

EVALUATION OF THE RELIABILITY OF COLD PIPING DESIGNED TO ASME BOILER AND PRESSURE VESSEL CODE ALLOWABLES AS A BASIS FOR RISK INFORMED DESIGN

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1.0 INTRODUCTION

The purpose of this paper is to describe the procedures used and the results obtained in the analysis of the probability of failure of a cold^[2] piping crosssection loaded to code limits in piping designed to various editions of the ASME Code for nuclear power plant safety-related piping.

The failure mode considered is plastic instability (sometimes known otherwise as ductile rupture) due to overload involving the largest design basis load combination to which the piping is subjected. The failure probability is equal to the probability that the applied loads exceed the Code defined load carrying capacity of the piping.

The statistical variables considered are the tensile properties (capacity) of the pipe material, the conditional seismic inertia stress for a given zero-period acceleration, ZPA, with the ZPA defined for a median occurrence probability of $10^{-4}/\text{yr}$ and $10^{-5}/\text{yr}$ (corresponding to the median seismic risk level). It is assumed that load carrying capacity of the pipe crosssection is defined by the ultimate stress in the outermost fiber being reached computed by elastic analysis. It should be noted that statistical variation could be applied to many of the other variables used in this evaluation, but the other potential statistical variables are not considered to have a significant effect on failure probability.

2.0 CODE PIPING SUBJECT TO PLASTIC INSTABILITY FAILURE MODE

The probabilistic analysis is applied to ASME B31.1 and ASME BPVC Section III Class 2 and 3 cold piping in accordance with current Code equations which assume plastic instability (ductile rupture) as the mode of failure. Three random variables are considered in this study: i) a seismic inertia loading has occurred as defined by a seismic risk curve, ii) the conditional probability of failure given a specific level earthquake has occurred, and iii) the piping material strength. The uncertainty in the resultant seismic demand stresses is one of the primary factors in the analysis. The following discussion covers conservatism in procedures used for estimation of Code defined seismic stresses.

As confirmed by experimental tests, actual pipe failure, in terms of leakage or through wall crack when subjected to strong motion type earthquake cyclic motions, occurs by ratcheting with average strains through the pipe wall in the $\pm 2\text{-}3\%$ strain range with 50 to 100 cycles in response to a earthquake time history input motion and earthquake duration of strong motion in the 30 to 50 second range.(1)

The Code defined plastic instability failure occurs when pipe wall outermost fiber strains computed on an elastic basis are ± 0.1 to ± 0.25 percent strain. It should be noted the Code defined failure is considerably more conservative than that observed in experimental failure tests. While the actual failure is by cyclic ratcheting the direct consideration of this failure mode in piping design would greatly complicate the design of the 100,000 feet of cold Class 2, 3 and B31.1 piping in a typical nuclear power plant. It should be noted that the Code defined allowable load equations for Class 2 and 3 piping which assume a plastic instability type of failure do not permit actual stress or strains to approach the ratcheting load limits.

There are five failure, malfunction or damage states that might be considered in the Code design of cold pipe for Design Basis Earthquake as a function of the era of piping design.

1. Elastic seismic input and near yield Elastic Response, (prior to 1971) $S_{\text{all}} = 1.8 S_c$
2. Elastic seismic input and cycling elastically (prior to 1995), $S_{\text{all}} = 3.0 S_c$
3. Elastic seismic input and limited inelastic response(1995 –2000), $S_{\text{all}} = 4.5S_c$.
4. Reduction of the stress indices B_2 as defined in the Code for tees and elbows by dividing each B_2 by 1.5
5. Inelastic seismic input (2.5 leakage and 4.0 rupture Spectral Reduction Factor)

Where notations used are as defined in the ASME B&PVC Section III. Div. 1.

2.1 Conservatism in Estimation of Seismic Stresses

There are seven major areas that can be identified with the introduction of conservatism in piping design to resist seismic loading. These seven areas are summarized in Table 1.

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^[2] Cold piping is piping where the differential temperature range in the piping system is less than 150F° and had an initial installation temperature of 50 to 170°F.

This report identifies two potential damage states, one associated with leakage using an inelastic demand ration, R_7 equal to 2.5 and one of pipe rupture using an R_7 equal to 4.0 in cold pipe.

3.0 COMPUTATION OF FAILURE PROBABILITIES

Once a fragility curve $f(a)$ for a piping crosssection, as shown in Figure 1, is convolved with the hazard curve $H(a)$ shown in Figure 2, a total probability of failure can be determined: (2,3)

$$P_f = \int_a^{\infty} H(a)f(a)da \quad (1)$$

where $f(a)$ is the probability distribution function corresponding to the pipe fragility curve. Using the assumption that the fragility results from a lognormal probability density function leads to the following:

$$P_F = \int_a^{\infty} H(a) \frac{e^{-\frac{\left(\ln \frac{a}{a_{50}}\right)^2}{2\zeta^2}}}{a\zeta\sqrt{2\pi}} da \quad (2)$$

where a_{50} is the ground acceleration that would cause failure with a probability of 50% (given that it occurred). The a_{50} can be determined knowing ζ and the conditional failure probability at the DBE. Equation 2 can be evaluated by numerical integration for an arbitrary $H(a)$, such as those shown in Figure 2. Resultant ASME piping crosssection Code failure probabilities are found in Tables 2 and 3. It should be noted there are failure probabilities based on Code defined failure modes. Actual failure of piping associated with leakage or rupture including the limiting seismic load case have been determined by tests well into the inelastic response region and are typically 2 or 3 orders of magnitude less than the values given in Tables 2 and 3.

4.0 CONCLUSIONS

A procedure has been developed which defines relative failure probabilities based on current and past ASME Code defined design requirements and failure modes which can be used to evaluate target failure probabilities for any proposed modification of code piping design equations.

5.0 REFERENCES

- [1] Presentations made to the ASME Boiler and Pressure Vessel Code Special Working Group on Seismic Piping Rules on the Results of Dynamic Piping Tests Sponsored by NUPEC, Japan, 1998 – 1999.
- [2] Hajian, A.E., “Extension of Seismic Zonation Maps for Design at any Pre-selected Probability,” 12th WCEE Paper No. 1811/8/A, Jan. 28 – Feb. 4, 2000.
- [3] Kennedy, R.P., and Short, S.A., Basis for Seismic Provisions of DOE Std. 1020 UCRL-CR-111478, 1994.

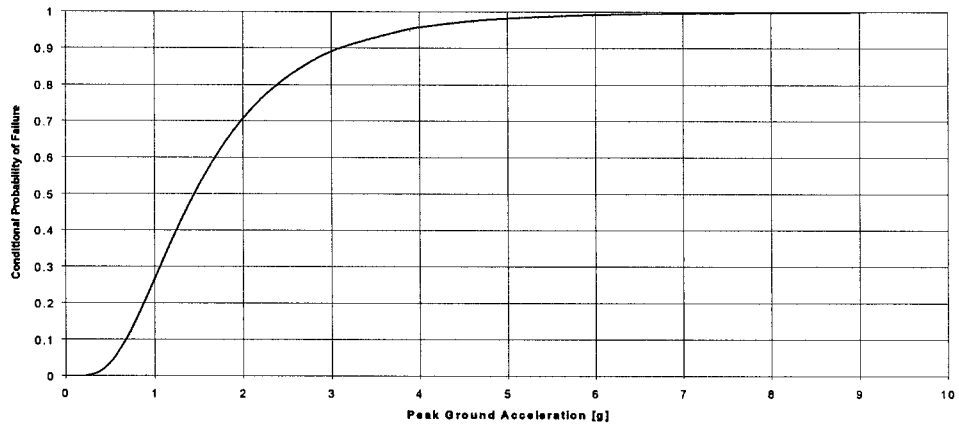


Figure 1: Typical Fragility Curve

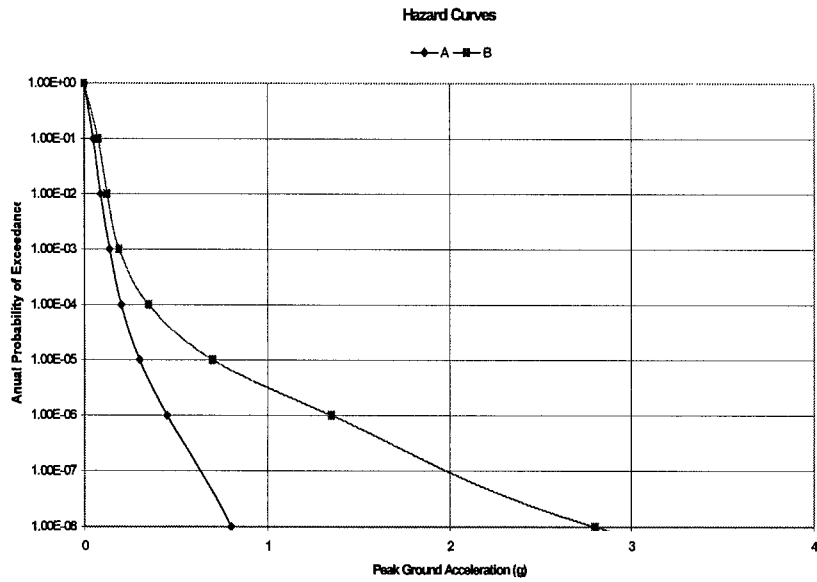


Figure 2: Seismic Hazard Curves, A is for Low Hazard and B is for Moderate Hazard

Table 1: Sources and Quantification of Conservatism Used in Estimation of Seismic Reduction Factors, R for ASME BPVC Section III Cold Piping

R No.	Description	ERA 1 ASME BPVC Section III Class 2 & 3-1971 or B31.1 1967 – 1974	ERA 2 ASME BPVC Section III Class 2 & 3 1975 – 1995 ⁽⁹⁾	ERA 3 ASME BPVC Section III Class 2 & 3 1995 to Pres.
R ₁	Ratio of code limit seismic stress to specified ultimate stress ⁽¹⁾	$[4.0-(0.15+0.50)]/1.8 = 1.86$	$[4.0-(0.15+0.50)]/3.0 = 1.12$	$[4.0-(0.15+0.50)]/4.5 = 0.74$
R ₂	Piping shape factor ⁽²⁾	1.27	1.27	1.27
R ₃	Load redistribution factor ^(2,3)	1.33	1.33	1.33
R ₄	Best estimate damping and spectral shape conversion factor for specified spectral shape and damping ⁽⁴⁾	6.2/2.12 = 2.92 (0.5%) 4.6/2.12 = 2.17 (1.0%)	4.25/2.12 = 2.0 (2.0%) 3.61/2.12 = 1.74 (3.0%) 3.12/2.12 = 1.48 (5.0%)	NUREG: 1.00 (5%)
R ₅	Mass ratio effect; effectively increasing damping from 5 to 8% ⁽⁵⁾	1.17	1.17	1.17
R ₆	Realistic B ₂ index for fittings(elbows & tees) Code Values/by Test Values ⁽⁶⁾	1.5	1.5	1.5
R ₇	Inelastic energy absorption factor ^(7,8) a. Passive-Leakage b. Passive-Rupture	0.5% 1.0% 2.5 2.5 4.0 4.0	2% 3% 2.5 2.5 4.0 3.61	5% 2.12 2.12

Combinations of Reduction Factors from Table 1:

ERA 1

Housner Spectral Input

0.5% Damp:

0.5% Damp: $R_4R_5=2.92 \times 1.17=3.42$

Straight Pipe $R_4R_5R_6R_7=2.92 \times 1.17 \times 1.0 \times 2.5=8.54$

Tees&Elbows $R_4R_5R_6R_7$

$=2.92 \times 1.17 \times 1.5 \times 2.5=12.81$

1.0% Damp:

1.0% Damp: $R_4R_5=2.17 \times 1.17 = 2.54$

Straight Pipe $R_4R_5R_6R_7 = 2.17 \times 1.17 \times 1.0 \times 2.5=6.35$

Tees&Elbows $R_4R_5R_6R_7 = 2.17 \times 1.17 \times 1.5 \times 2.5=9.52$

ERA 2

R.G. 1.60 Spectral Input

2% Damp:

$R_4R_5=2.0 \times 1.17=2.34$

Straight Pipe $R_4R_5R_6R_7=2.34 \times 1.0 \times 2.5=5.85$

Tees&Elbows $R_4R_5R_6R_7=2.34 \times 1.5 \times 2.5=8.78$

3% Damp:

$R_4R_5=1.74 \times 1.17=2.04$

Straight Pipe $R_4R_5R_6R_7 = 2.04 \times 1.17 \times 1.0 \times 2.5=5.10$

Tees&Elbows $R_4R_5R_6R_7 = 2.04 \times 1.17 \times 1.5 \times 2.5=7.65$

5% Damp:

$R_4R_5=1.48 \times 1.17=1.73$

Straight Pipe $R_4R_5R_6R_7 = 1.48 \times 1.17 \times 1.0 \times 2.5=4.34$

Tees&Elbows $R_4R_5R_6R_7 = 1.0 \times 1.17 \times 1.5 \times 2.5=6.51$

ERA 3

NUREG/CR-0098 Spectral Input

5% damping

$R_4R_5 = 1.0 \times 1.17 = 1.17$

Straight Pipe $R_4R_5R_6R_7 =$

$1.0 \times 1.17 \times 1.0 \times 2.1=2.46$

Tees&Elbows

$R_4R_5R_6R_7=1.0 \times 1.17 \times 1.5 \times 2.1=3.69$

Notes to Table 1:

- (1) The values shown in the numerator are the total allowable seismic stress defined as $(S_u - S_d - S_p)$ where the denominator is the limiting value of S_c by ASME Code.
- (2) These factors are considered in defining failure when S_u is reached in the outermost fiber of the pipe based on an elastic analysis. It is implicitly assumed that $S_u = 1.27 \times 1.33 = 1.69 S_y$ which effectively account for reduction factors 2 and 3 since $S_u=1.69 S_y$.
- (3) Not available for cantilever or simply supported pipe system geometries.
- (4) The median damping value for piping is taken as 5 % critically damping. The numbers shown are the ratios of the maximum spectral acceleration in the frequency range of 1.0 to 8.0 Hz which is the dominate frequency range for most nuclear safety related piping in the specified design spectra, with the damping percent indicated to the maximum acceleration in the same frequency range for a 5.0 percent damped NUREG/CR 0098 median shaped spectrum.
- (5) The ASME and U.S. NRC permit coupled analysis where the primary system (building) is dynamically connected to the secondary system (piping). This dynamic coupling has the effect of introducing the mass ratio effect. Not available if effective mass ratio is less than about one tenth of a percent.
- (6) The realistic B₂ index is taken from existing literature on the subject.

(7) The U.S. NRC currently does not permit the use of inelastic seismic spectra in the design or verification of nuclear safety related piping while the U.S. DOE and IAEA does. The inelastic energy reduction factors shown are based on ductility factors recommended to the U.S. NRC by Newman and Hall [5,6] and Coats[11].

(8) The values Rx shown are used by dividing their product into the seismic stress allowable to compute the best estimate median seismic stress in the piping crosssection

(9) Since no U.S. nuclear power plant has been designed since 1980, it is not clear what criteria would be permitted by U.S. NRC Division of Reactor Regulation.

Table 2 -- Failure Probability for Straight Pipe Segments as Obtained by Numerical Integration of (Eq. 2)

		Eq. 1	Eq. 1	Eq. 2	Eq. 2	Eq. 2	Eq. 3	Eq. 3
		Housner 0.2g 0.5%	Housner 0.2g 1%	RG 1.60 0.2g 2%	RG 1.60 0.2g 3%	RG 1.60 0.2g 5%	NUREG 0098 0.2g 5%	NUREG 0098 0.3g 5%
Elastic Response	$\sigma_{seismic, median}$	7.5	10.2	15.06	17.28	25.23	49.38	49.38
	P_{IDBE}	2.926×10^{-2}	7.797×10^{-2}	5.155×10^{-2}	7.708×10^{-2}	1.995×10^{-1}	3.263×10^{-1}	3.290×10^{-1}
	P_{Ftot} LH	7.791×10^{-5}	3.095×10^{-4}	1.694×10^{-4}	3.042×10^{-4}	1.425×10^{-3}	3.661×10^{-3}	8.047×10^{-4}
	MH	4.287×10^{-4}	1.446×10^{-3}	8.476×10^{-4}	1.424×10^{-3}	5.628×10^{-3}	1.294×10^{-2}	3.385×10^{-3}
2.5 Median Inelastic factor	$\sigma_{seismic, median}$	3.0	4.04	6.03	6.91	10.6	24.68	24.68
	P_{IDBE}	4.810×10^{-4}	2.229×10^{-3}	1.161×10^{-3}	2.289×10^{-3}	1.476×10^{-2}	6.468×10^{-2}	6.565×10^{-2}
	P_{Ftot} LH	7.333×10^{-7}	3.594×10^{-6}	1.796×10^{-6}	3.700×10^{-6}	3.229×10^{-5}	2.348×10^{-4}	3.705×10^{-5}
	MH	1.063×10^{-5}	3.400×10^{-5}	2.021×10^{-5}	3.477×10^{-5}	2.009×10^{-4}	1.131×10^{-3}	2.258×10^{-4}
4.0 Median Inelastic factor	$\sigma_{seismic, median}$	1.875	2.525	3.77	3.90	5.17	24.68	24.68
	P_{IDBE}	2.855×10^{-5}	1.806×10^{-4}	8.224×10^{-5}	1.014×10^{-4}	5.163×10^{-4}	6.468×10^{-2}	6.565×10^{-2}
	P_{Ftot} LH	5.457×10^{-8}	2.853×10^{-7}	1.384×10^{-7}	1.673×10^{-7}	7.867×10^{-7}	2.348×10^{-4}	3.705×10^{-5}
	MH	1.896×10^{-6}	5.570×10^{-6}	3.453×10^{-6}	3.910×10^{-6}	1.117×10^{-5}	1.131×10^{-3}	2.258×10^{-4}

LH = low hazard (curve A), MH = moderate hazard (curve B)

Table 3 - Failure Probability for Tees and Elbows as Obtained by Numerical Integration of (Eq. 2)

		Eq. 1	Eq. 1	Eq. 2	Eq. 2	Eq. 2	Eq. 3	Eq. 3
		Housner 0.2g 0.5%	Housner 0.2g 1%	RG 1.60 0.2g 2%	RG 1.60 0.2g 3%	RG 1.60 0.2g 5%	NUREG 0098 0.2g 5%	NUREG 0098 0.3g 5%
Elastic Response	$\sigma_{seismic, median}$	7.5	10.2	15.06	17.28	25.23	49.38	49.38
	P_{IDBE}	2.926×10^{-2}	7.797×10^{-2}	5.155×10^{-2}	7.708×10^{-2}	1.995×10^{-1}	3.263×10^{-1}	3.290×10^{-1}
	P_{Ftot} LH	7.791×10^{-5}	3.095×10^{-4}	1.694×10^{-4}	3.042×10^{-4}	1.425×10^{-3}	3.661×10^{-3}	8.047×10^{-4}
	MH	4.287×10^{-4}	1.446×10^{-3}	8.476×10^{-4}	1.424×10^{-3}	5.628×10^{-3}	1.294×10^{-2}	3.385×10^{-3}
2.5 Median Inelastic factor	$\sigma_{seismic, median}$	2.0	2.69	4.02	4.61	7.07	16.45	16.45
	P_{IDBE}	4.332×10^{-5}	2.626×10^{-4}	1.216×10^{-4}	2.714×10^{-4}	2.559×10^{-3}	1.616×10^{-2}	1.647×10^{-2}
	P_{Ftot} LH	7.832×10^{-8}	4.068×10^{-7}	1.975×10^{-7}	4.199×10^{-7}	4.178×10^{-6}	3.616×10^{-5}	4.833×10^{-6}
	MH	2.389×10^{-6}	7.077×10^{-6}	4.361×10^{-6}	7.232×10^{-6}	3.817×10^{-5}	2.212×10^{-4}	4.273×10^{-5}
4.0 Median Inelastic factor	$\sigma_{seismic, median}$	1.25	1.68	2.51	2.60	3.45	16.45	16.45
	P_{IDBE}	1.673×10^{-6}	1.391×10^{-5}	5.618×10^{-6}	7.150×10^{-6}	4.705×10^{-5}	1.616×10^{-2}	1.647×10^{-2}
	P_{Ftot} LH	5.434×10^{-9}	2.971×10^{-8}	1.415×10^{-8}	1.719×10^{-8}	8.420×10^{-8}	3.616×10^{-5}	4.833×10^{-6}
	MH	4.485×10^{-7}	1.291×10^{-6}	8.112×10^{-7}	9.162×10^{-7}	2.503×10^{-6}	2.212×10^{-4}	4.273×10^{-5}

LH = low hazard (curve A), MH = moderate hazard (curve B) – P_{Ftot} are per year

Note: These are ASME Code based failure probabilities.