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A technical basis for establishing seismic margins in nuclear plant piping

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ABSTRACT

Some results of ongoing research being conducted for the U.S. Nuclear Regulatory Commission (NRC) at the Energy Technology Engineering Center (ETEC) are reported. These results include the development of a methodology for establishing and estimating appropriate seismic margins in nuclear plant piping.

INTRODUCTION

During the deliberations which led to the revision of portions of the ASME Boiler and Pressure Vessel Code, Section III, dealing with the seismic design criteria for nuclear plant piping, and since the publication of the revised rules in 1994 Addenda, several issues have been raised regarding the adequacy of the technical basis for the revision. Some of the issues, in part, deal with how to evaluate test data on which the revision is based. The primary basis for the revision is the piping component testing conducted by the Electric Power Research Institute (EPRI) and US NRC under the Piping and Fitting Dynamic Reliability (PFDR) Program (Guzy, 1988; EPRI, 1994). In applying the test data , two of the key issues are: (1) how to define an acceptable or adequate margin level; and (2) how to establish margins from the test data. The first issue is independent of the test data and is the focus of this paper. The Special Working Group on Seismic Rules (SWG-SR), formed by ASME Subgroup on Design (SGD) in September 1995, is also evaluating this issue along with the other issues. The concepts developed in this paper on how to define adequate margin have been presented to the SWG-SR and published at the 1996 ASME Pressure Vessel and Piping Conference (Kennedy, Chokshi, and Chen, 1996). In a meeting in February 1997, the members of the SWG-SR voted to accept a specific margin value based largely on the approach described in this paper.

The approach presented in this paper is based on considerations of current seismic PRA evaluation methods. Specifically, margins are established such that piping will not control the plant High-Confidence-Low-Probability-of-Failure (HCLPF) seismic capacity, and consequently the current seismic PRA methodology can be maintained. The principal author of the paper has studied this approach in detail and more comprehensively to address general issues on establishing seismic design criteria to achieve an acceptable margin (Kennedy, 1996).

In the following, only the framework of the approach is provided. Additionally, judgement has been exercised in a number of places in order to establish specific values of appropriate margin.

MARGIN DEVELOPMENT

The required seismic margin for a piping system will depend upon the required seismic margin for the plant as a whole for some damage state such as seismic induced core damage. Currently, the NRC has requested that all existing plants define their plant seismic margin in terms of the High-Confidence-Low-Probability-of-Failure (HCLPF) seismic capacity. The seismic margin for the design basis Safe Shutdown Earthquake (SSE) is then defined by the ratio R_H, between the HCLPF and SSE ground motion levels, i.e.,

$$R_H = \left(\frac{HCLPF}{SSE}\right) \qquad (1)$$

Initially, the HCLPF seismic capacity was defined as the level at which one had approximately 95% confidence of less than about 5% probability of failure. However, in NUREG - 1407 (US NRC, 1991a) the NRC has suggested that this HCLPF seismic capacity can be approximated as the 1% composite (mean) probability of failure. With this approximation, one does not have to separate their estimates of variability into "uncertainty," and "randomness," but can work with a single composite (mean) fragility curve which defines mean probability of failure versus ground motion level. For simplicity, this composite (mean) approximation of the HCLPF capacity will be used herein.

After anchorage, seismic-interaction, or other significant deficiencies identified as a result of a careful seismic walkdown of a plant have been corrected, seismic probabilistic risk assessments (PRA) and seismic margin studies conducted on existing nuclear power plants have reported in ERI/NRC 94-502 (Energy Research, Inc., 1994) that:

$$\text{For Existing Plants: } R_H \geq 1.25 \qquad (2)$$

In addition, target goal for the standardized Advanced Light Water Reactor (ALWR) designs has been established as:

$$\text{For ALWRs: } R_H > 1.67 \qquad (3)$$

These levels for R_H will be used herein to establish the required seismic margin for piping systems.

In addition, based upon the pre-1994 ASME Code Addenda seismic design criteria, seismic PRA and seismic margin studies have concluded that piping is not a significant contributor to the seismic risk of a nuclear power plant and does not control the HCLPF seismic capacity of the plant. A desirable goal is to not liberalize piping seismic design criteria so much that piping begins to control the HCLPF seismic capacity of the plant.

However, because of the large number of at-least partially independent piping segments , piping will control the plant HCLPF capacity unless piping has substantially less than a 1% probability of failure at the plant HCLPF capacity. In order to provide reasonable assurance that piping will not control the plant HCLPF capacity, it is suggested that the probability of failure P_{pf} of a piping segment be limited to about 0.1% at the plant HCLPF seismic capacity level (the results of a sensitivity study in which P_{pf} has been varied from 0.02% to 0.5% are presented later in the paper), i.e.:

$$P_{pf} < 0.1\% \quad \text{at Plant HCLPF Level} \qquad (4)$$

Derivation of Required Seismic Margin for Structures and Other Components

The ratio of the median (50% probability of failure) seismic capacity of any component to the design basis SSE can be defined by a median factor of safety $F_{50\%}$ given by:

$$F_{50\%} = \left(\frac{Median}{SSE}\right) \tag{5}$$

This median factor of safety can be defined by the product of the median capacity factor of safety $F_{C_{50\%}}$ and the median response factor of safety, $F_{R50\%}$,i.e.:

$$F_{50\%} = (F_{C_{50\%}})(F_{R_{50\%}}) \tag{6}$$

The variability [logarithmic standard deviation or approximate coefficient of variation (COV)], β, on the factor of safety can be obtained by adding capacity and response variances (β_C^2 and β_R^2, respectively) or:

$$\beta^2 = \beta_C^2 + \beta_R^2 \tag{7}$$

where β_C and β_R include both randomness and uncertainty.

Since the plant HCLPF is defined at the 1% probability of failure, then assuming a log-normal distribution:

$$R_H = F_{50\%} e^{-2.326\beta} \tag{8}$$

where (-2.326) is the standardized normal coefficient corresponding to the 1% probability of failure.

Investigations (Kennedy and Short, 1994) of Code minimum ultimate, Code limit-state, or Code Service Level D capacities indicate a capacity factor $R_{C_{1\%}}$ greater than unity on the 1% non-exceedance probability (NEP) capacity. Thus:

$$F_{C_{50\%}} = R_{C_{1\%}} e^{2.326\beta_C} \tag{9}$$

Furthermore, the response analyses conducted in accordance with the Standard Review Plan (SRP, US NRC, 1991b) are aimed at defining the seismic response at the 84% NEP. However, because of either excess conservatism in some aspects of the SRP response requirements, or because of excess conservatism introduced by the analyst, most response analyses achieve a response factor $R_{R_{84\%}}$ greater than unity when compared to a probabilistic computed 84% NEP response. Thus:

$$F_{R_{50\%}} = R_{R_{84\%}} e^{\beta_R} \tag{10}$$

By combining Equations (6) through (10):

$$R_H = (R_{C_{1\%}})(R_{R_{84\%}})(f_\beta) \tag{11}$$

where:

$$f_\beta = e^{\beta_R - 2.326(\beta - \beta_C)} \tag{12}$$

However, for structures and most other components, the factor f_β will be very close to unity over the likely range of β_C from 0.2 to 0.4 and β_R from 0.2 to 0.3 as is shown in Table 1. Therefore, R_H may be closely approximated by:

$$R_H \approx (R_{C_{1\%}})(R_{R_{84\%}}) \tag{13}$$

Thus, to estimate a seismic margin ratio R_H, defined as the ratio of the HCLPF/SSE capacity, it is sufficient to establish the capacity factor $R_{C_{1\%}}$ above the 1% NEP capacity and to establish the response factor $R_{R_{84\%}}$ on the 84% NEP response. Equation (13) can then be used to estimate R_H without having to explicitly estimate the variabilities β_C and β_R. Equation (13) defines the essence of the Conservative-Deterministic-Failure-Margin (CDFM) method for finding the HCLPF seismic capacity.

For structures, and other compact components, it is estimated that:

$$R_{C_{1\%}} = 1.25 \; to \; 1.9 \tag{14}$$

The lower estimate of 1.25 corresponds to brittle failure modes where there is negligible inelastic energy absorption such as a welded connection, or out-of-plane shear failure of a concrete member without shear reinforcement. The high estimate is for ductile failure modes with significant inelastic energy absorption capability defined as the ratio by which linear elastically computed responses can exceed the ultimate capacity for oscillatory, limited duration dynamic events.

Based upon reviews of design basis response analyses, for structures and other compact components it is estimated that:

$$R_{R_{84\%}} = 1.0 \; to \; 2.0 \tag{15}$$

At low elevations for structures founded on rock, $R_{R_{84\%}} = 1.0$ for response analyses which satisfy the SRP. Higher values often occur at higher elevations and for structures embedded in soil. However, there is no consistency in these higher values so that they cannot be counted upon to reduce the required capacity factor $R_{C_{1\%}}$. It is judged that all that can be counted upon is:

$$R_{R_{84\%}} \geq 1.0 \; for \; Existing \; Plants, \; 1.25 \; for \; ALWR \tag{16}$$

The estimate that $R_{R_{84\%}} \geq 1.25$ for standardized ALWR plants is based on the design seismic responses for these plants being an envelope of the responses computed for many sites and thus being conservative for any particular site.

Thus, combining Equations (13), (14), and (16) with the plant seismic margin R_H goals defined by Equations (2) and (3), one obtains for the minimum required $R_{C_{1\%}}$.

Plant Type	R_H	$R_{R_{84\%}}$	$R_{C_{1\%}} = (R_H / R_{R_{84\%}})$
Existing Plants	1.25	1.00	1.25
ALWR	1.67	1.25	1.33

In conclusion, for structures and compact components, it is believed that an adequate capacity factor $R_{C_{1\%}}$ on the 1% probability of failure capacity is in the range of 1.25 to 1.33. However, it is not believed that this is an adequate capacity factor for distribution systems such as piping which have a large number of segments with at-least partially independent failure locations.

Derivation of Required Seismic Margin for Piping and Other Distribution Systems With Large Numbers of Segments

As summarized in Equation (4), it is recommend that the probability of failure P_{pf} for piping and other multiple segment distribution systems be limited to about 0.1% at the plant HCLPF level. To achieve this lesser probability of failure, Equations (11) and (12) must be modified for piping as follows:

$$R_{CP_{1\%}} = (R_H / R_{RP_{84\%}}) \, (f_{\beta P})^{-1} \tag{17}$$

where:

$$f_{\beta P} = e^{\beta_{RP} + X_{CP}\beta_{CP} - X_{fP}\beta_P} \tag{18}$$

$X_{CP} = 2.326$ (1% NEP)
$X_{fP} = 3.090$ (0.1% NEP)

and the subscript P refers to piping specific estimates.

For distributed, i.e., extended, piping systems, the capacity variability β_{CP} and possibly the response variability β_{RP} are typically larger than those tabulated in Table 1 for structures and other compact components. In addition, the coefficient X_{fP} of 3.090 in Equation (18) for $f_{\beta P}$ associated with 0.1% NEP is larger than the corresponding coefficient of 2.326 in Equation (12) for f_β associated with 1% NEP. Table 2 presents the resulting estimates for $(f_{\beta P})^{-1}$ for piping systems. Note that $(f_{\beta P})^{-1}$ is nearly constant over the estimated typical ranges of β_{CP} and β_{RP}. The mean value $(f_{\beta P})^{-1}$ is 1.42 with a small COV of 0.07. It is recommended that $(f_{\beta P})^{-1}$ be taken at about the 84% NEP level given by:

$$(f_{\beta P})^{-1} = \overline{(f_{\beta P})^{-1}} \, (1 + COV) = 1.50 \tag{19}$$

For piping the response margin $R_{RP_{84\%}}$ is highly variable and is often excessively conservative particularly at high elevations in structures at frequencies near resonance with the structure frequencies. It is judged that:

$$R_{RP_{84\%}} = 1.0 \; to 4.0 \tag{20}$$

Here again, at low elevations for structures founded on rock, $R_{RP_{84\%}} = 1.0$ for response analyses which satisfy the SRP. Therefore, no credit for the potentially excess but highly uncertain conservatism in $R_{RP_{84\%}}$ should be taken. It is recommended that $R_{P_{84}\%}$ be set equal to $R_{RP_{84\%}}$ from Equation (16).

Thus, from Equations (17) and (19):

Plant Type	$(R_H / R_{RP_{84\%}})$	$R_{CP_{1\%}}$
Existing Plants	1.25	1.875
ALWR	1.33	2.0

In conclusion, it is recommended that an adequate capacity margin $R_{CP_{1\%}}$ on the 1% probability of failure piping capacity is in the range of 1.875 to 2.0. This recommendation is based on the goal of limiting the probability of failure of a piping segment P_{pf} about 0.1% at the plant HCLPF seismic capacity level. It was judged that this goal is sufficient to provide reasonable assurance that piping will not control the plant HCLPF seismic capacity. In order to determine the sensitivity of the capacity factor $R_{CP_{1\%}}$ to the selected probability of failure P_{pf} at the plant HCLPF level, this probability of failure was varied from a credible lower bound of 0.02% to a credible upper bound of 0.5% following the same approach as described above. The results of this sensitivity study are as follows:

P_{pf}	$(f_{\beta P})^{-1}$	$R_{CP_{1\%}}$
0.50%	1.13	1.4 to 1.5
0.10%	1.50	1.875 to 2.0
0.02%	2.02	2.5 to 2.7

Over this range of credible P_{pf} values, $R_{CP_{1\%}}$ should be selected to lie within the range of 1.5 to 2.5 centered on the recommended value of 2.0.

However, it may not be possible to define the 1% probability of failure piping capacity from a limited number of component seismic tests. Therefore, it may be necessary to define the required capacity margin $R_{CPY\%}$ in terms of some higher Y% probability of failure. At a Y% other than 1%, the desired stability of $(f_{\beta P})^{-1}$ shown in Table 2 for Y = 1% will not be so well achieved. For example at Y = 5% the Coefficient of Variation (COV) increases to 0. 12 versus 0.07 at Y = 1%. Even so, this COV is still reasonably small. For Y > 1% the largest $(f_{\beta P})^{-1}$ will always occur at the largest typical β_{CP} of 0.6. Therefore, at some other Y% probability of failure, the required capacity margin $R_{CPY\%}$ can be slightly conservatively estimated from:

$$R_{CPY\%} = (R_{CP_{1\%}})\, e^{\alpha \beta_{CPmax}} \tag{21}$$

where:

$$\beta_{CP_{max}} = 0.6$$

$$\alpha = 2.326 - X_{CPY\%}$$

Y	$X_{CPY\%}$	α	$(R_{CP_{Y\%}} / R_{CP_{1\%}})$
1%	2.326	0	1.00
2%	2.054	0.272	1.175
3%	1.881	0.445	1.30
5%	1.645	0.681	1.50

Thus, if $R_{CP_{1\%}} = 2.0$ is deemed sufficient for piping as per the prior recommendation, then:

Y	$R_{CPY\%}$
1%	2.00
2%	2.35
3%	2.60
5%	3.00

The required capacity margin for piping on the Y% probability of failure seismic capacity can be specified by any of these $R_{CPY\%}$ values. Thus, for the 1% to 5% probability of failure capacities, the required seismic capacity margin should range from about 2.0 at 1% NEP capacity to 3.0 at the 5% NEP capacity.

SUMMARY

In this paper an approach for determining and estimating appropriate seismic margins in nuclear plant piping has presented. This approach is based on the assumption that the probability of failure of a segment of a piping system be limited to about 0.1% of the plant HCLPF seismic capacity level. For this probability of failure, piping will not control the plant HCLPF capacity and current seismic PRA methods can be maintained.

It was estimated that for 1% to 5% probability of failure capacities, the required seismic capacity margin should range from about 2.0 at 1% NEP capacity to 3.0 at the 5% NEP capacity.

DEDICATION

This paper is dedicated to the memory of Dr. Wellington Paul Chen, the ETEC principal investigator and program manager of the Seismic Analysis of Piping Research Program. Until his tragic death, Dr. Chen, as a principal investigator, provided very effective technical leadership to the program. His friendship and technical acumen will be greatly missed.

DISCLAIMER

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Table 1

Typical Values for Factor f_β Structures and Other Non-Distribution System Components

	f_β	
β_C	$\beta_R = 0.2$	$\beta_R = 0.3$
0.2	1.01	0.93
0.3	1.06	1.01
0.4	1.09	1.07

Table 2

Typical Values for Factor $f_{\beta P}$ for Piping Systems

	$(f_{\beta P})^{-1}$		
β_{CP}	$\beta_{RP} = 0.2$	$\beta_{RP} = 0.3$	$\beta_{RP} = 0.4$
0.3	1.24	1.37	1.56
0.4	1.29	1.37	1.52
0.5	1.35	1.40	1.52
0.6	1.43	1.46	1.54