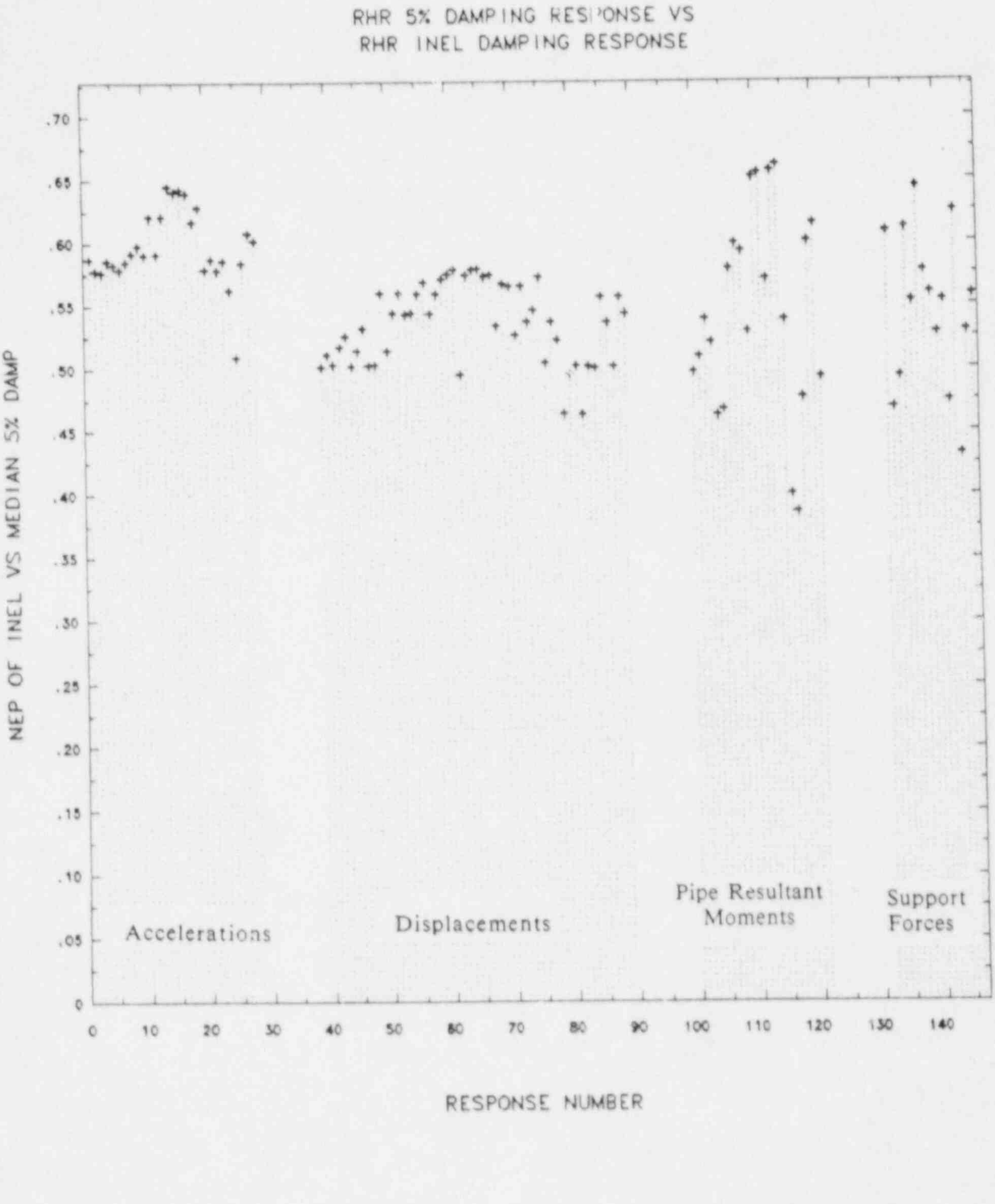


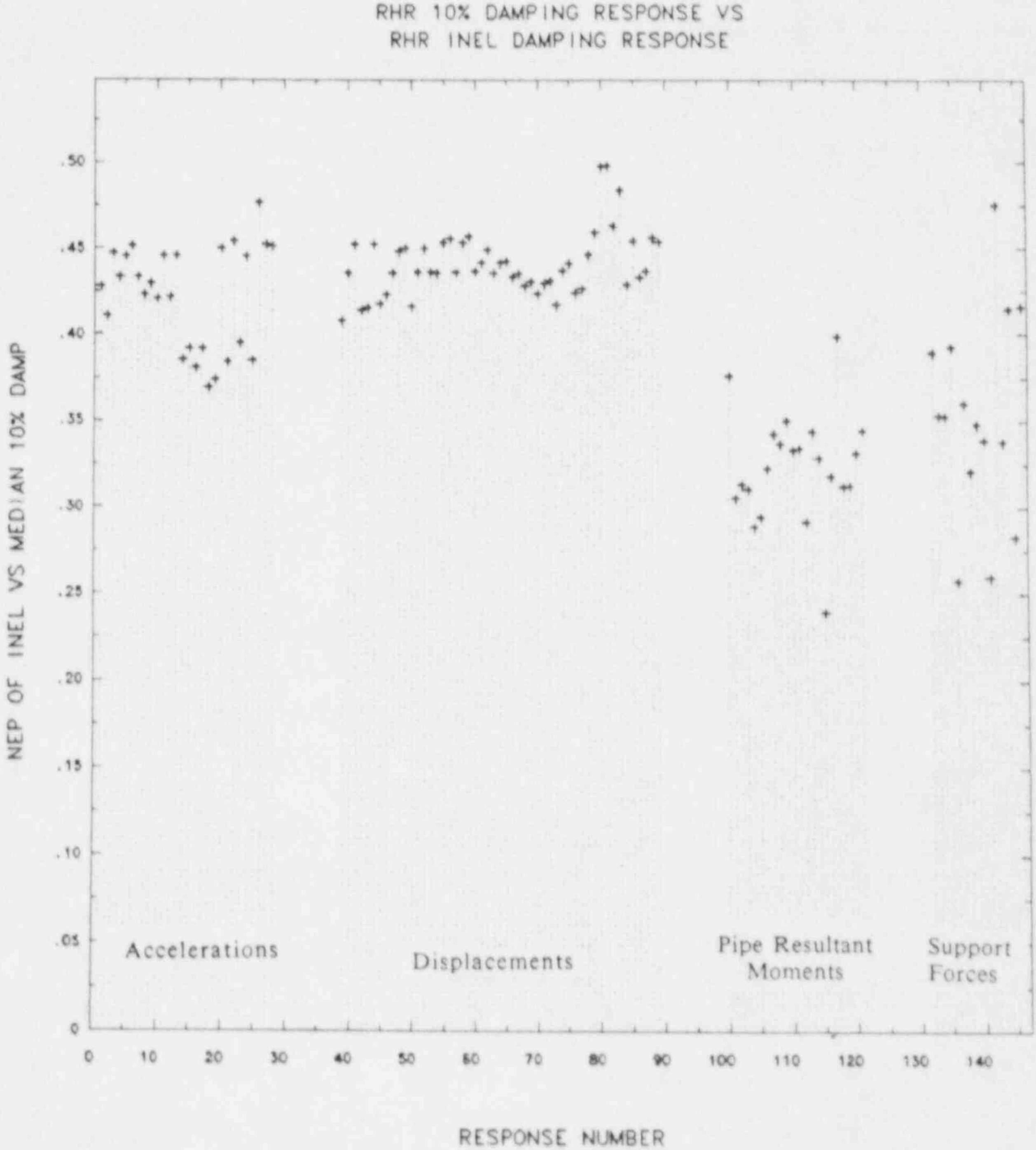


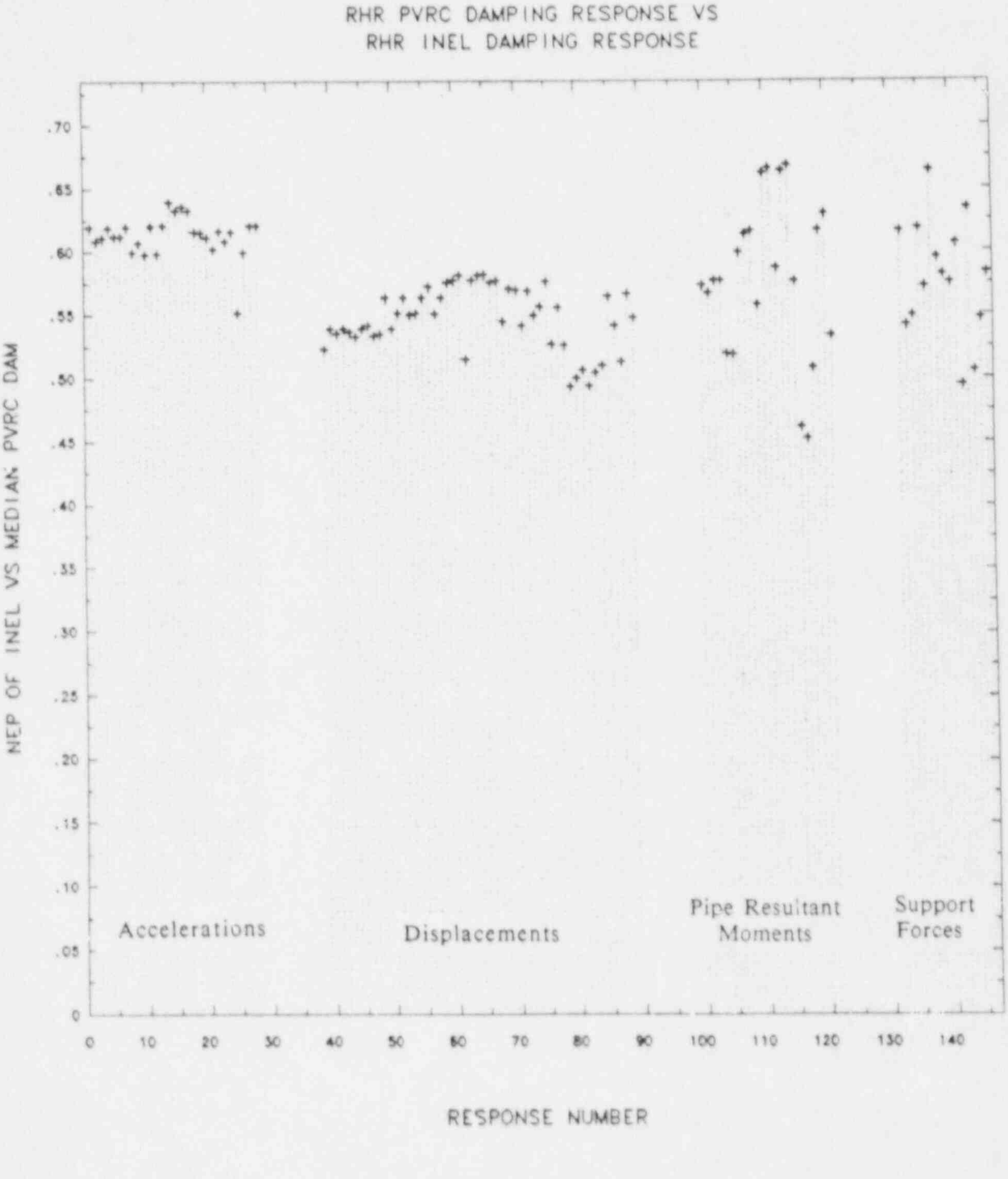
RHR 1% DAMPING RESPONSE VS
RHR INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 1% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant
Moments
Support
Forces


RHR 2% DAMPING RESPONSE VS
RHR INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 2% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant
Moments
Support
Forces
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140


RHR 4% DAMPING RESPONSE VS
RHR INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 4% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces


RHR 5% DAMPING RESPONSE VS
RHR INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 5% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces

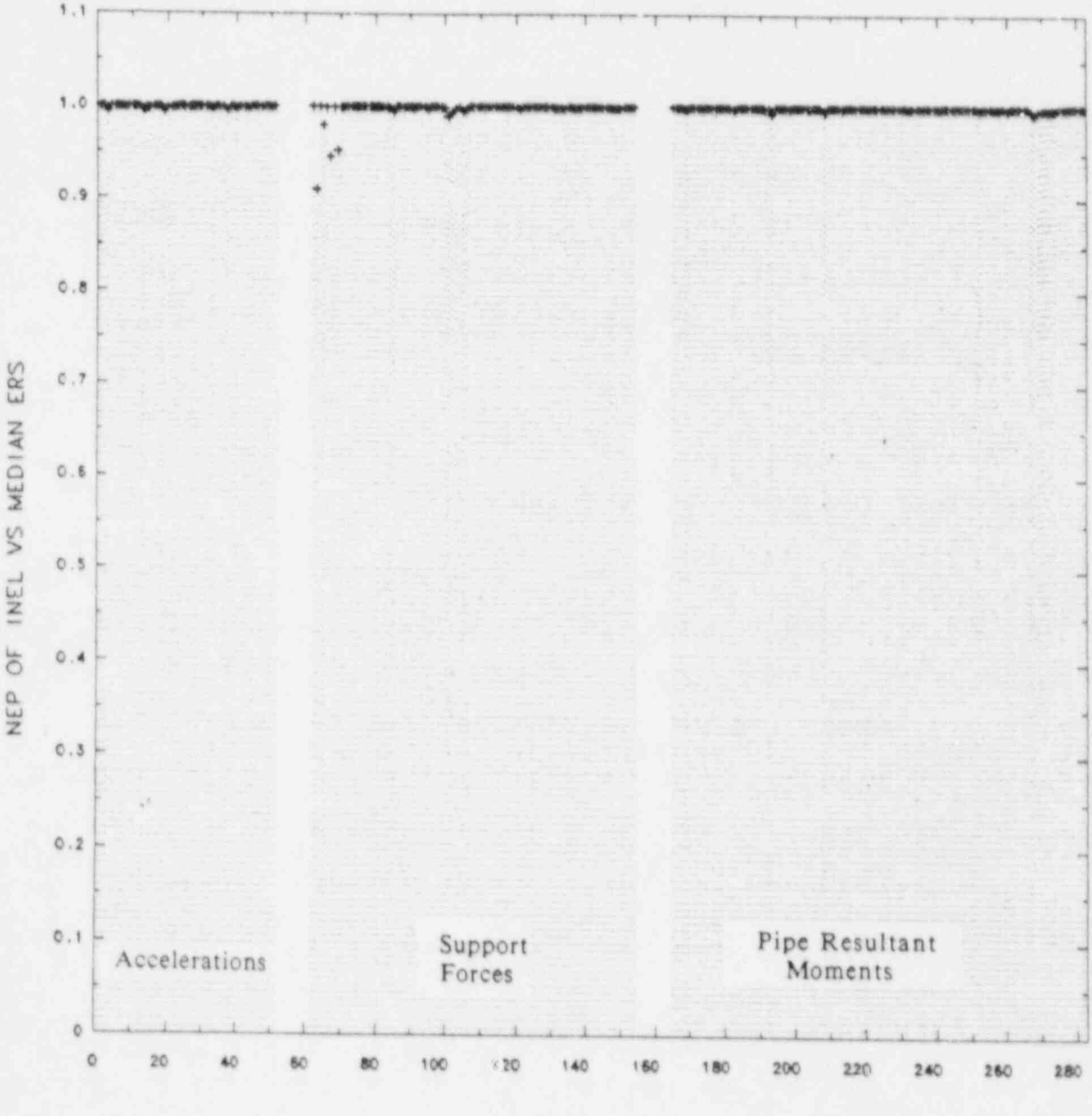

RHR 10% DAMPING RESPONSE VS
RHR INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 10% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces

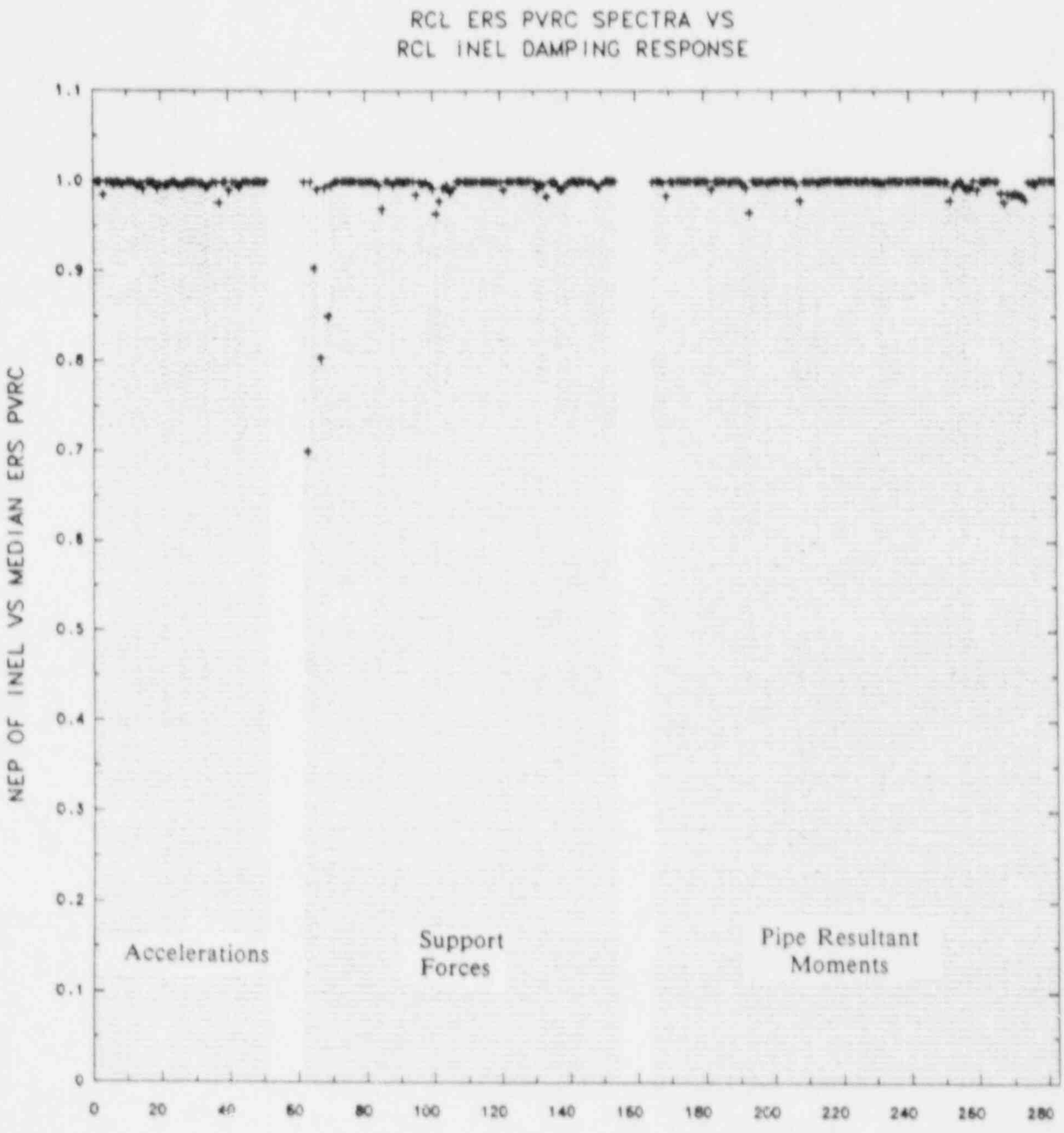


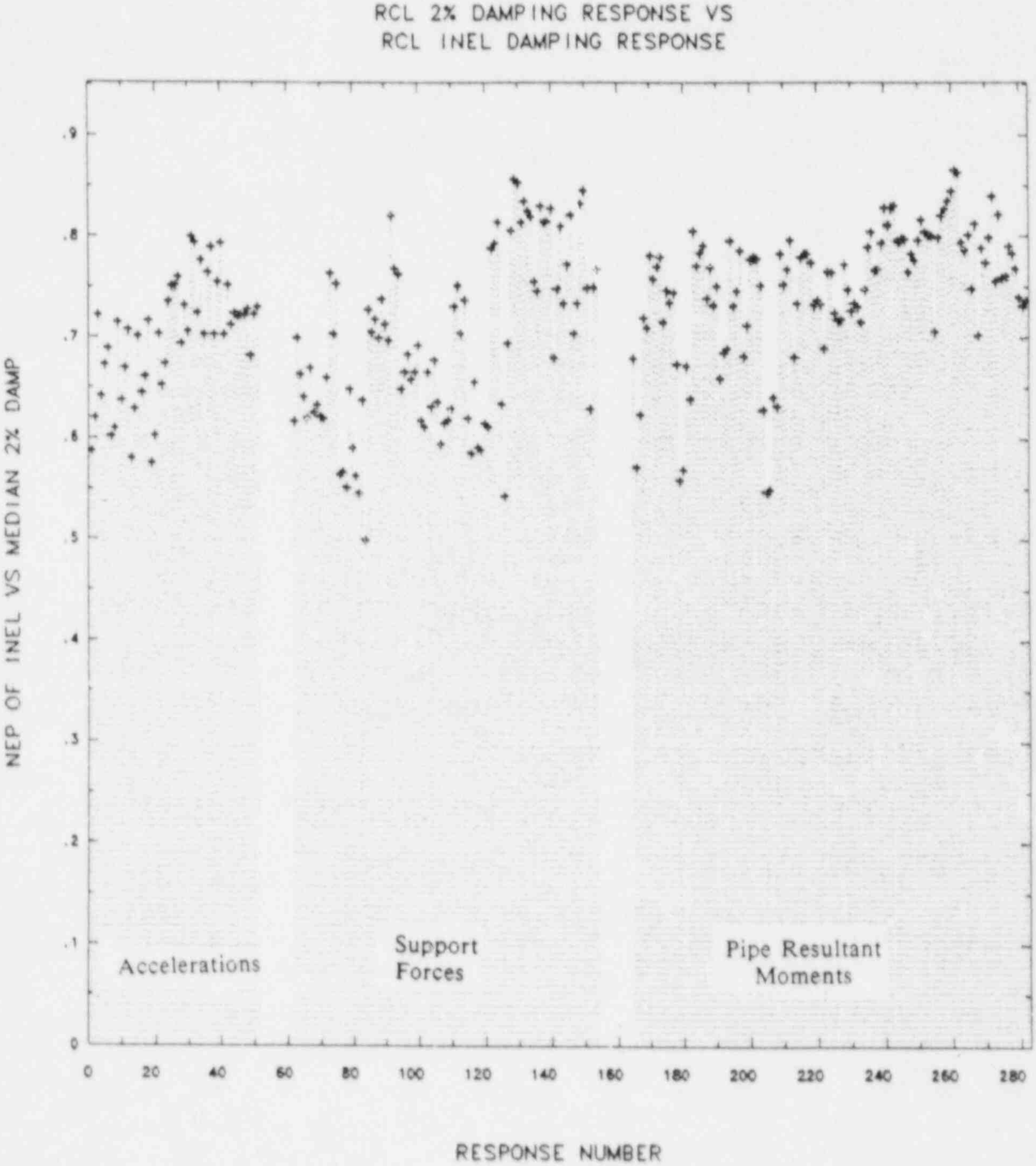
RHR PVRC DAMPING RESPONSE VS
RHR INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN PVRC DAM
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces

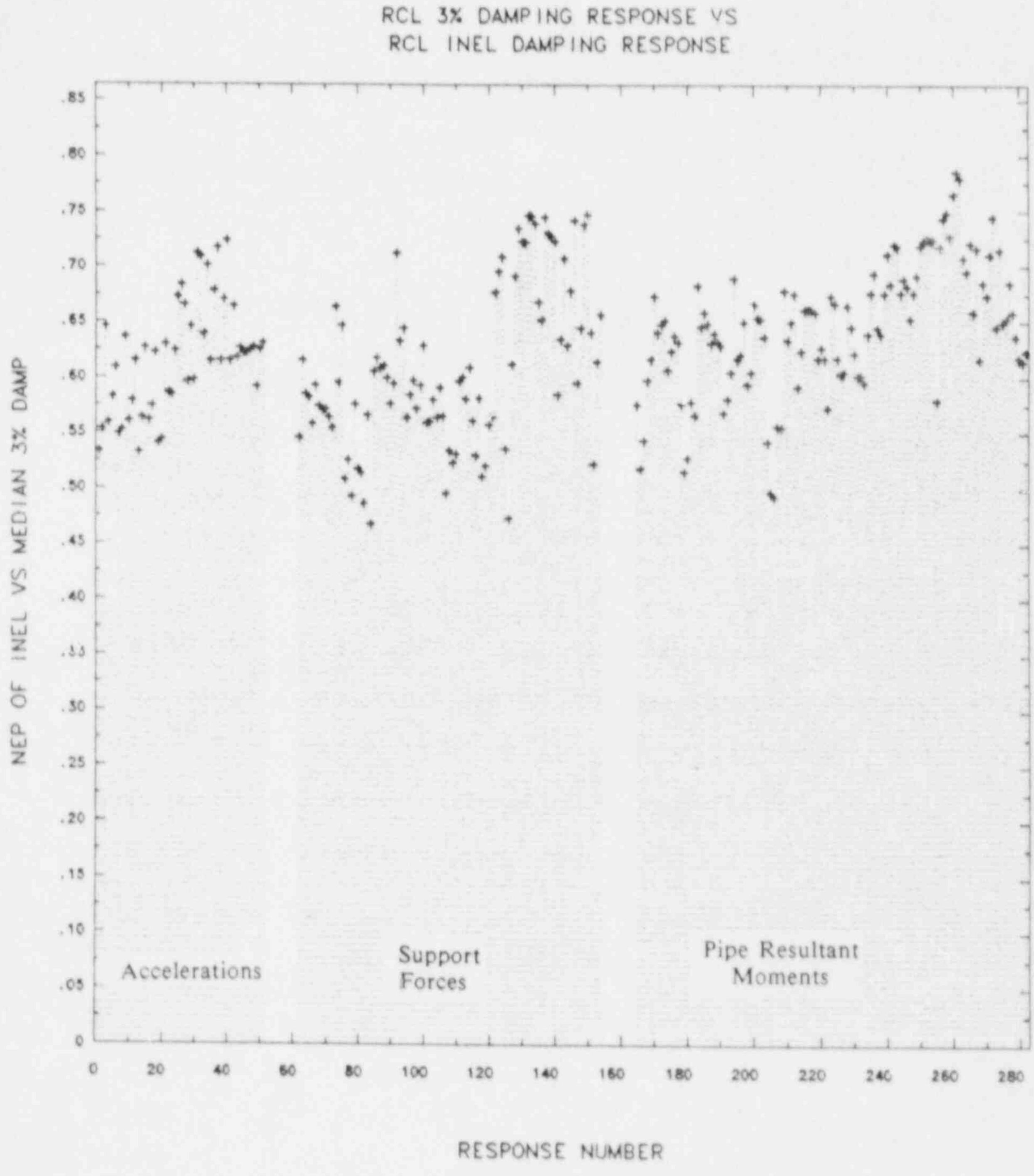
RCL Piping System Model

RCL ERS(2%) SPECTRA VS
RCL INEL DAMPING RESPONSE




RCL ERS PVRC SPECTRA VS
RCL INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN ERS PVRC
RESPONSE NUMBER
Accelerations
Support
Forces
Pipe Resultant
Moments


RCL 2% DAMPING RESPONSE VS
RCL INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 2% DAMP
RESPONSE NUMBER
Accelerations
Support Forces
Pipe Resultant Moments
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280


RCL 3% DAMPING RESPONSE VS
RCL INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 3% DAMP
RESPONSE NUMBER
Accelerations
Support
Forces
Pipe Resultant
Moments
.85
.80
.75
.70
.65
.60
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
0
0
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60
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140
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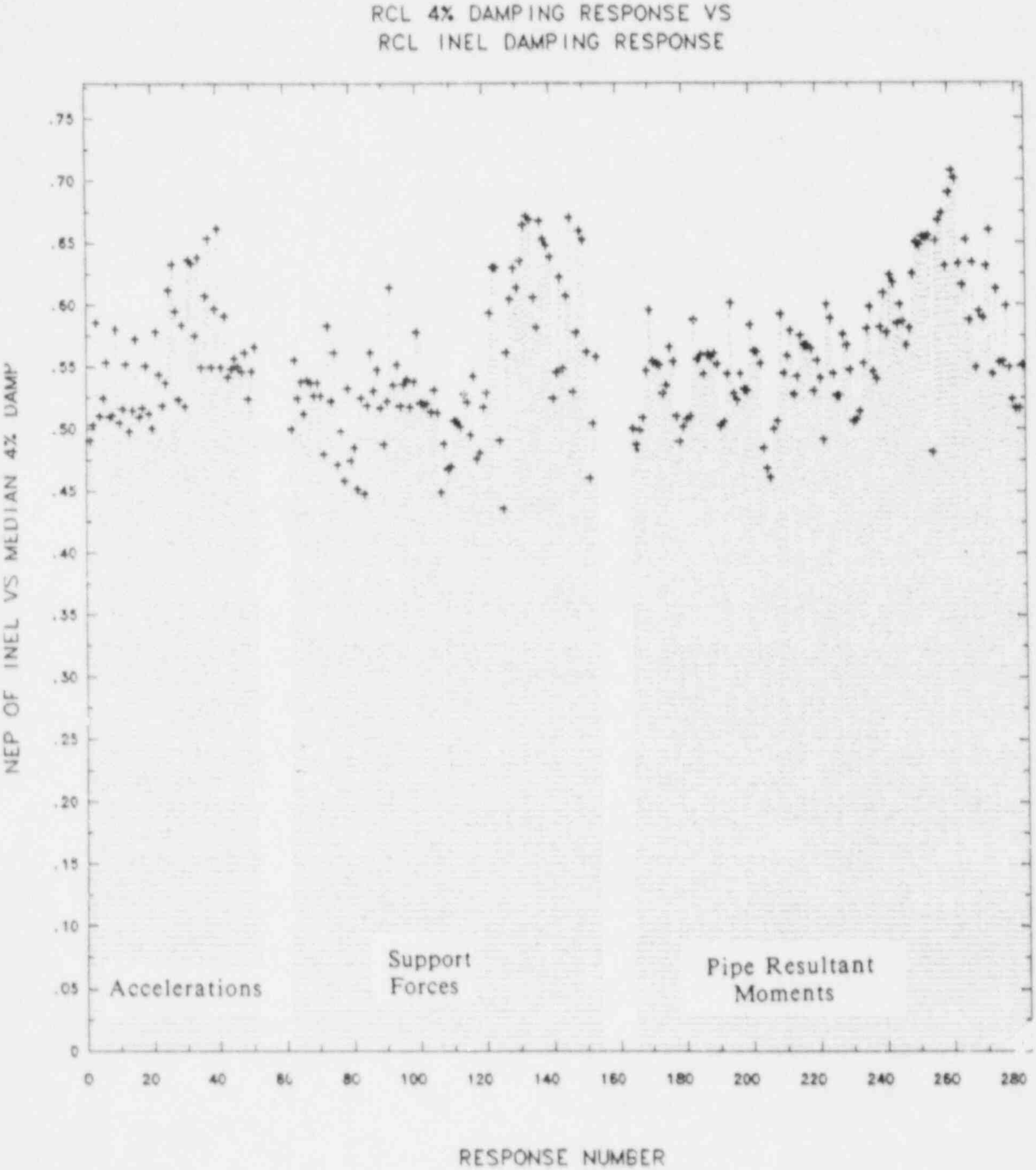
200
220
240
260
280


RCL 4% DAMPING RESPONSE VS
RCL INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 4% DAMP
RESPONSE NUMBER
Accelerations
Support
Forces
Pipe Resultant
Moments
.75
.70
.65
.60
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
0
0
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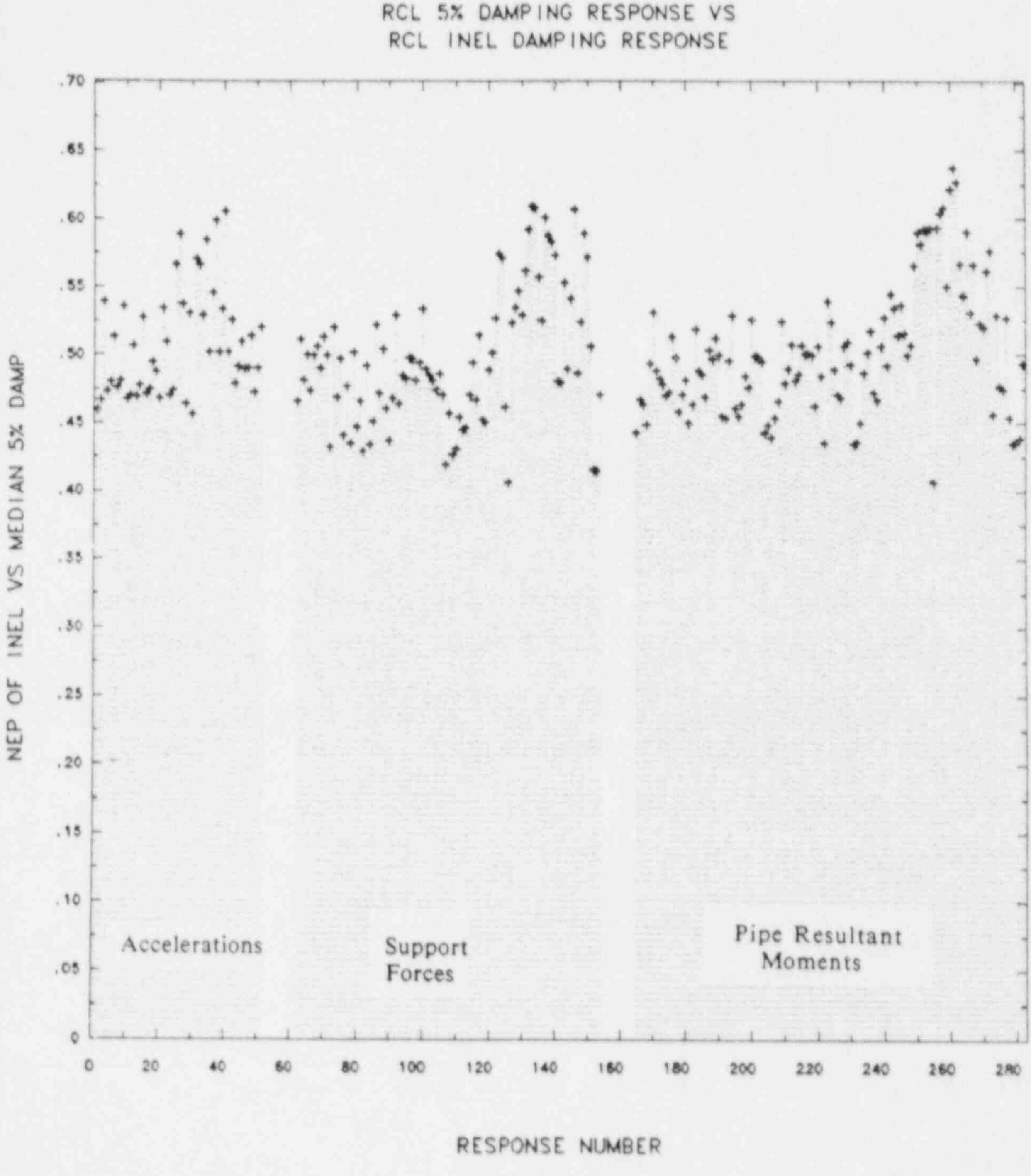
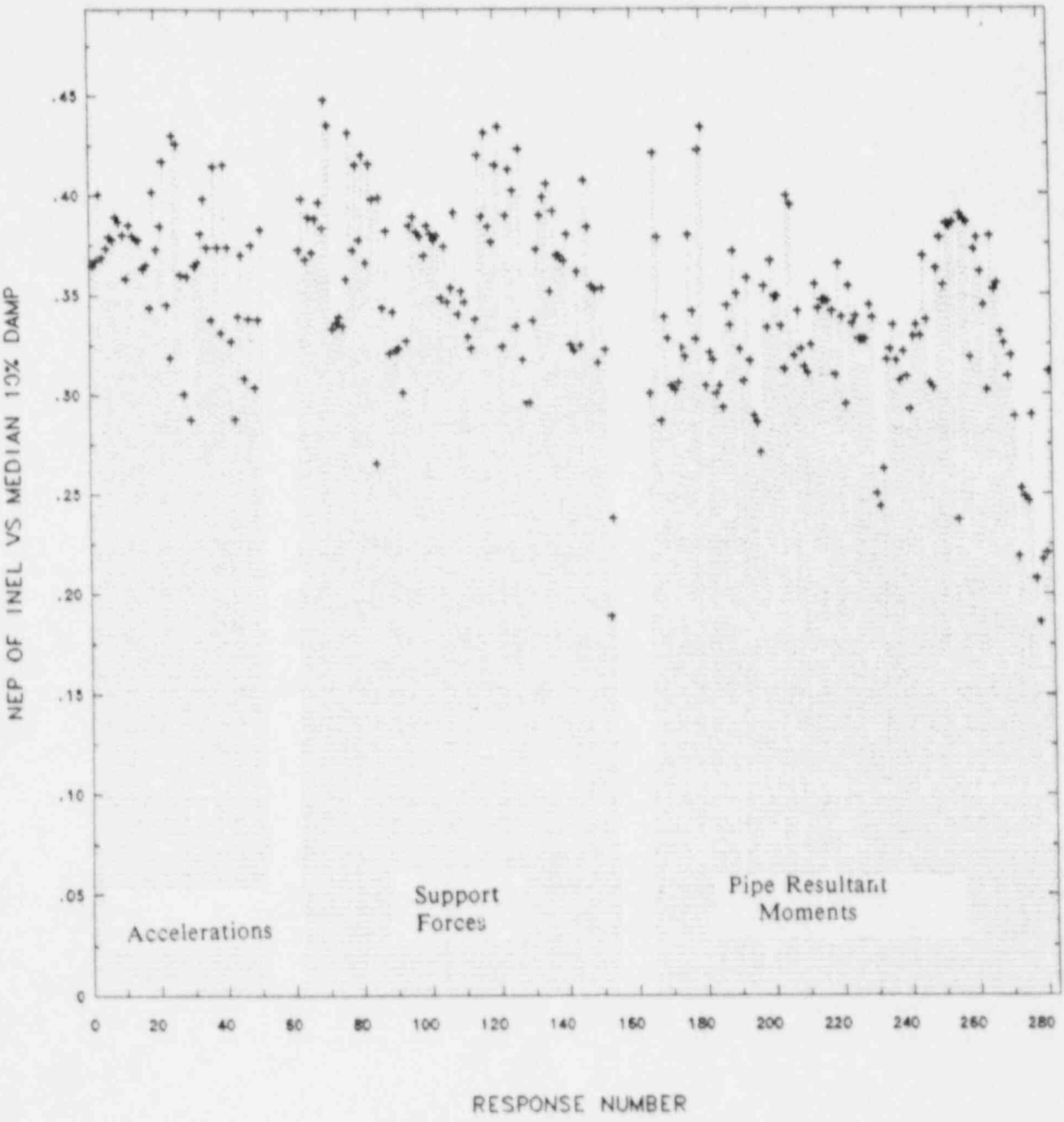
40
60
80
100
120
140
160
180
200
220
240
260
280

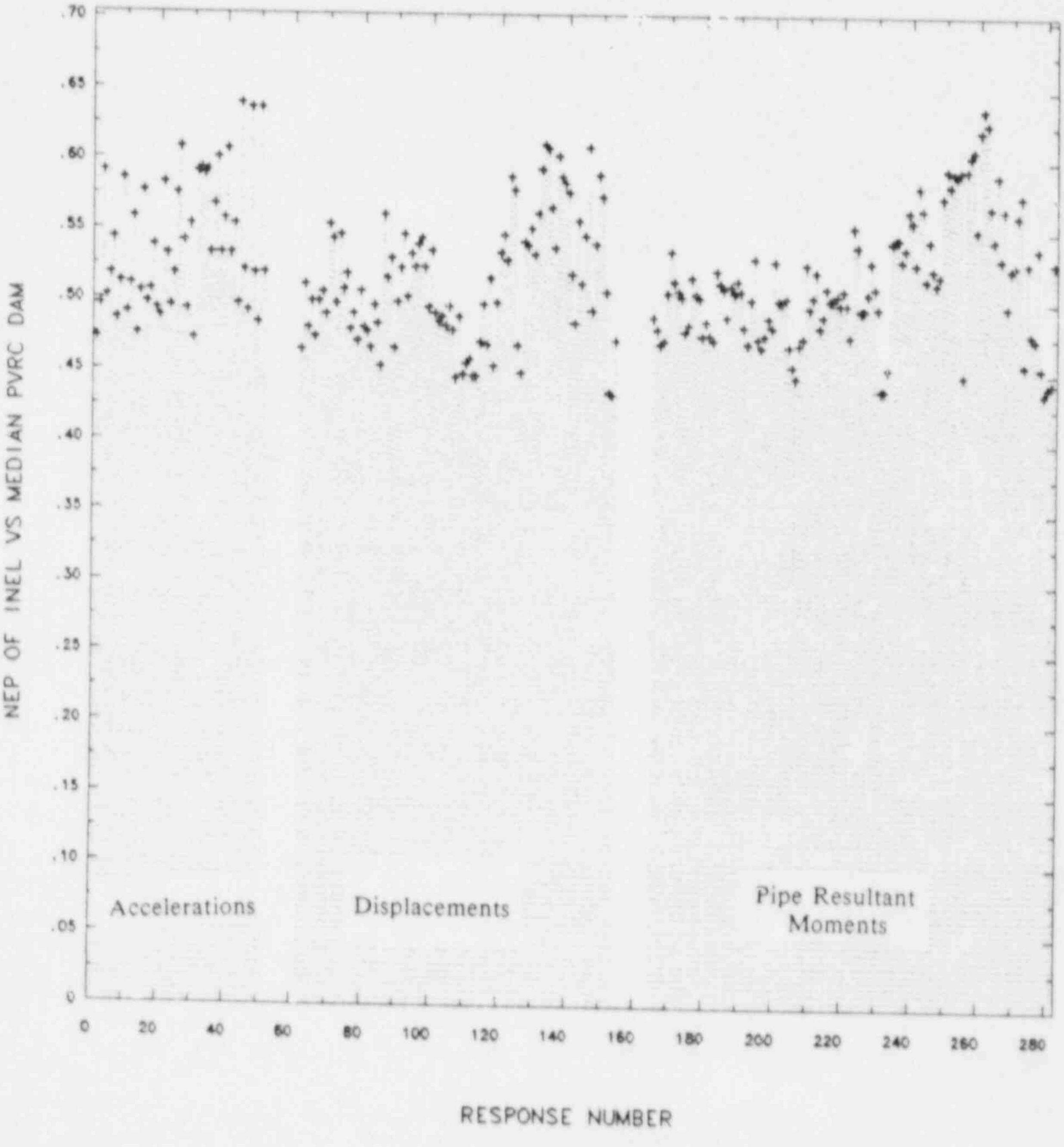


RCL 5% DAMPING RESPONSE VS
RCL INEL DAMPING RESPONSE
NEP OF INEL VS MEDIAN 5% DAMP
RESPONSE NUMBER
Accelerations
Support
Forces
Pipe Resultant
Moments

RCL 10% DAMPING RESPONSE VS
RCL INEL DAMPING RESPONSE



RCL PVRC DAMPING RESPONSE VS
RCL INEL DAMPING RESPONSE



Appendix B

Plots of Nonexceedance Probabilities for the Distribution of Best Estimate Responses

Appendix B contains plots that graphically illustrate the nonexceedance probabilities for all response quantities for each of the three piping systems considered in the study. In this Appendix, the basis for comparison is the distribution of INEL damping time history responses. For a given response quantity, e.g., a nodal acceleration, and a given analysis method, e.g., constant 1% damping time history analysis, the plotted value is the probability that an INEL damping response will not exceed the median response of the alternate analysis method.

For the AFW and RHR piping system models, nonexceedance probabilities for the following analysis methods are given:

- envelope response spectrum analysis using 2% damping
- envelope response spectrum analysis using PVRC damping
- independent support motion response spectrum analysis using 2% damping
- independent support motion response spectrum analysis using PVRC damping (RHR only)
- multi-support time history analysis using constant 1% damping
- multi-support time history analysis using constant 2% damping
- multi-support time history analysis using 4% constant damping
- multi-support time history analysis using 5% constant damping
- multi-support time history analysis using 10% constant damping
- multi-support time history analysis using PVRC damping

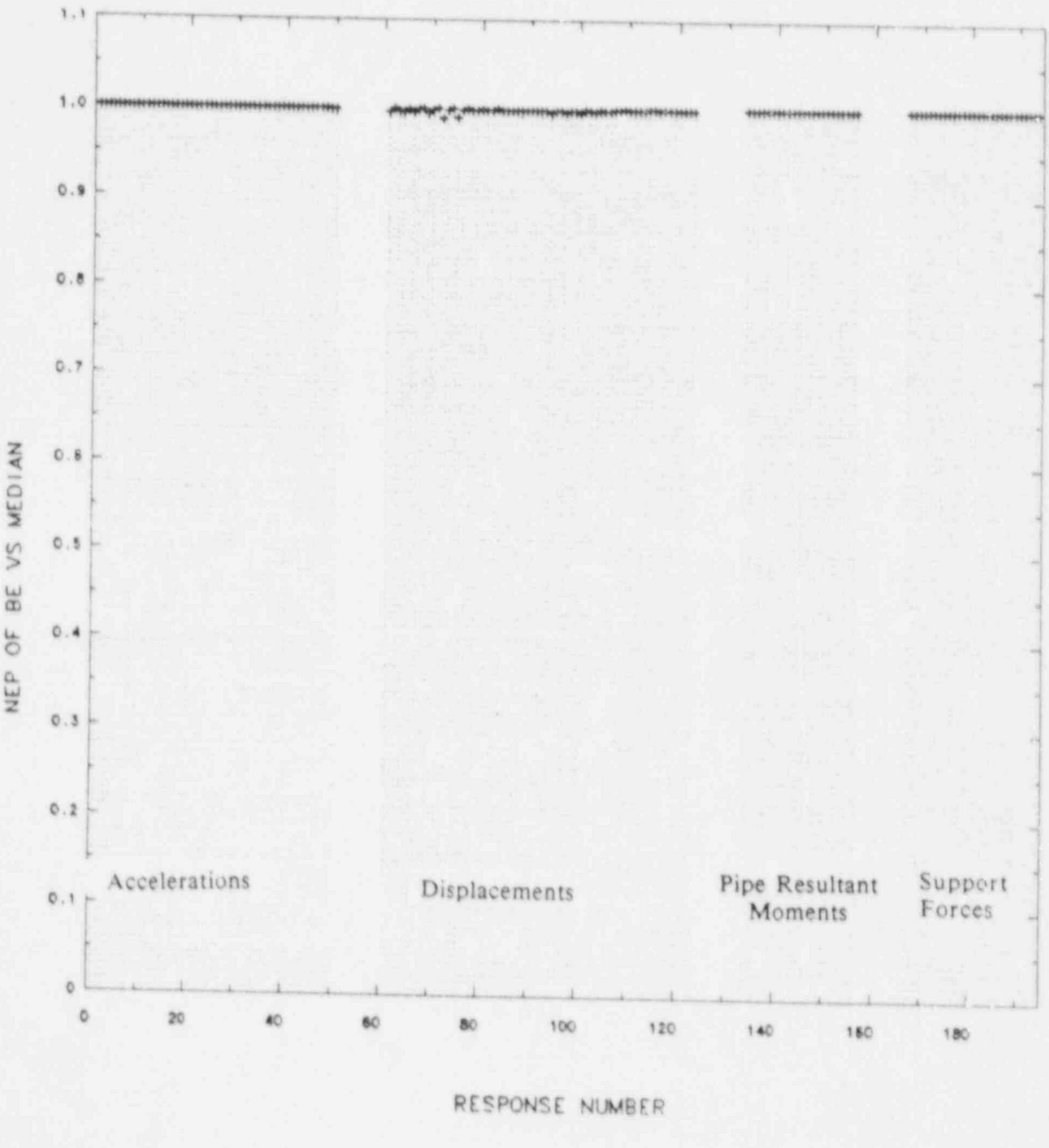
For the RCL piping system model, plots are given for the following analyses:

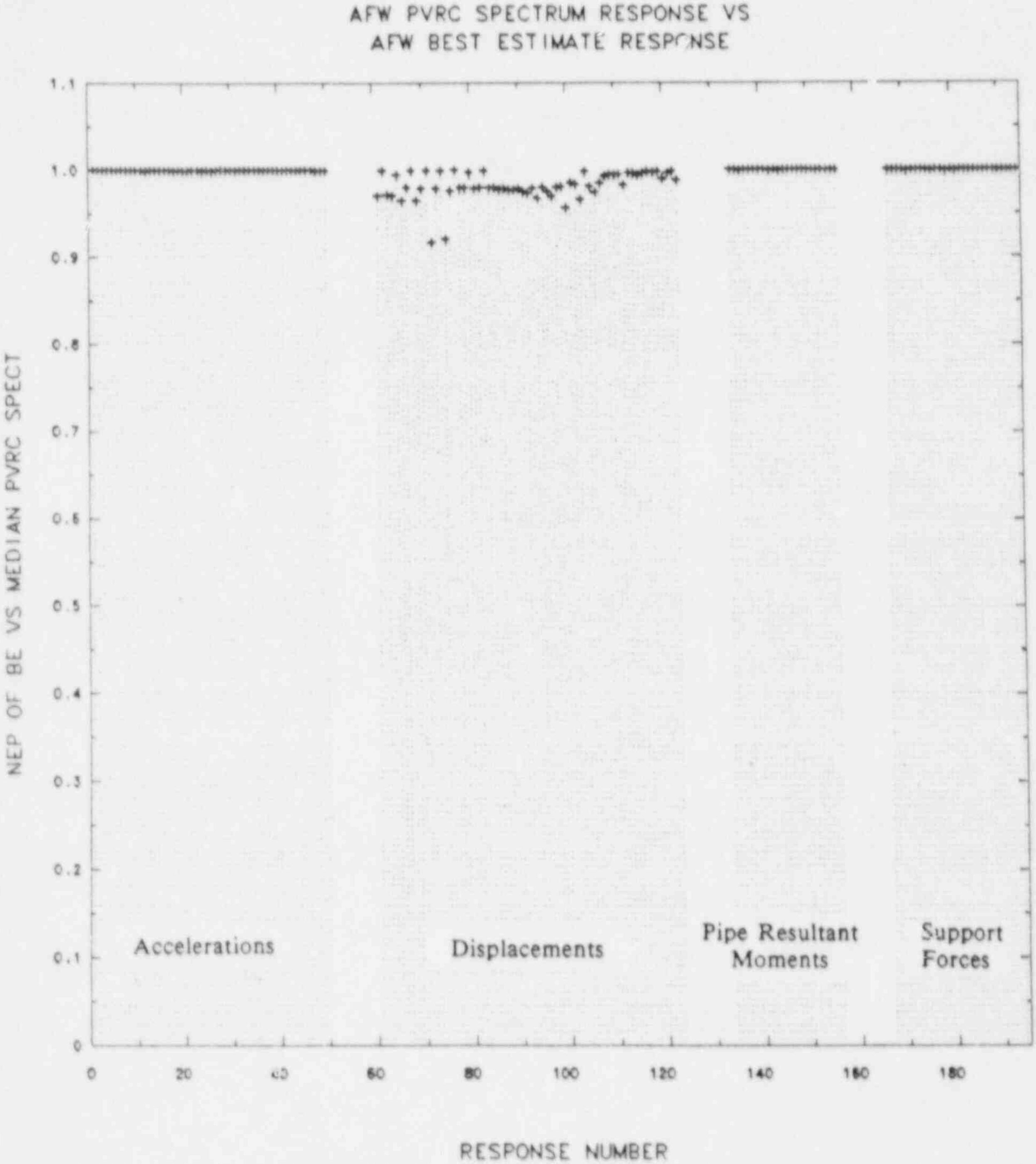
- envelope response spectrum analysis using 2% damping
- envelope response spectrum analysis using PVRC damping
- multi-support time history analysis using constant 2% damping
- multi-support time history analysis using constant 3% damping
- multi-support time history analysis using 4% constant damping
- multi-support time history analysis using 5% constant damping
- multi-support time history analysis using 10% constant damping
- multi-support time history analysis using PVRC damping

The data is presented in a format that has been used in previous reports. Each plot shows the data for all response quantities calculated for a piping system model by a given analysis method. The response quantities for the AFW and RHR piping system models and the order in which they appear on a plot are nodal accelerations, nodal displacements, piping element resultant moments, support forces. For the RCL piping system model, the order of response quantities is nodal accelerations, support forces, piping element resultant moments.

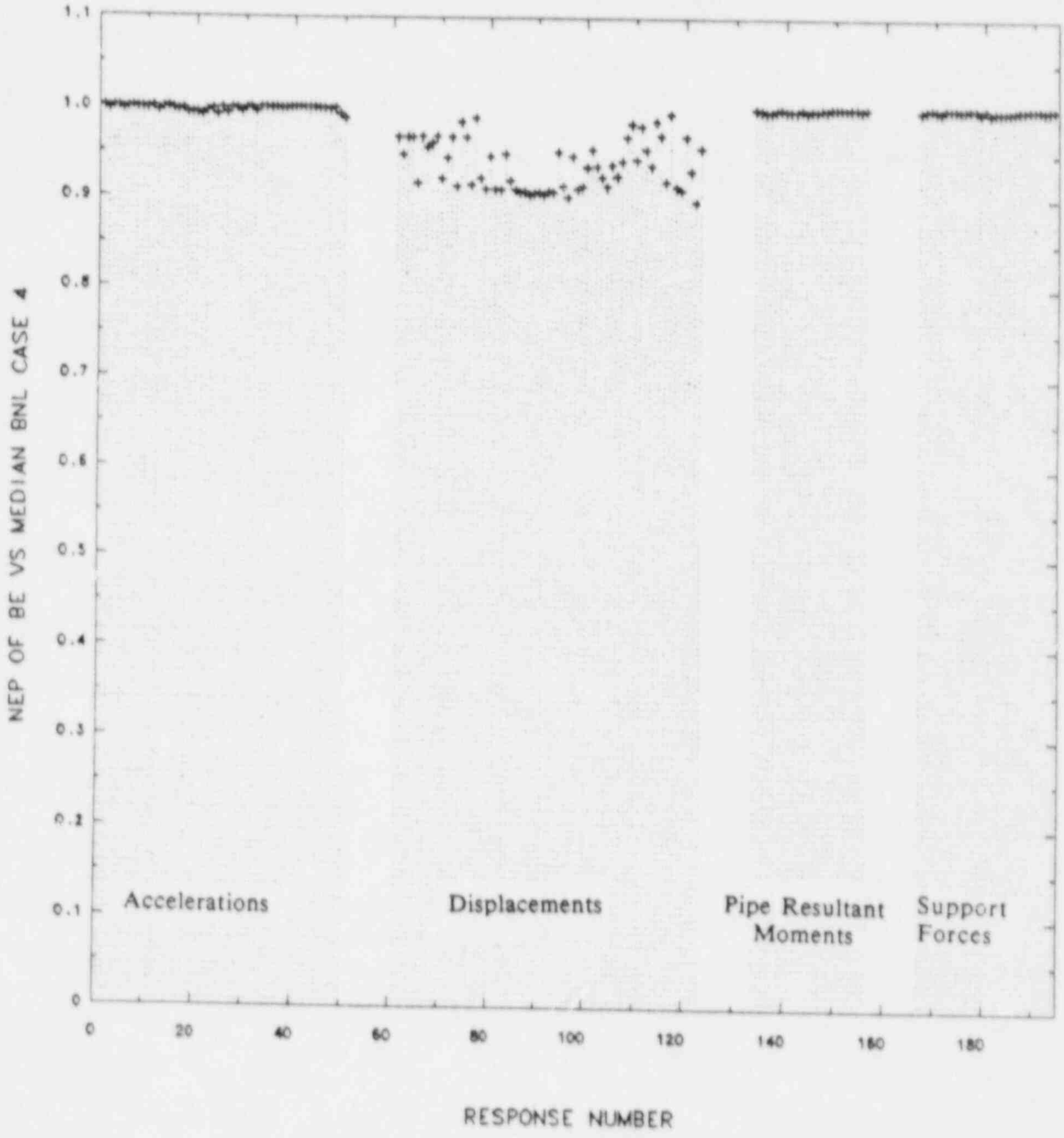
AFW Piping System Model

AFW(2%) SPECTRUM RESPONSE VS
AFW BEST ESTIMATE RESPONSE

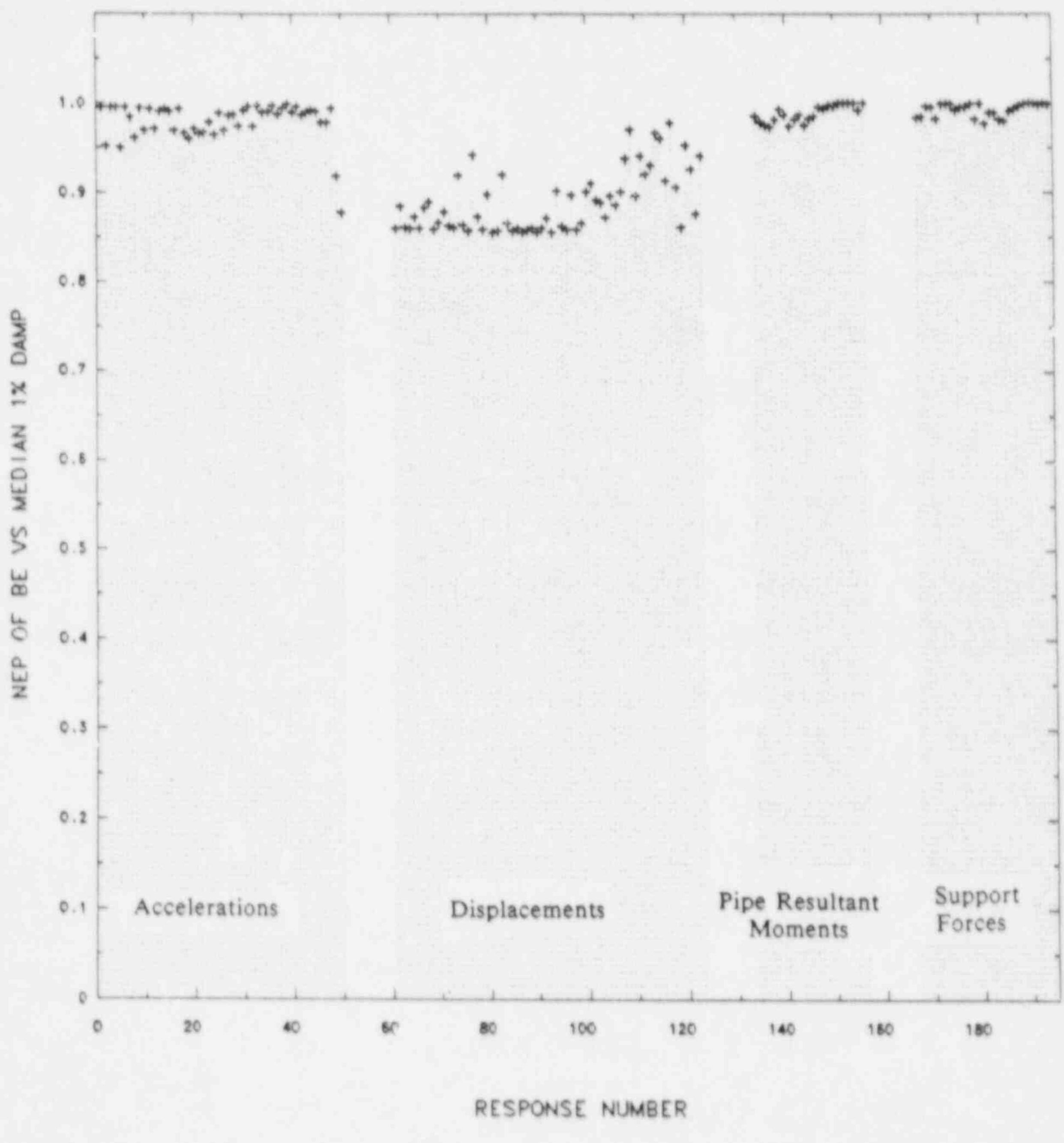


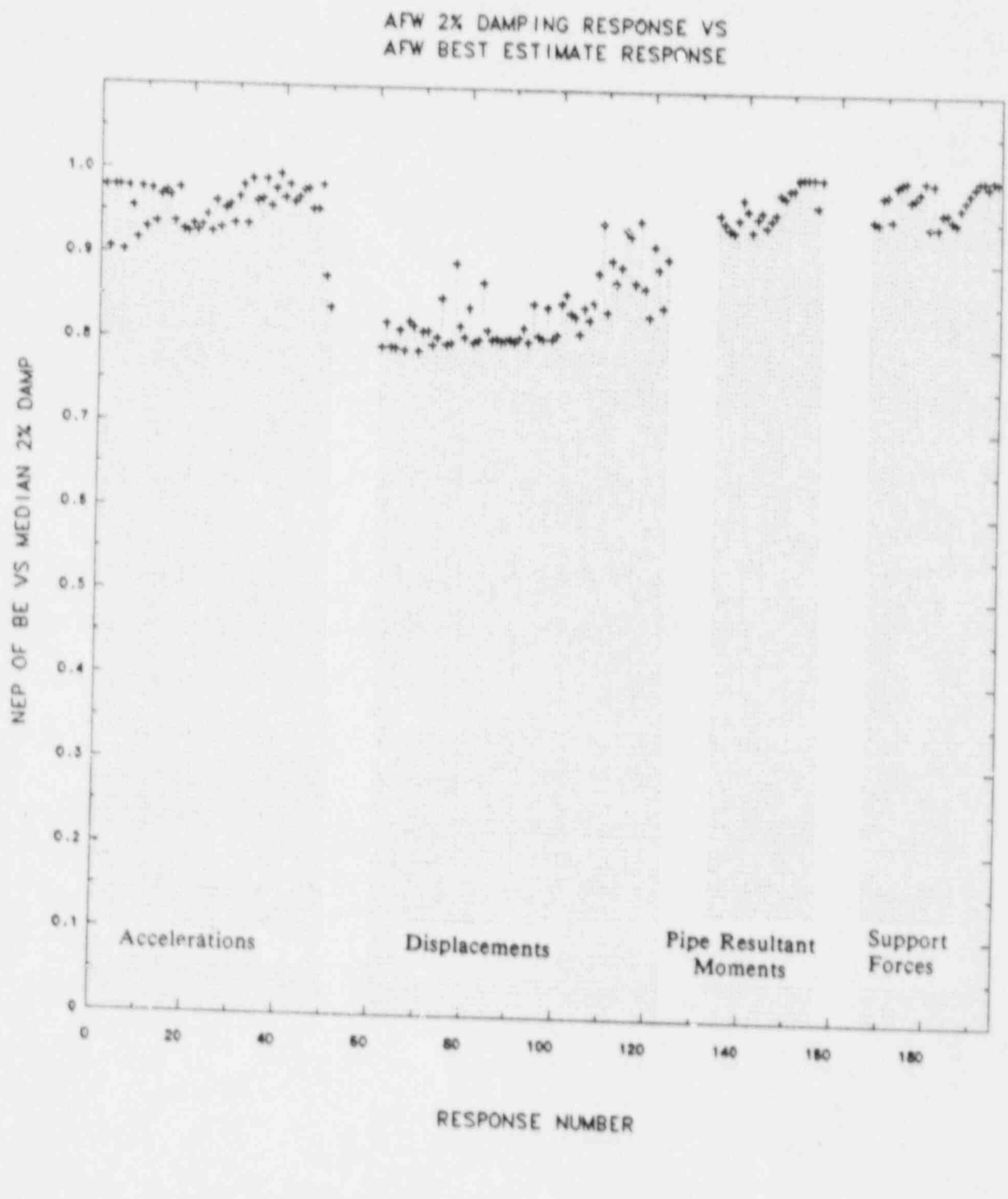

AFW PVRC SPECTRUM RESPONSE VS
AFW BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN PVRC SPECT
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant
Moments
Support
Forces
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
60
80
100
120
140
180

AFW BNL ISM/SRSS(2%) VS
AFW BEST ESTIMATE RESPONSE

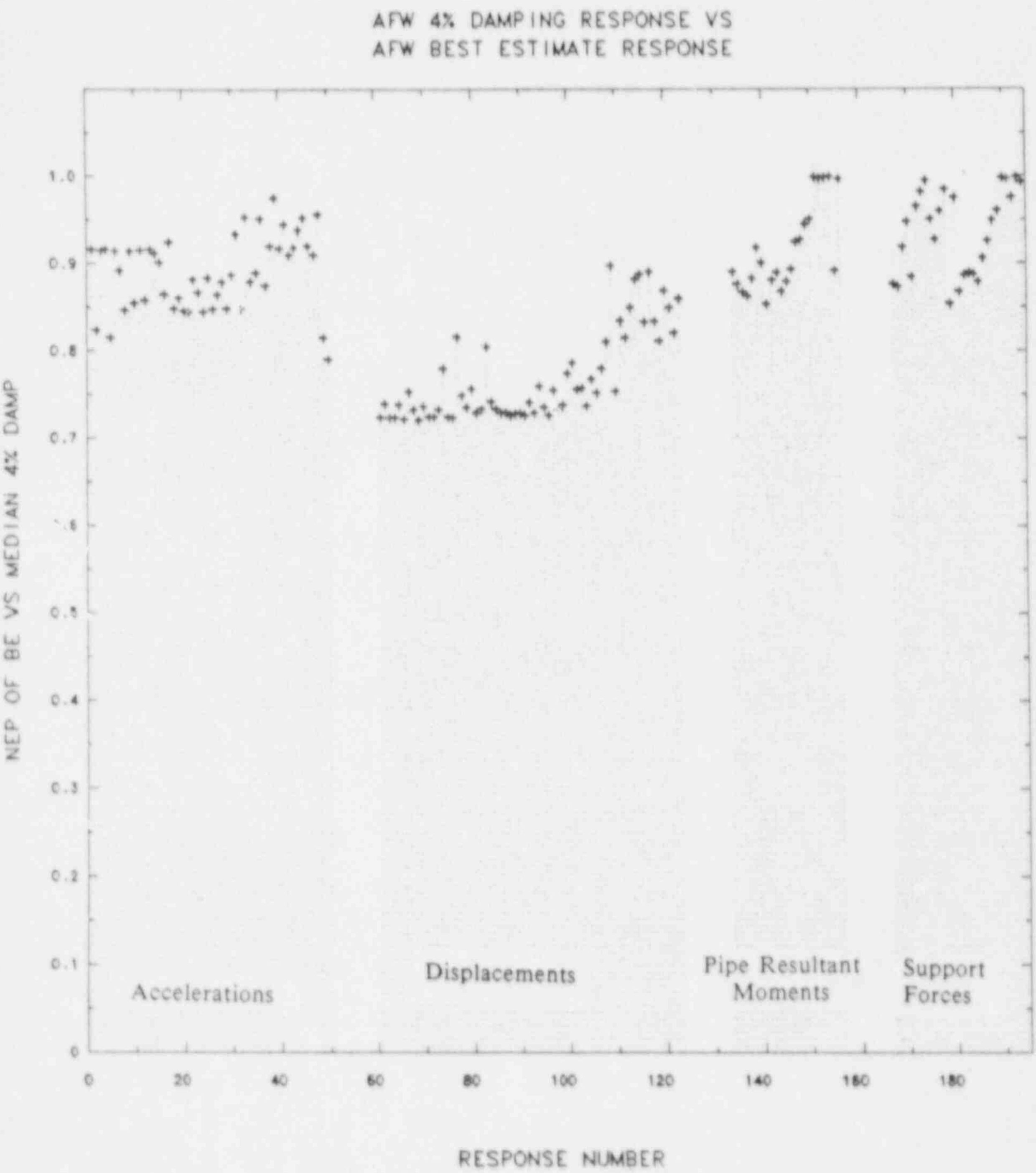


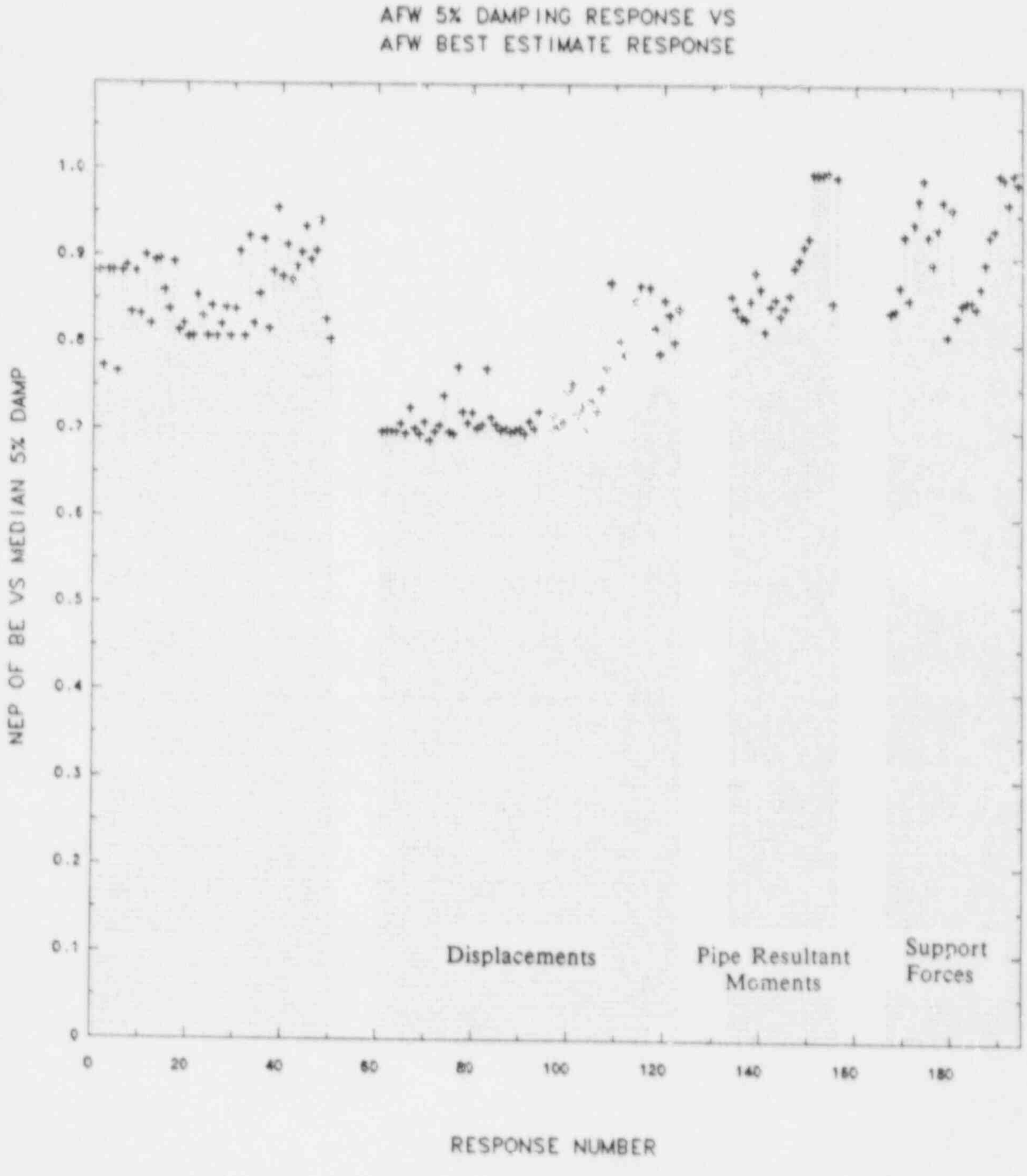
AFW 1% DAMPING RESPONSE VS
AFW BEST ESTIMATE RESPONSE

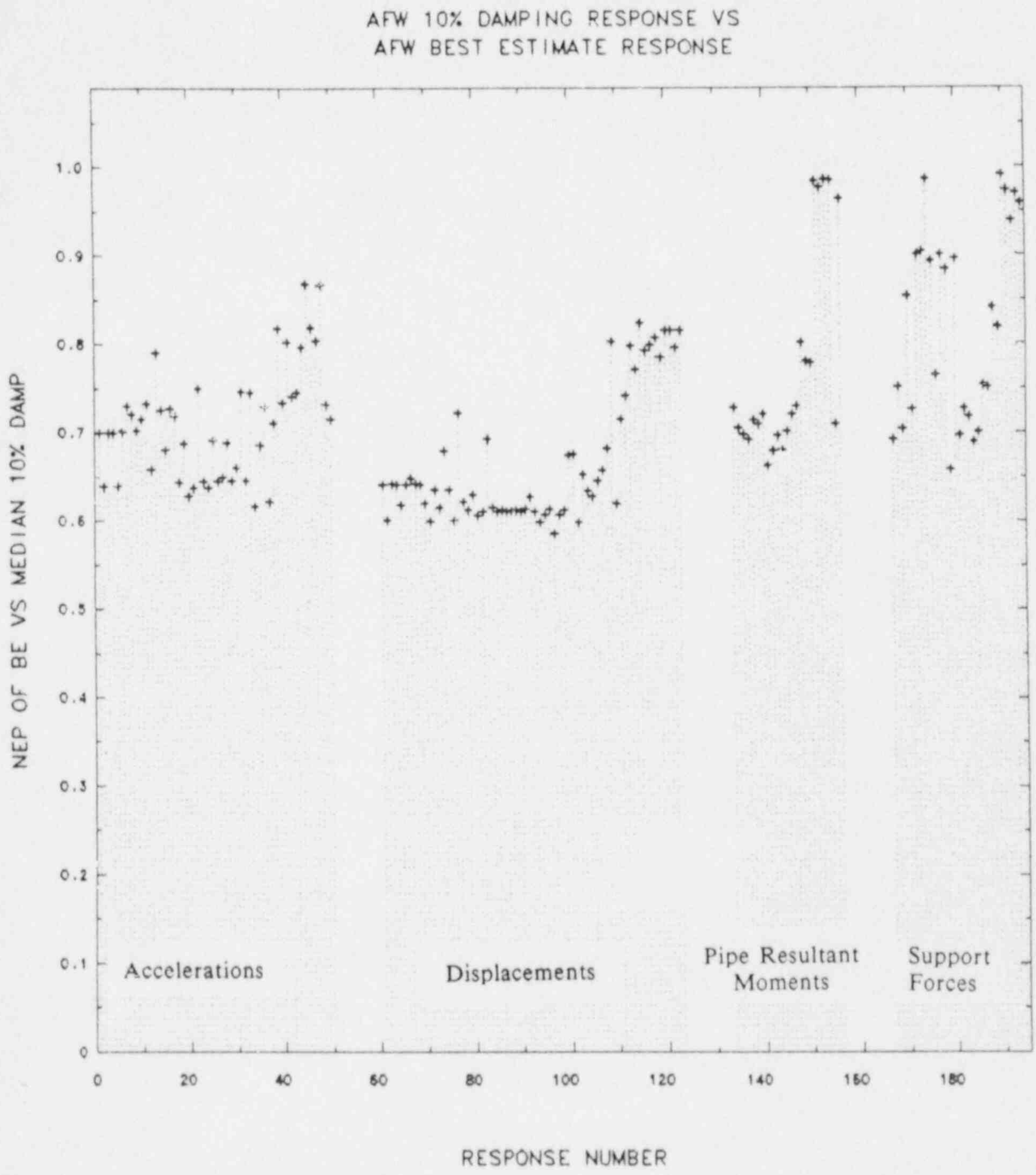


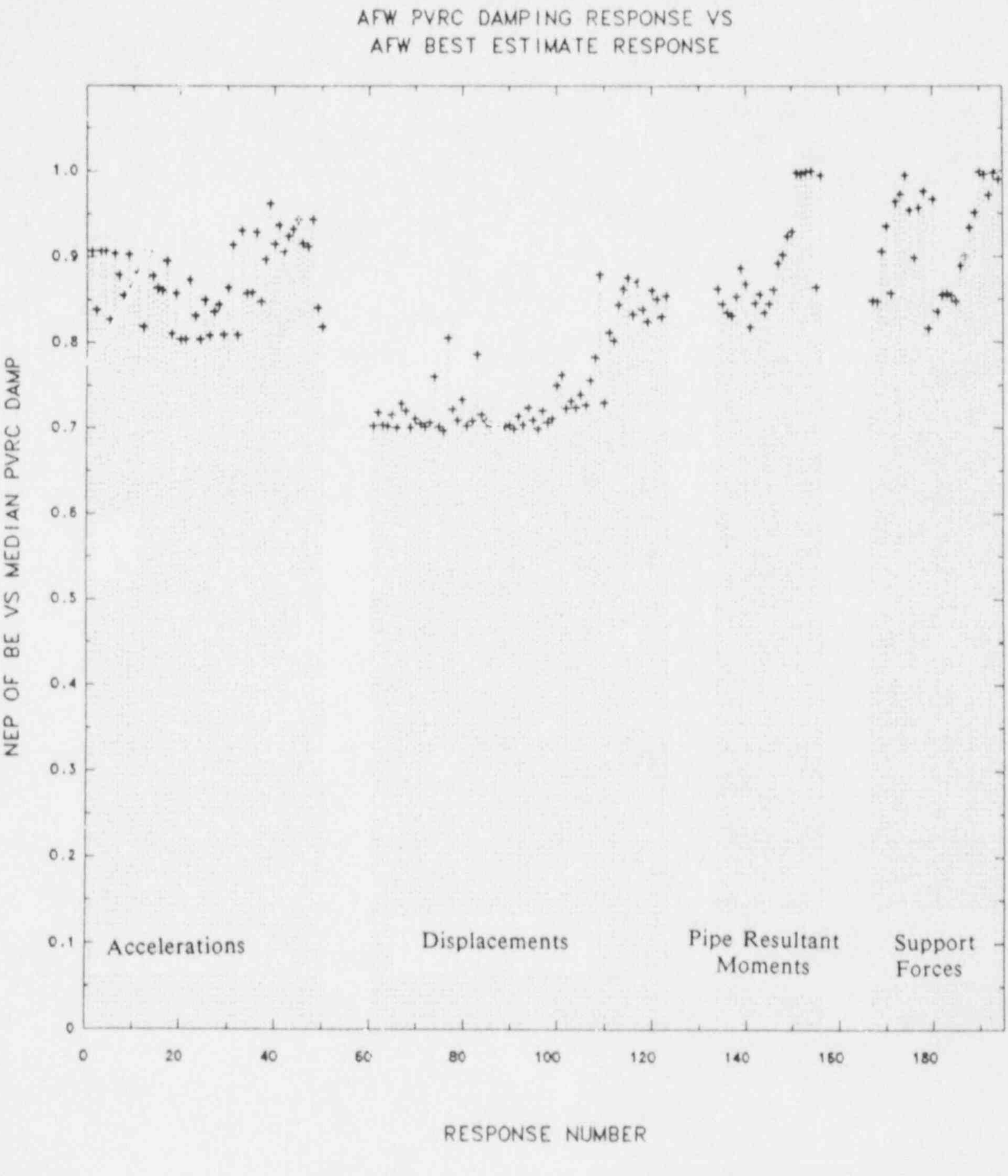


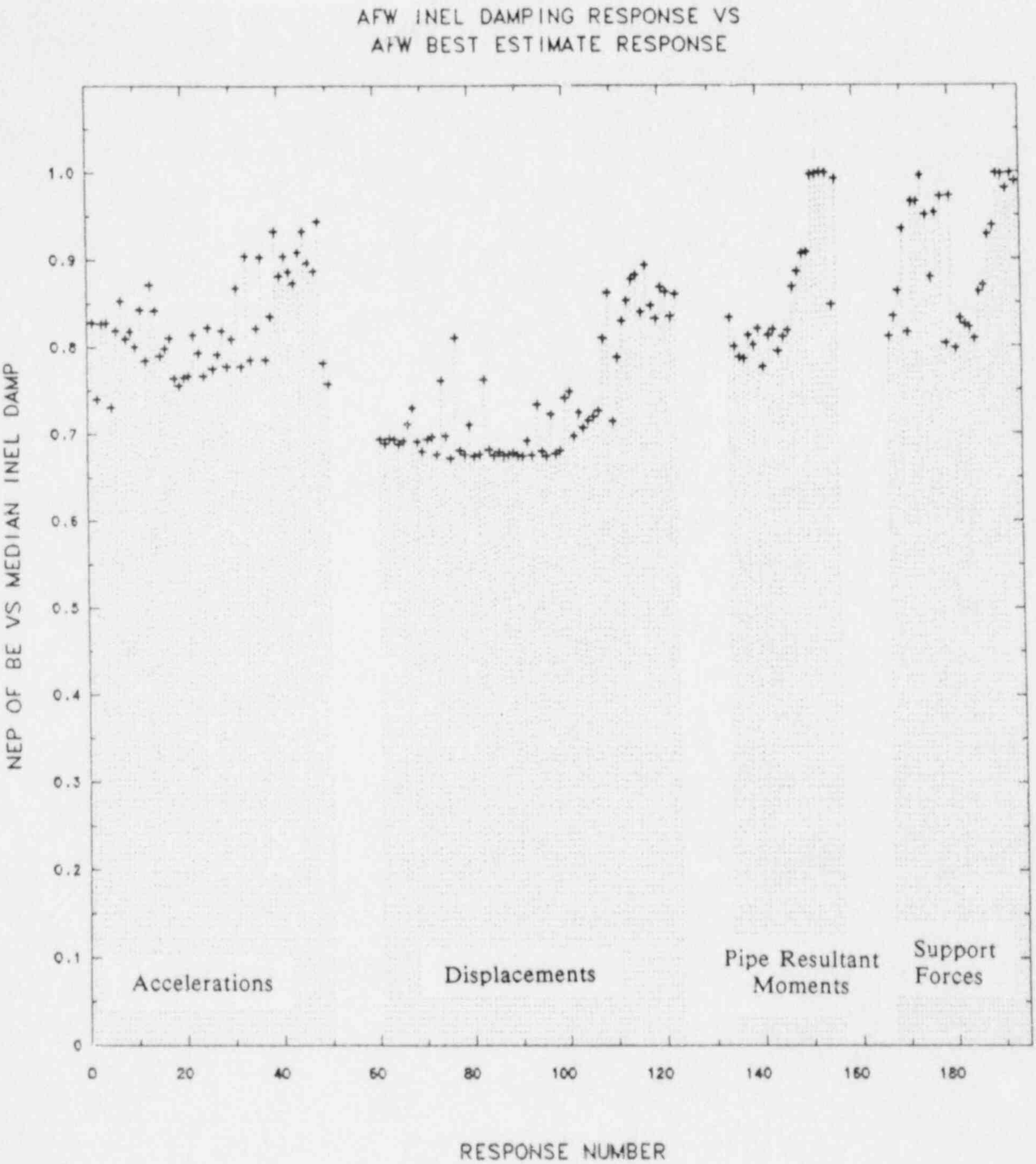
AFW 2% DAMPING RESPONSE VS
AFW BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 2% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces


AFW 4% DAMPING RESPONSE VS
AFW BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 4% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces


AFW 5% DAMPING RESPONSE VS
AFW BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 5% DAMP
RESPONSE NUMBER
Displacements
Pipe Resultant Moments
Support Forces
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
180

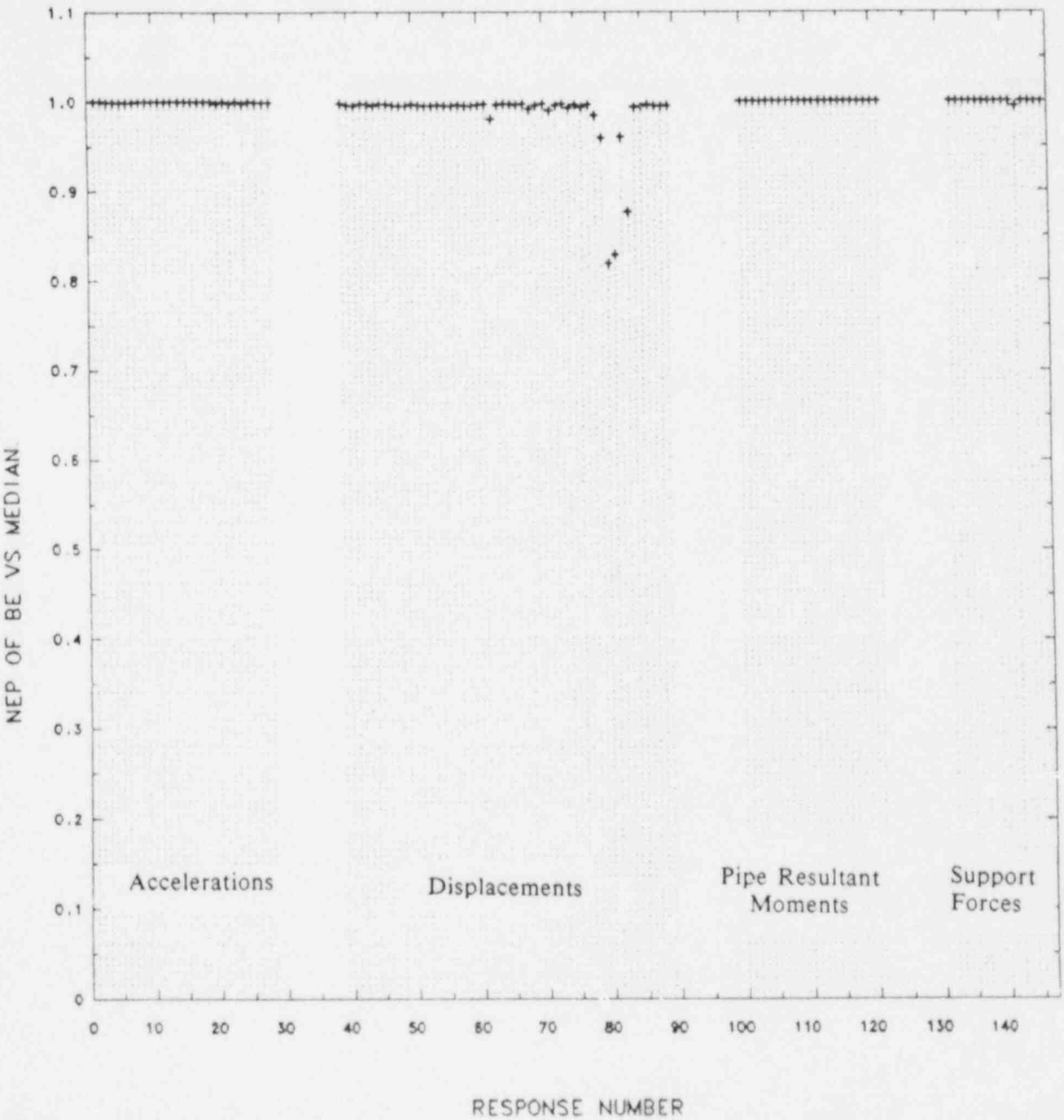

AFW 10% DAMPING RESPONSE VS
AFW BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 10% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces

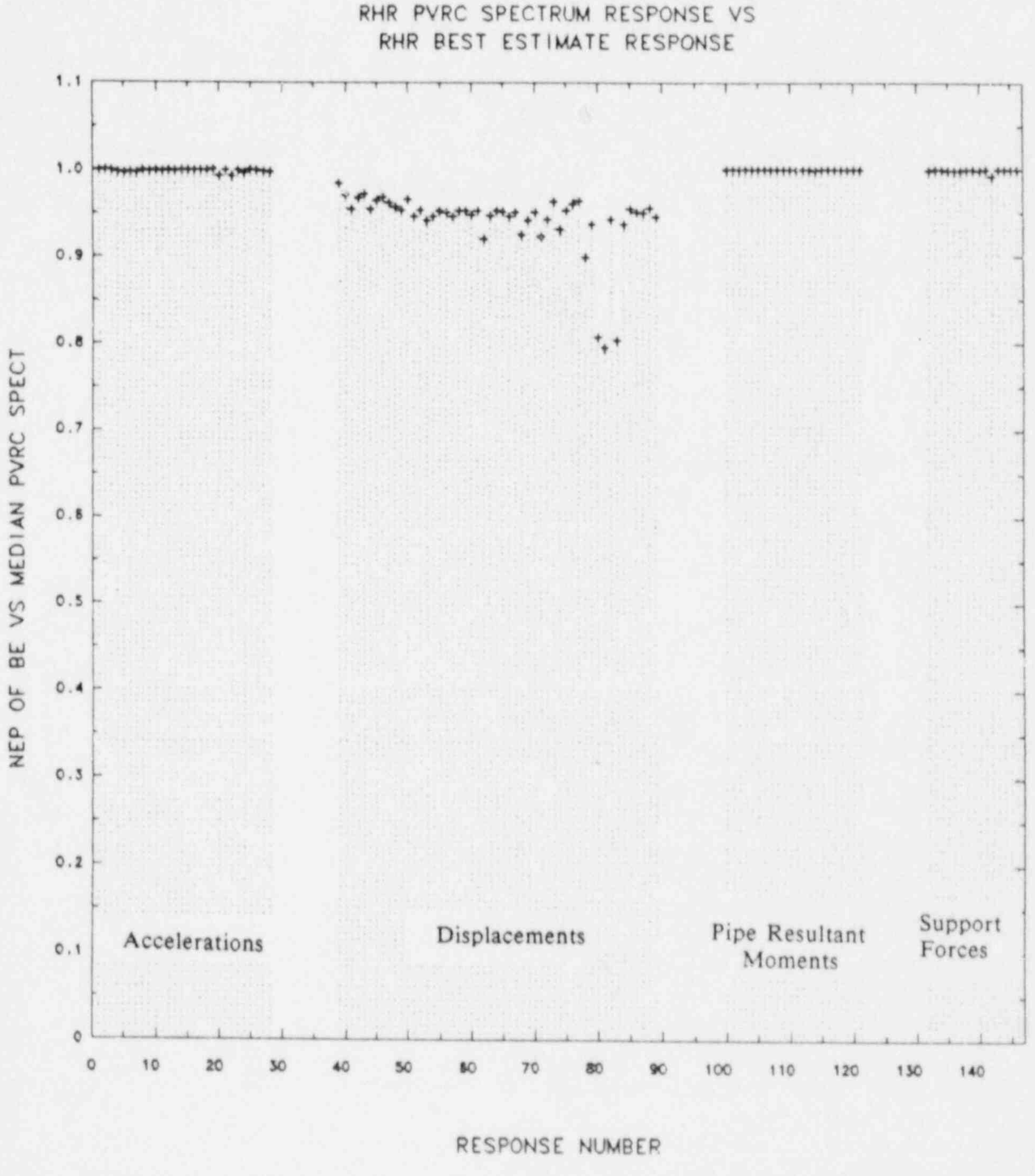

AFW PVRC DAMPING RESPONSE VS
AFW BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN PVRC DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
20
40
60
80
100
120
140
160
180


AFW INEL DAMPING RESPONSE VS
AFW BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN INEL DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
20
40
60
80
100
120
140
160
180

RHR Piping System Model

RHR(2%) SPECTRUM RESPONSE VS
RHR BEST ESTIMATE RESPONSE

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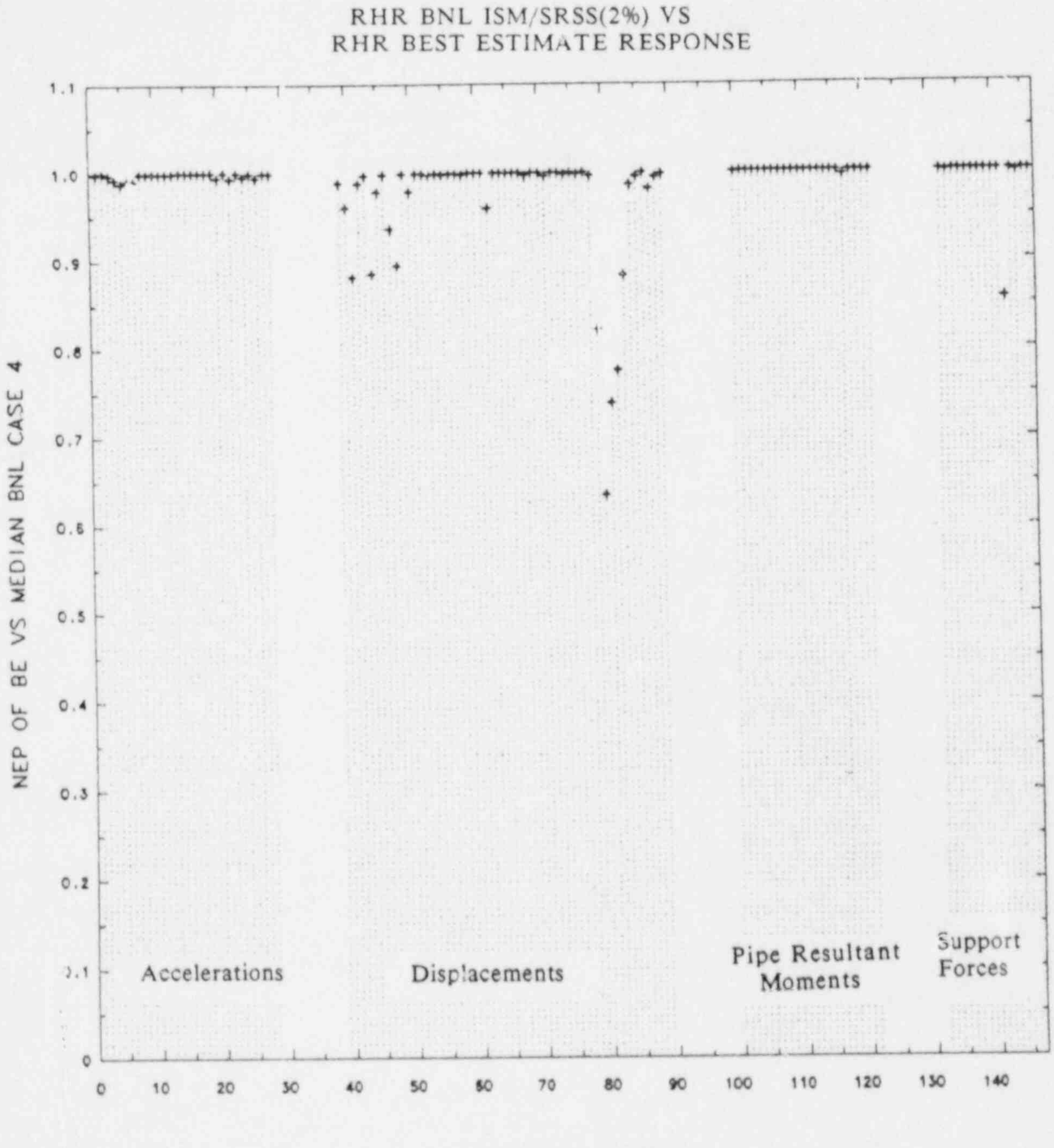
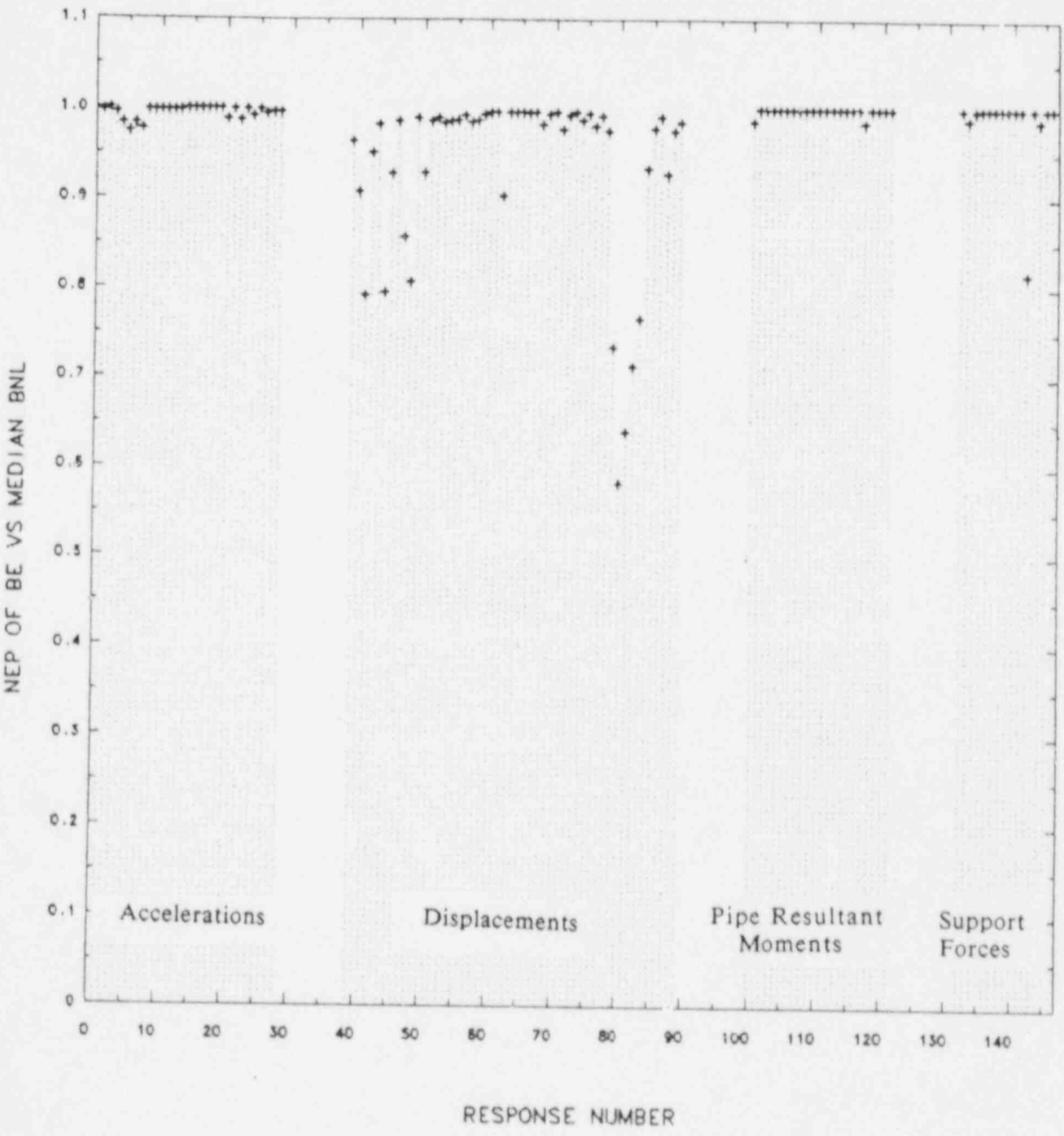
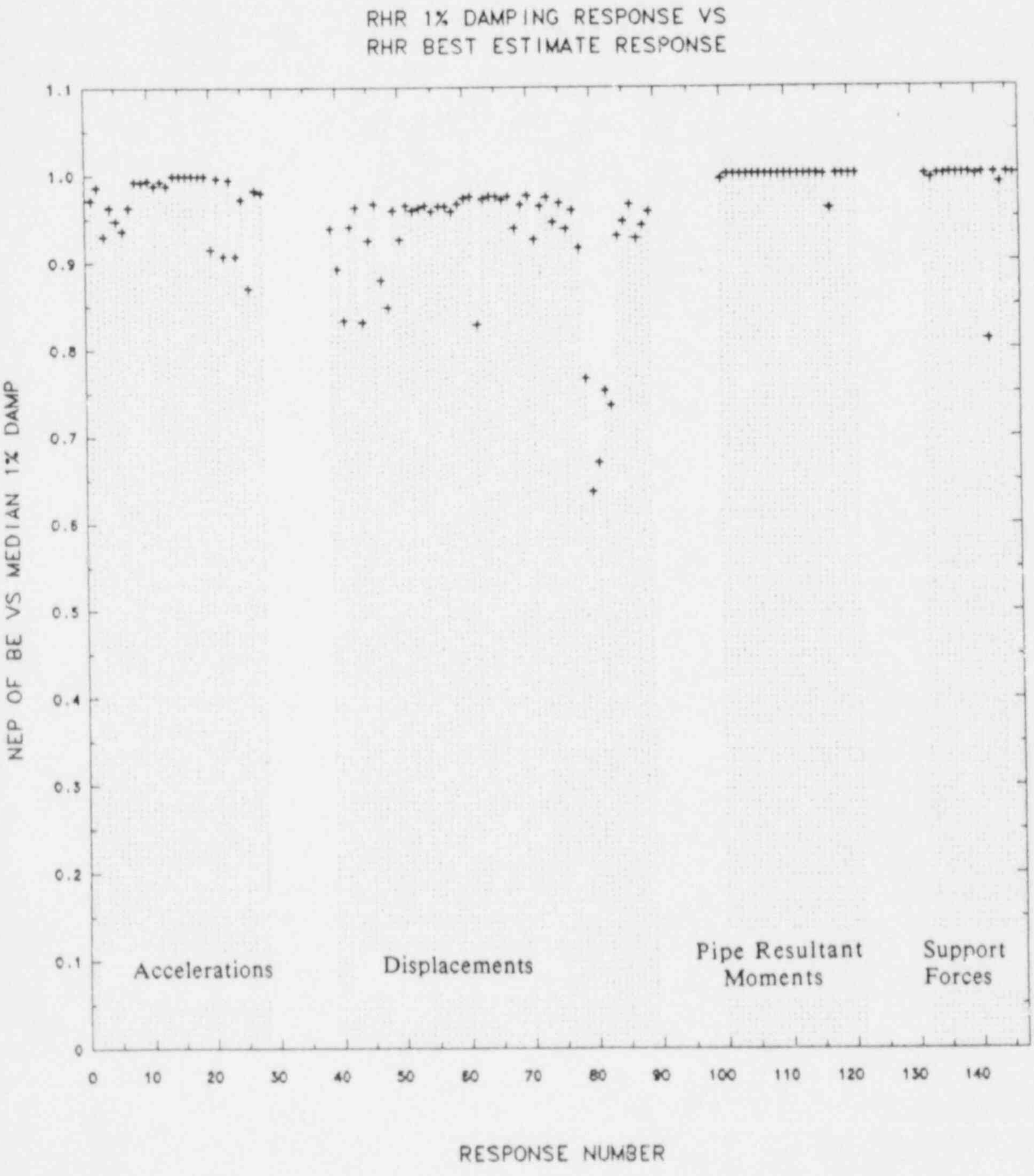
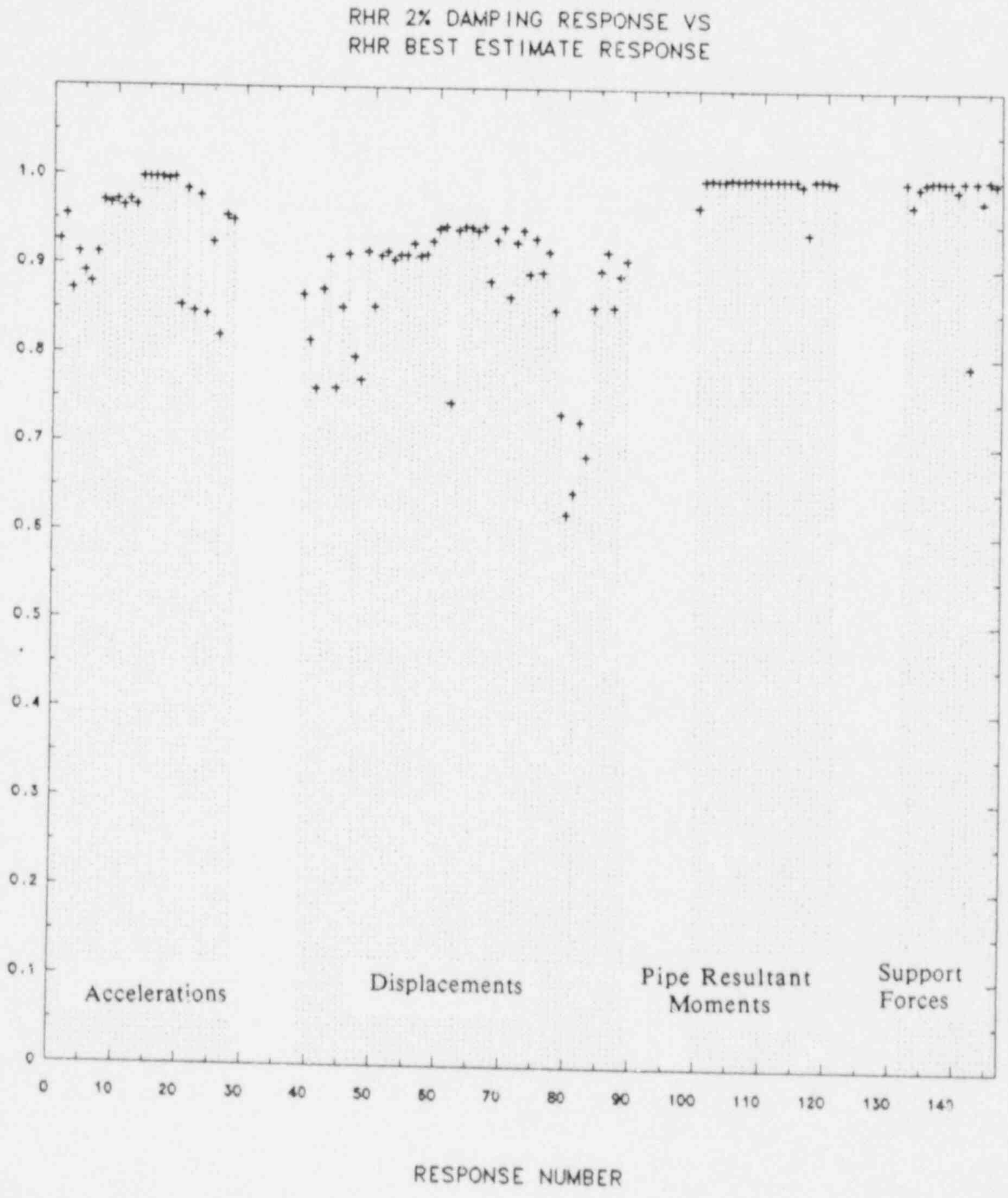
NEP OF BE VS MEDIAN PVRC SPECT
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces


RHR BNL ISM/SRSS(2%) VS
RHR BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN BNL CASE 4
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant
Moments
Support
Forces

RHR BNL ISM/SRSS(PVRC) VS
RHR BEST ESTIMATE RESPONSE

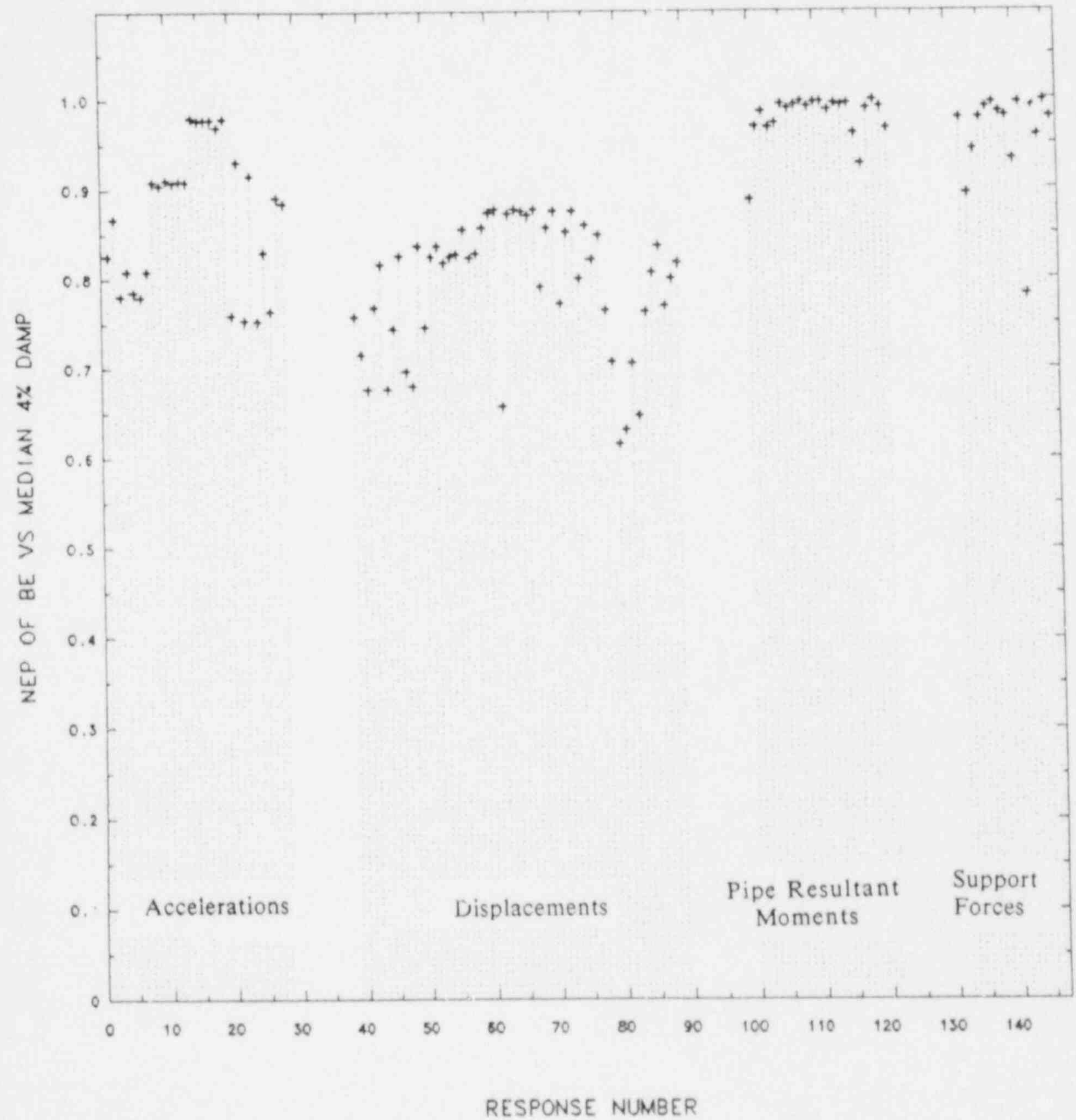


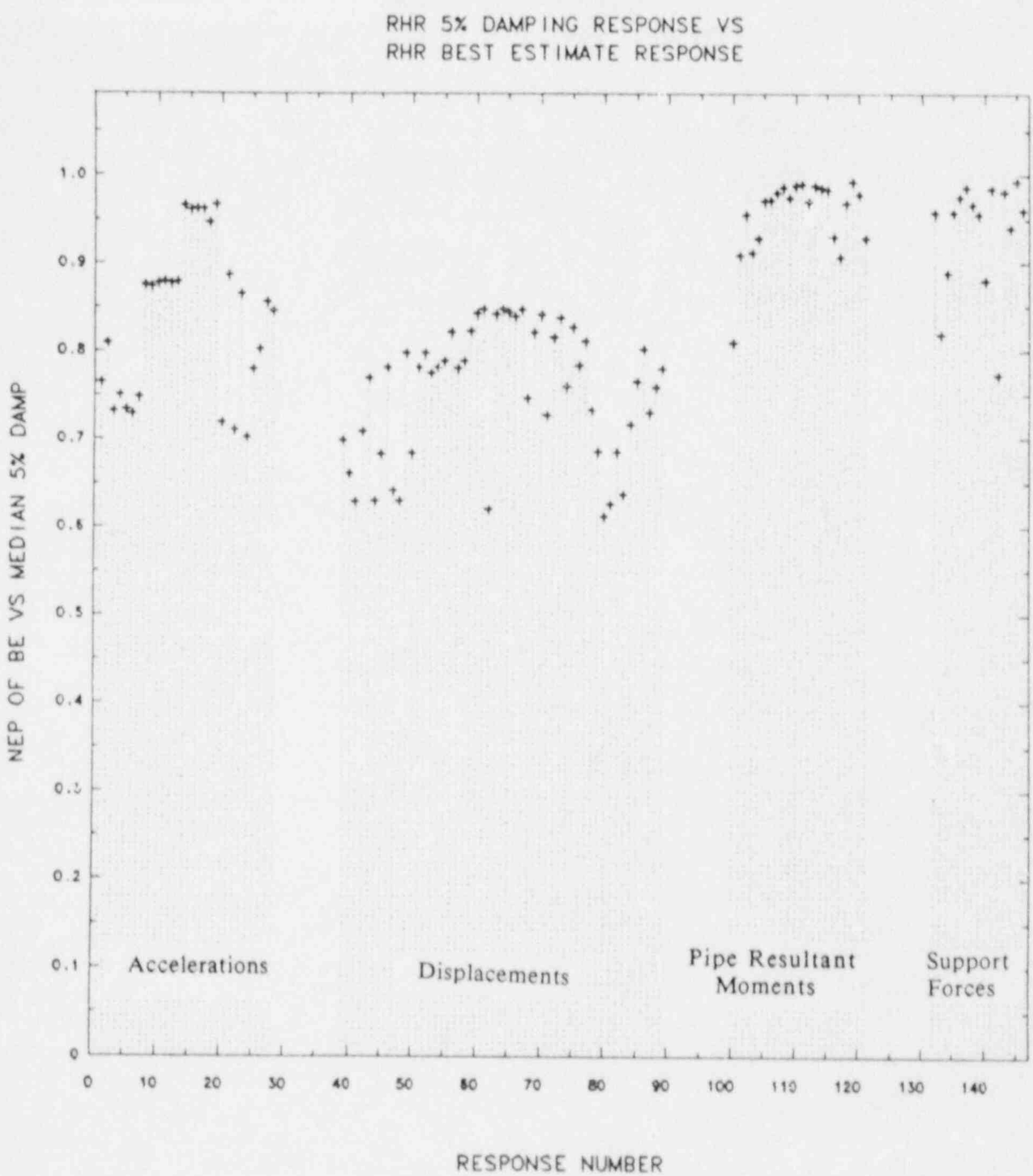

RHR 1% DAMPING RESPONSE VS
RHR BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 1% DAMP
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Accelerations
Displacements
Pipe Resultant Moments
Support Forces
RESPONSE NUMBER



RHR 2% DAMPING RESPONSE VS
RHR BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 2% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces

RHR 4% DAMPING RESPONSE VS
RHR BEST ESTIMATE RESPONSE




RHR 5% DAMPING RESPONSE VS
RHR BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 5% DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
10
20
30
40
50
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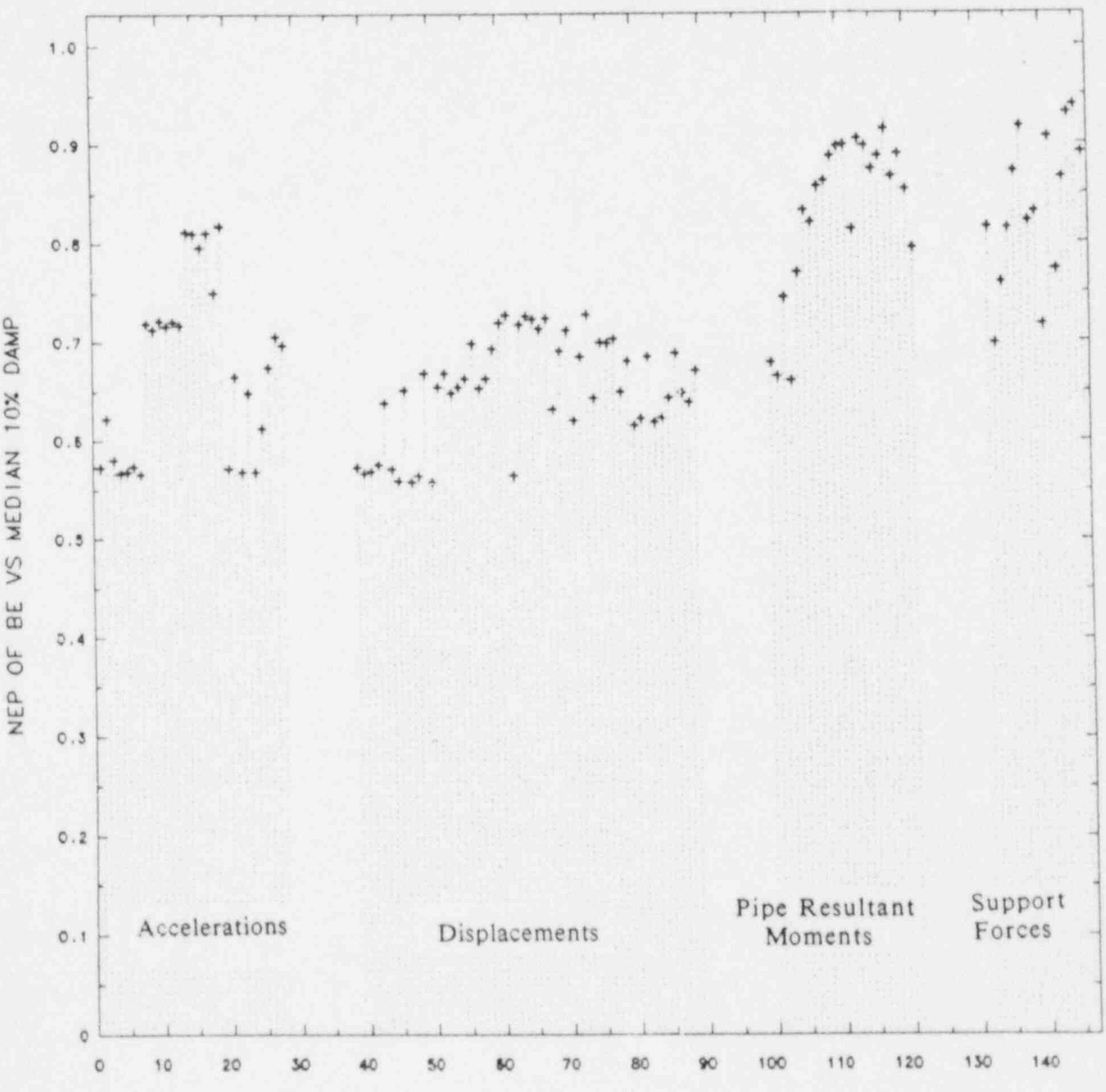
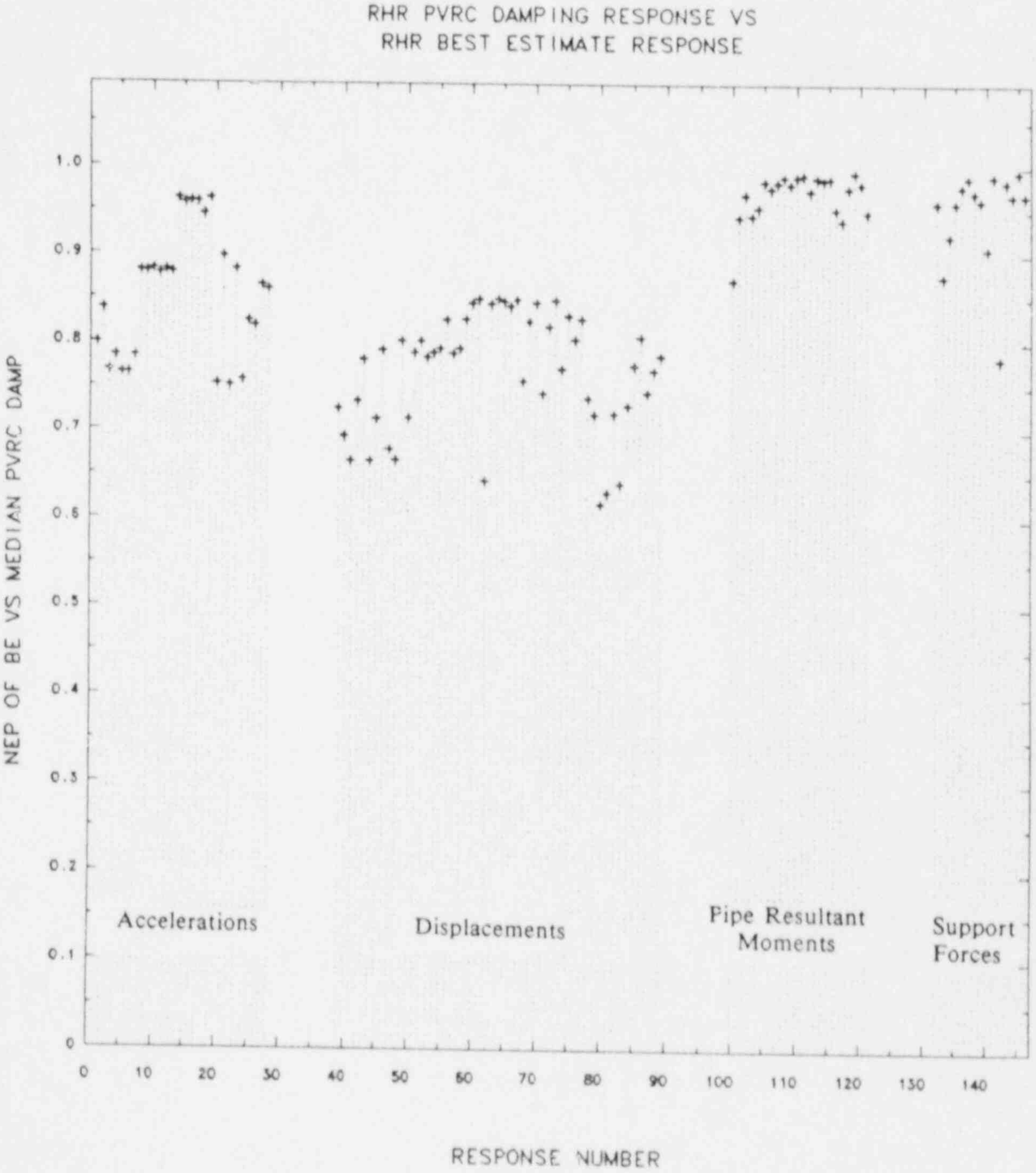
80
90
100
110
120
130
140

RHR 10% DAMPING RESPONSE VS
RHR BEST ESTIMATE RESPONSE

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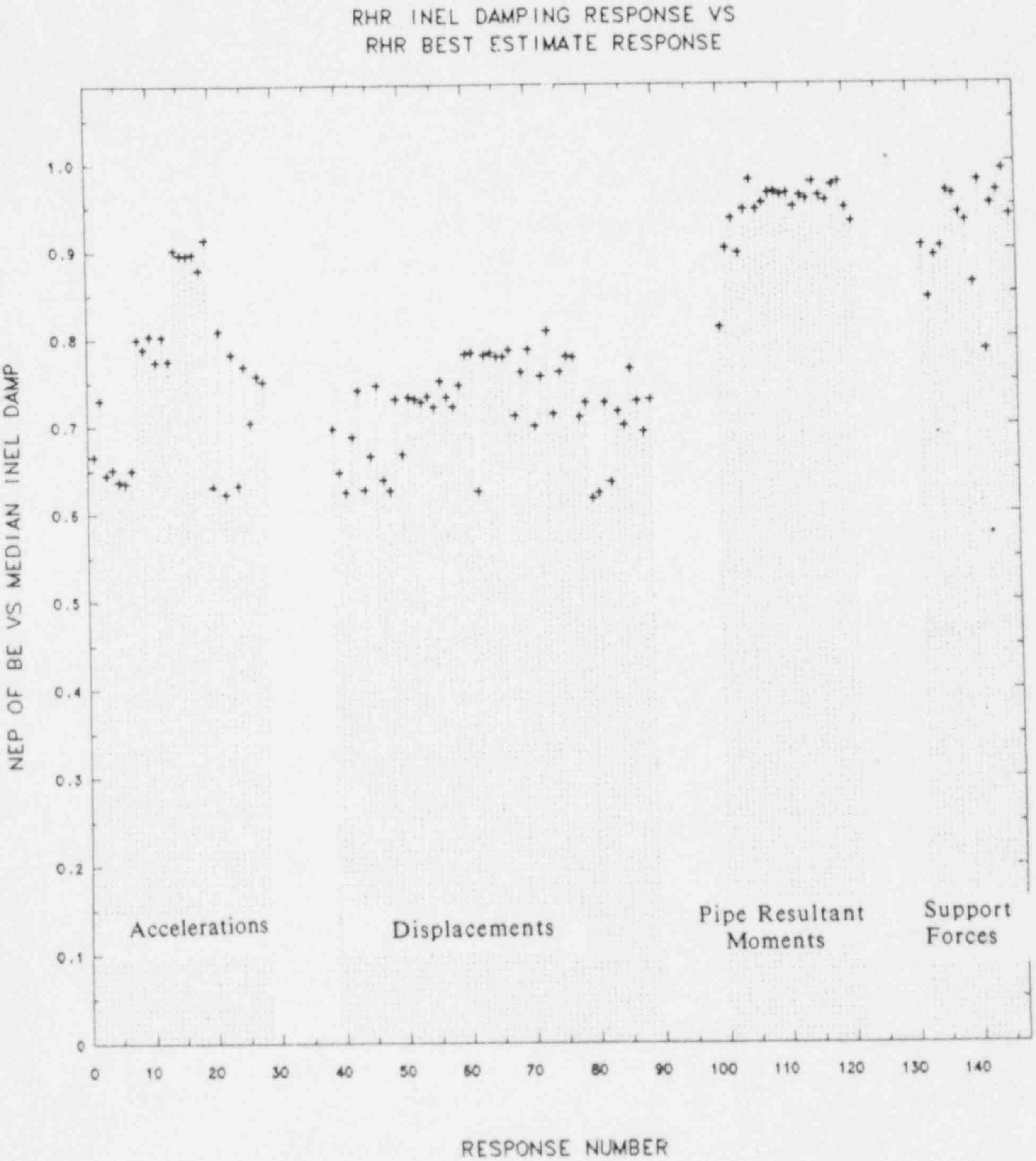
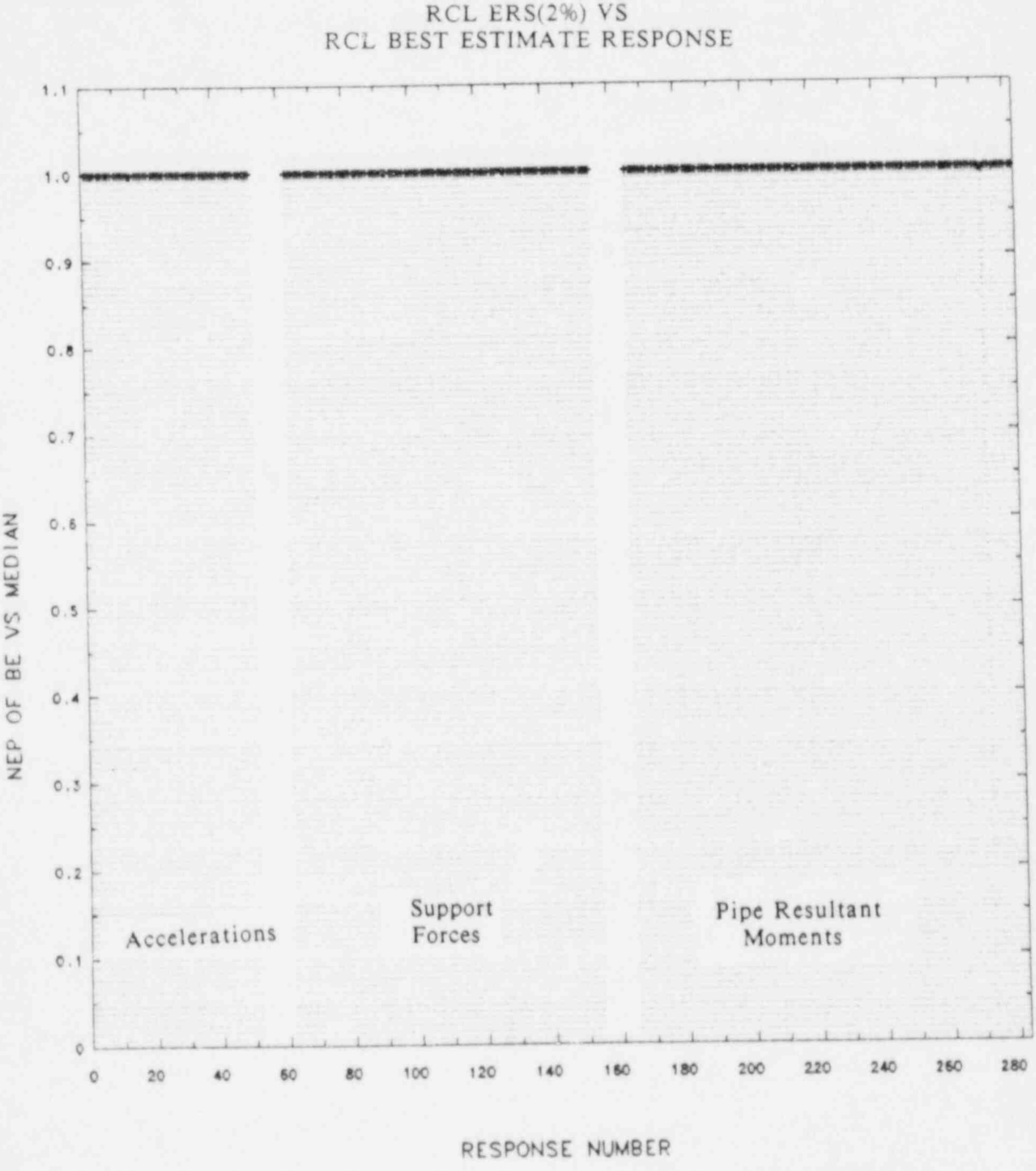
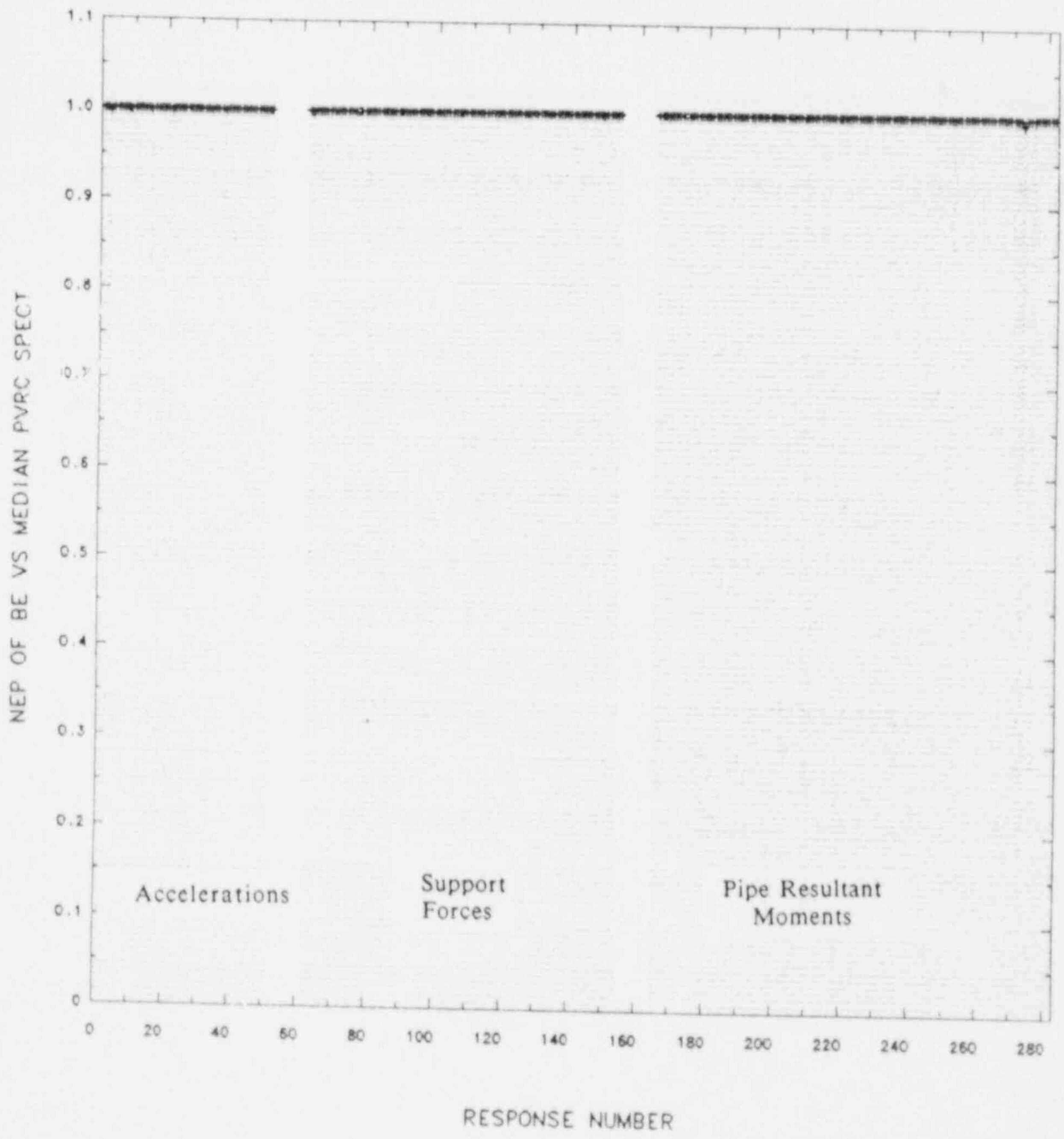
NEP OF BE VS MEDIAN PVRC DAMP
RESPONSE NUMBER
Accelerations
Displacements
Pipe Resultant Moments
Support Forces


RHR INEL DAMPING RESPONSE VS
RHR BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN INEL DAMP
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Accelerations
Displacements
Pipe Resultant
Moments
Support
Forces
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
RESPONSE NUMBER

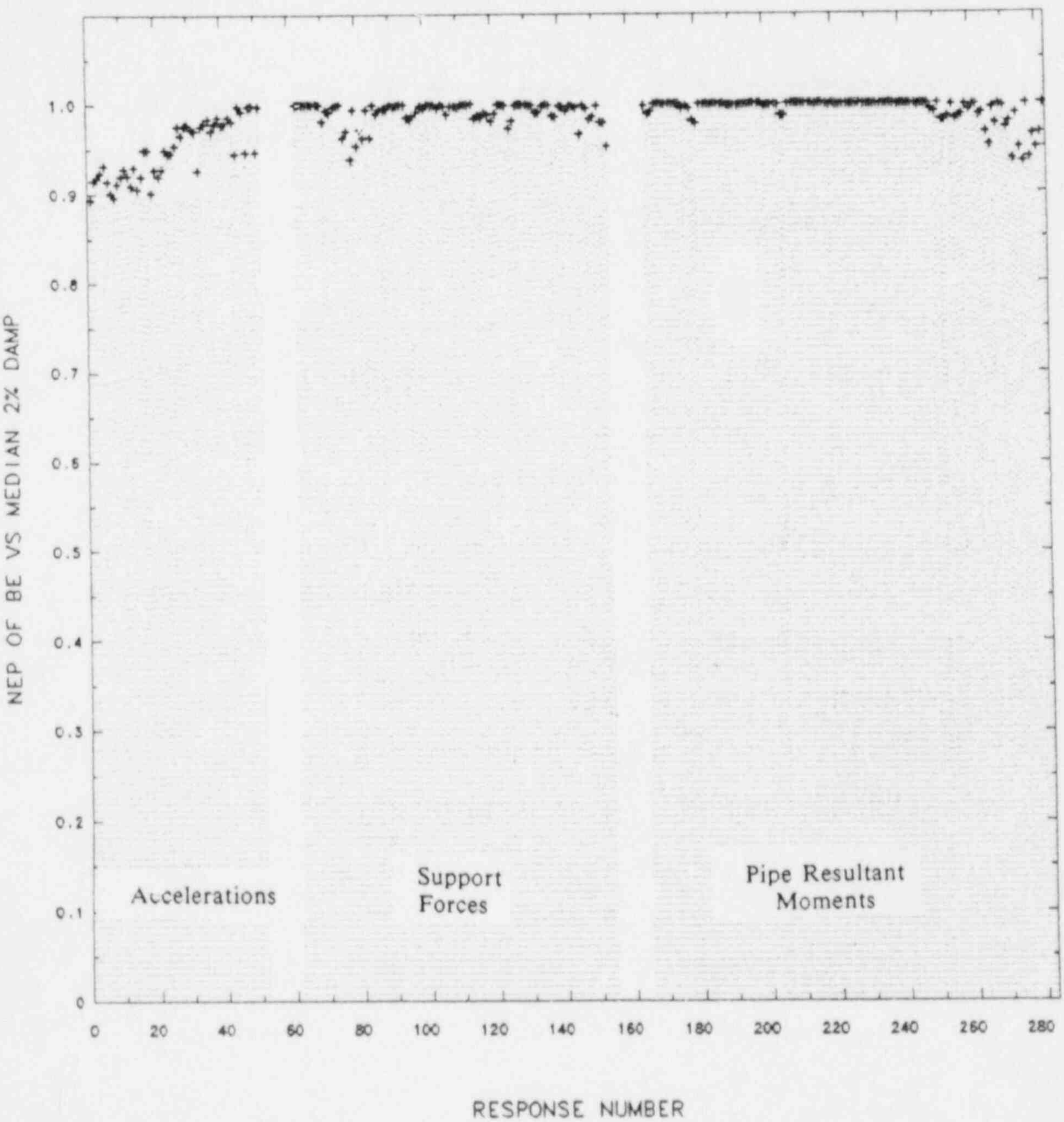
RCL Piping System Model

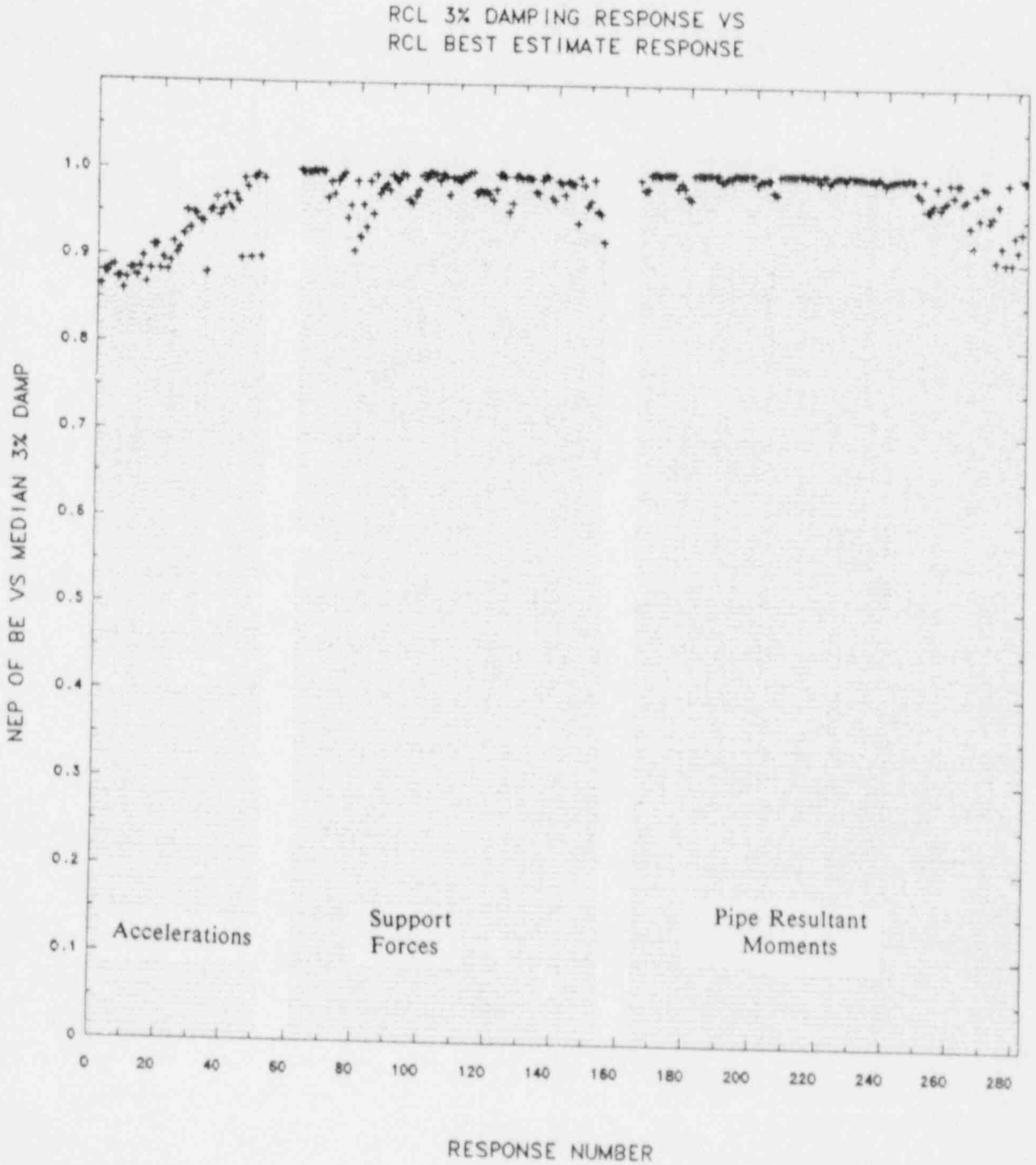

RCL ERS(2%) VS
RCL BEST ESTIMATE RESPONSE
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
NEP OF BE VS MEDIAN
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
RESPONSE NUMBER
Accelerations
Support
Forces
Pipe Resultant
Moments

RCL ERS(PVRC) VS
RCL BEST ESTIMATE RESPONSE

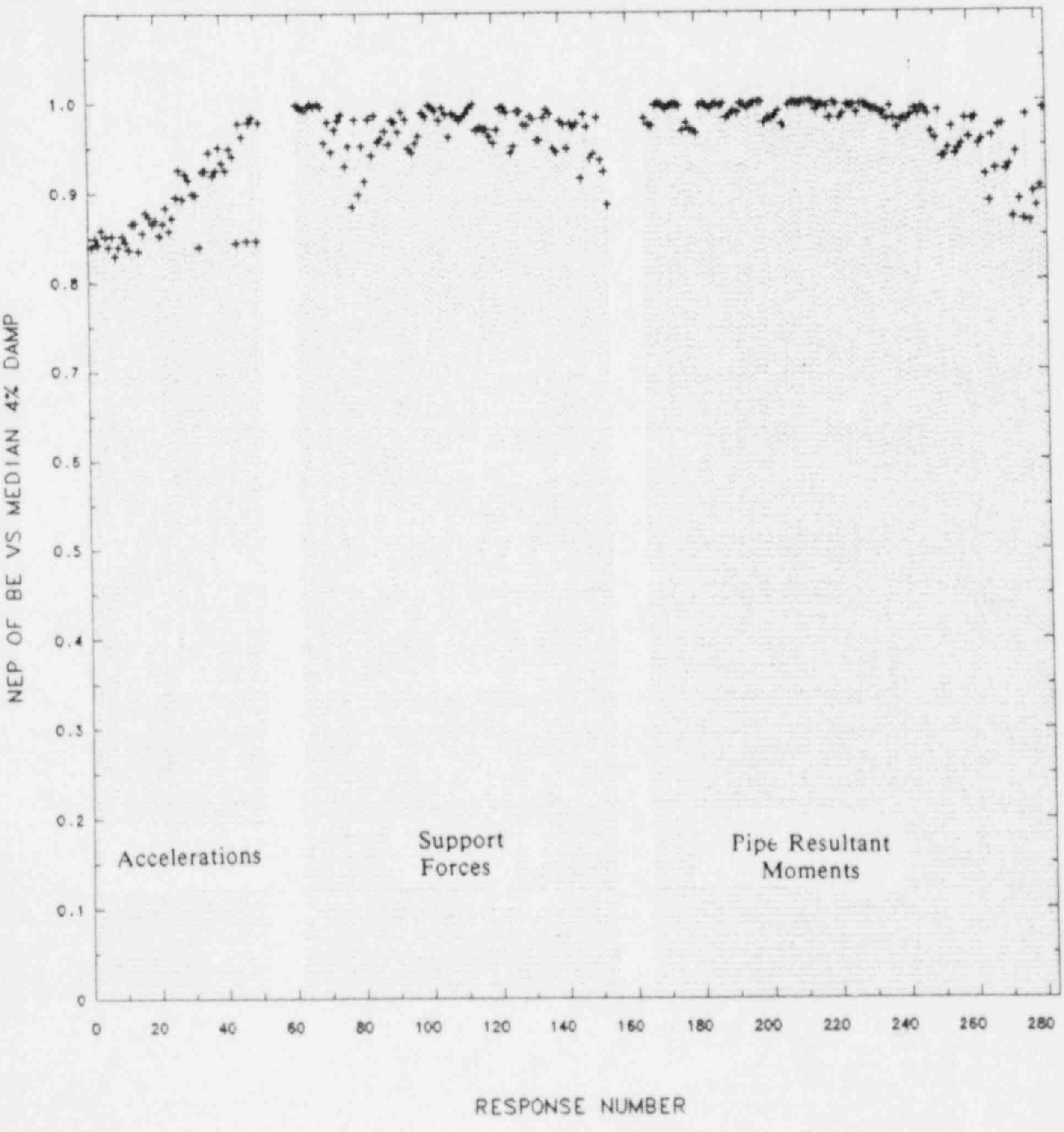


RCL 2% DAMPING RESPONSE VS
RCL BEST ESTIMATE RESPONSE

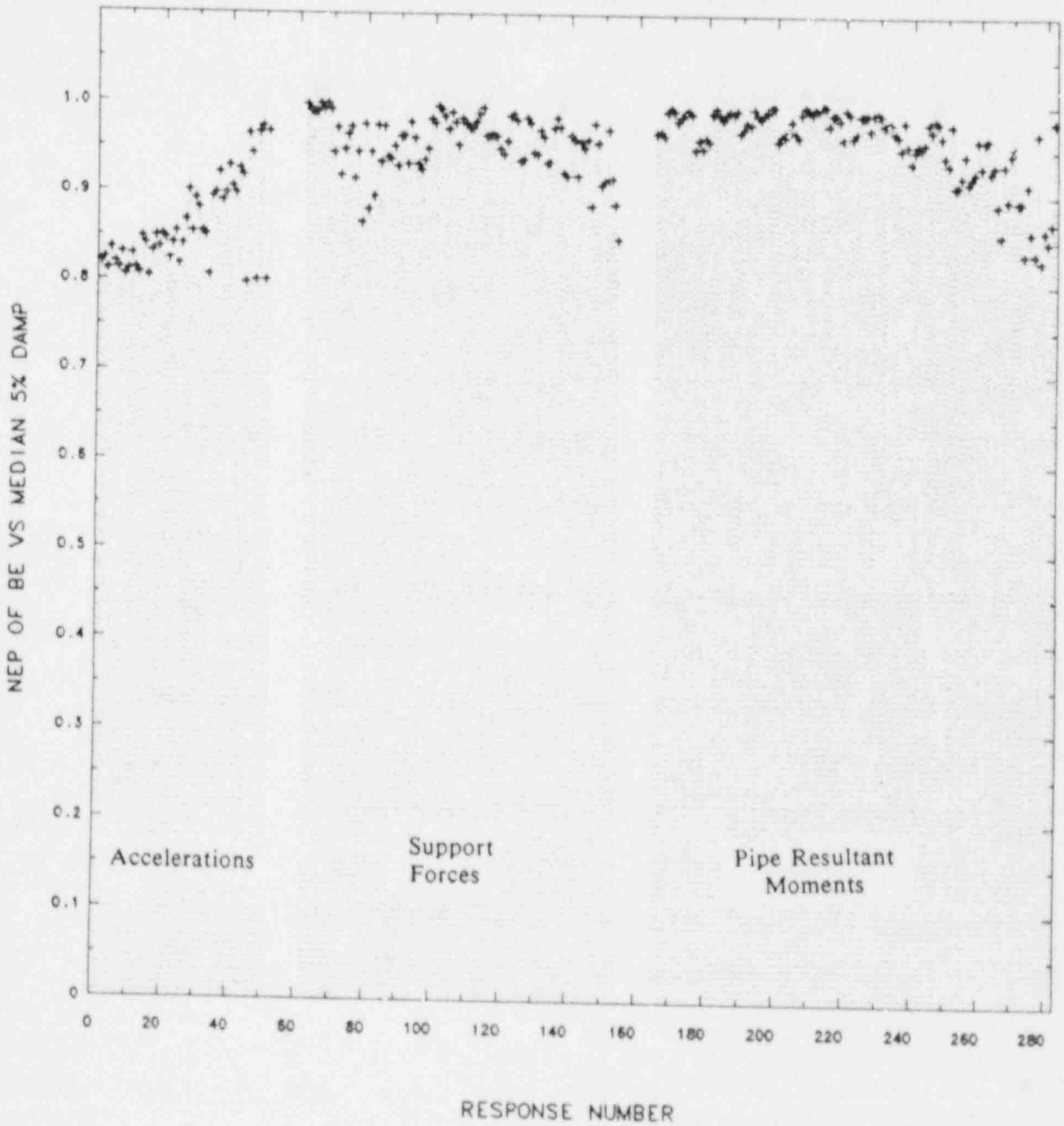


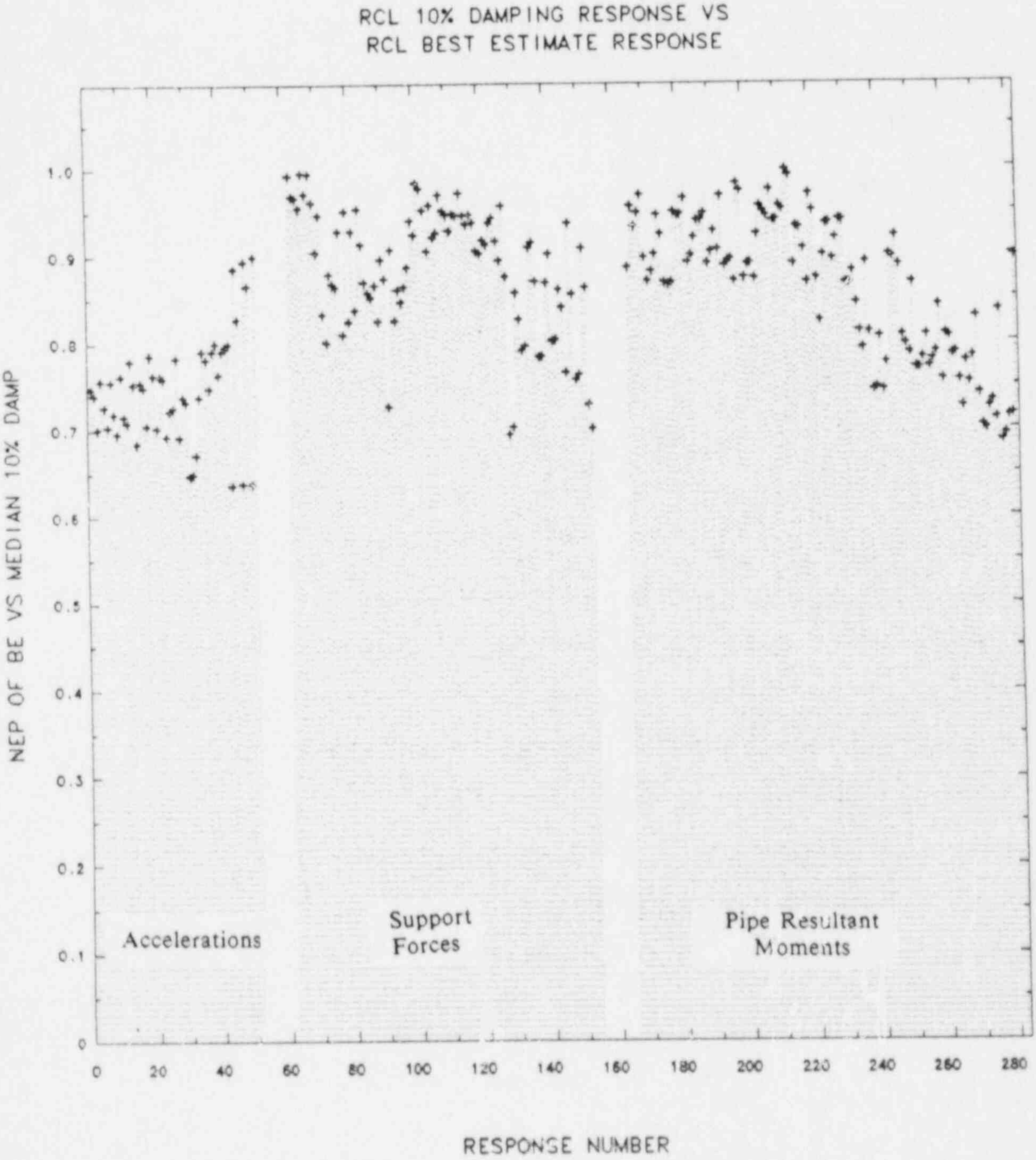

RCL 3% DAMPING RESPONSE VS
RCL BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 3% DAMP
RESPONSE NUMBER
Accelerations
Support
Forces
Pipe Resultant
Moments

RCL 4% DAMPING RESPONSE VS
RCL BEST ESTIMATE RESPONSE



RCL 5% DAMPING RESPONSE VS
RCL BEST ESTIMATE RESPONSE




RCL 10% DAMPING RESPONSE VS
RCL BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN 10% DAMP
RESPONSE NUMBER
Accelerations
Support Forces
Pipe Resultant Moments
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
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0
20
40
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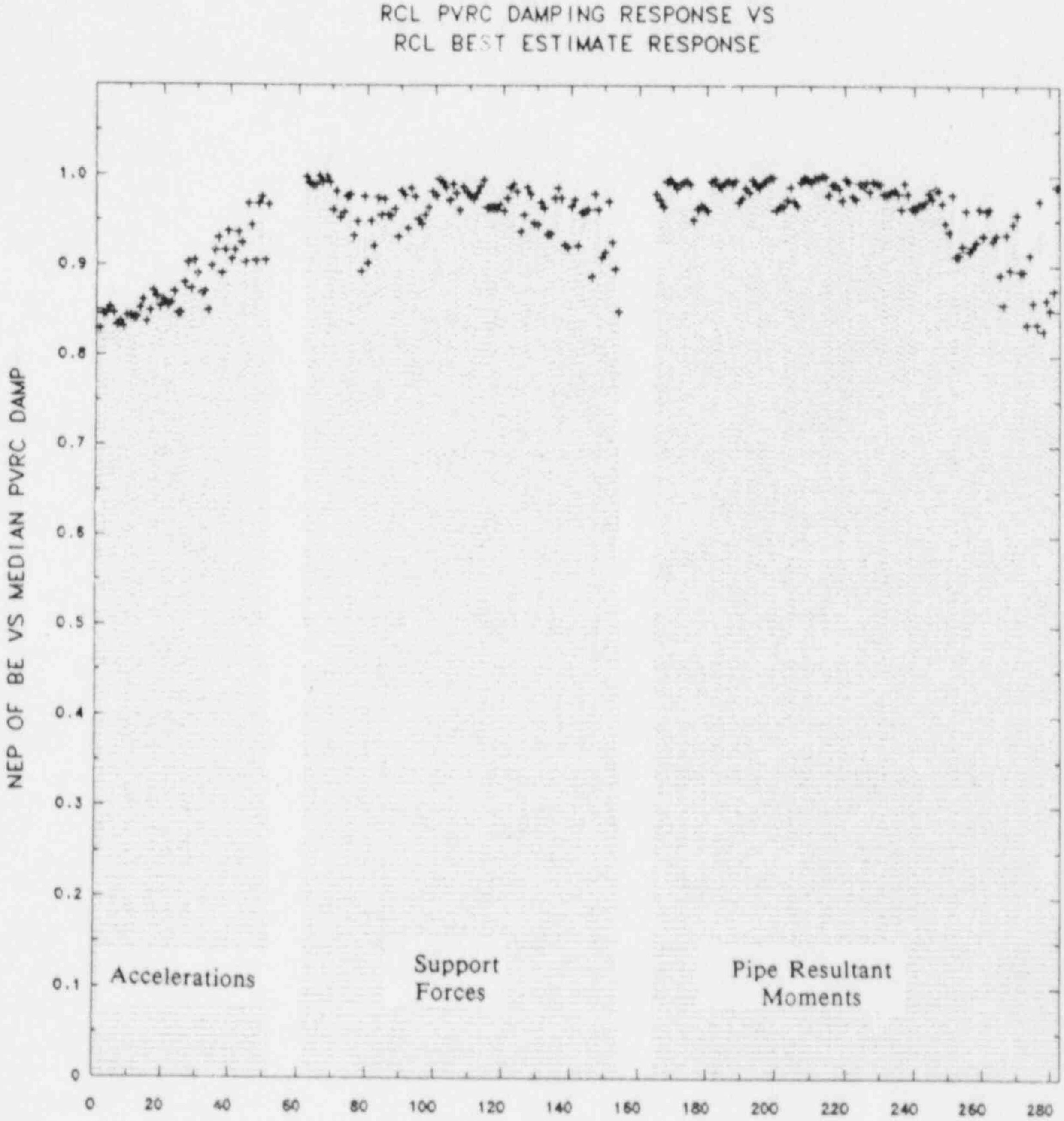
80
100
120
140
160
180
200
220
240
260
280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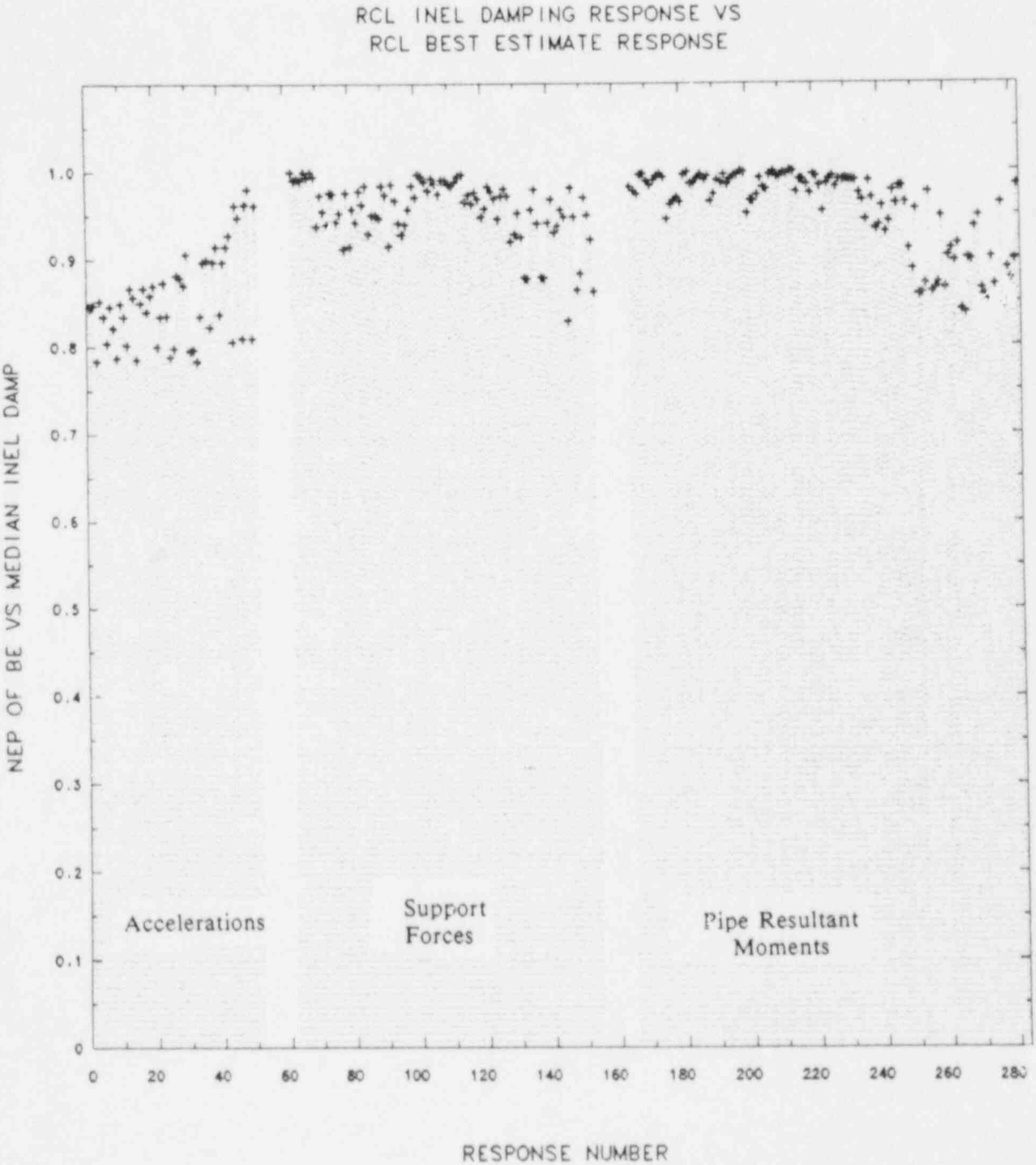
NEP OF BE VS MEDIAN PVRC DAMP
RESPONSE NUMBER
Accelerations
Support
Forces
Pipe Resultant
Moments



RCL INEL DAMPING RESPONSE VS
RCL BEST ESTIMATE RESPONSE
NEP OF BE VS MEDIAN INEL DAMP
RESPONSE NUMBER
Accelerations
Support
Forces
Pipe Resultant
Moments
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
20
40
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200
220
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260

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13. ABSTRACT (200 words or less)

The conservatism of seismic analysis and design of piping systems due to analysis methodologies and damping values was quantified. Envelope response spectrum analyses, independent support motion response spectrum analyses, and multi-support time history analysis methodologies were evaluated. Constant damping, ranging from 1% to 10%, and PVRC damping were considered. Conservatisms were evaluated with respect to best estimate responses of the entire seismic analysis chain and of the piping system alone.

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