White Paper on Continued Applicability of NUREG-1903

1 Introduction

U.S. Nuclear Regulatory Commission (NRC) requirements, as set forth in Title 10 of the *Code of Federal Regulations* (10 CFR) 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors," state that the emergency core cooling system shall be sized to provide adequate makeup water to compensate for a break of the largest diameter pipe in the primary system (i.e., so-called "double-ended guillotine break"). This prescriptive rule does not recognize the fact that the double-ended guillotine break is an extremely unlikely event. To define an alternative risk-informed break size, termed the transition break size (TBS), the NRC staff used the expert elicitation process to establish a baseline break size corresponding to a break frequency of once per 100,000 years (i.e., 1E-05 per year) in NUREG-1829, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process," issued June 2005 (NRC, 2005). The staff then adjusted this baseline break size to account for other significant contributing factors that the expert elicitation did not explicitly address, such as rare event loadings (e.g., seismic events). Recently, the staff has re-evaluated the results of NUREG-1829 and documented their continued adequacy in its "White Paper on Continued Applicability of NUREG-1829," issued 2024 (NRC, 2024a). In a separate study, the staff assessed potential seismic effects on the postulated TBS in NUREG-1903, "Seismic Considerations For the Transition Break Size," issued February 2008 (NRC, 2008). In this study, the staff used different approaches in evaluating flawed and unflawed piping and indirect failures of other components and component supports that could lead to piping failure. This study demonstrated that the critical flaws associated with the stresses induced by seismic events with an annual probability of exceedance of 1E-05 and 1E-6 are large, and, coupled with other mitigative measures, the probabilities of pipe breaks larger than the TBS are likely to be less than 1E-05 per year. Similarly, for the cases studied, the probabilities of indirect failures of large reactor coolant system (RCS) piping systems are less than 1E-05 per year.

Since the publication of the Lawrence Livermore National Laboratory (LLNL) seismic hazard and its use in the original seismic assessment performed for the TBS in NUREG-1903, nuclear power plant (NPP) licensees in the Central and Eastern United States (CEUS) re-evaluated and submitted their seismic hazard and screening reports (SHSRs). This was in response to the letter issued by the NRC under 10 CFR 50.54(f) (hereafter referred to as the "50.54(f) letter") and associated information requests (NRC, 2012) following the March 11, 2011, Great East Japan Earthquake and tsunami and resulting accident at the Fukushima Dai-ichi NPP. These updated seismic hazard data have superseded the LLNL hazard curves and uniform hazard spectrum (NRC, 1994) that were originally used in NUREG-1903. The purpose of the current study is to re-assess the effects of seismic loadings on the postulated TBS using the updated seismic hazard curves. For the sake of the evaluation process, the staff used essentially the same approaches and methodologies described in NUREG-1903 for evaluating direct (flawed and unflawed) and indirect piping failures, with the exception of minor enhancements to the approaches. Please note that the intent of the staff study is to obtain a representative measure of seismic effects on the proposed TBS, and not to produce bounding results that will apply to all U.S. plants by encompassing all potential variations, including site-to-site seismic hazard variabilities, and plant-to-plant design differences. A generic or bounding approach is not used because seismic-induced LOCA frequencies are highly site specific and heavily dependent on plant-specific design details.

2 Assessment of NUREG-1903 Results and Continued Applicability to Transition Break Size

NUREG-1903 considered the effects of direct (flawed and unflawed) and indirect piping failures on the selection of the TBS. For flawed and unflawed piping, the study used a hybrid deterministic and probabilistic fracture mechanics analysis. For indirect failure, the approach was based on an earlier study by LLNL (NRC, 1985a, 1985b, 1985c, and 1989). The staff documented the results of this study in NUREG-1903. In this section, the staff re-assesses these analysis cases using the SHSR submittals to measure the impact of the updated seismic hazards on the TBS frequency determination.

2.1 Unflawed Piping Failure

For the direct unflawed piping failure, the staff originally used a screening approach in which the probability of exceedance for stresses corresponding to 1 percent failure probability was obtained for the 26 pressurized-water reactors (PWRs) for the most highly stressed hot leg, cold leg, or cross-over (suction) legs. For this original assessment, the staff used the mean LLNL seismic hazard curves corresponding to each selected site (NRC, 1994) by following detailed analysis approaches and key steps laid out in Figure 1 (Figure 4-2 of NUREG-1903).

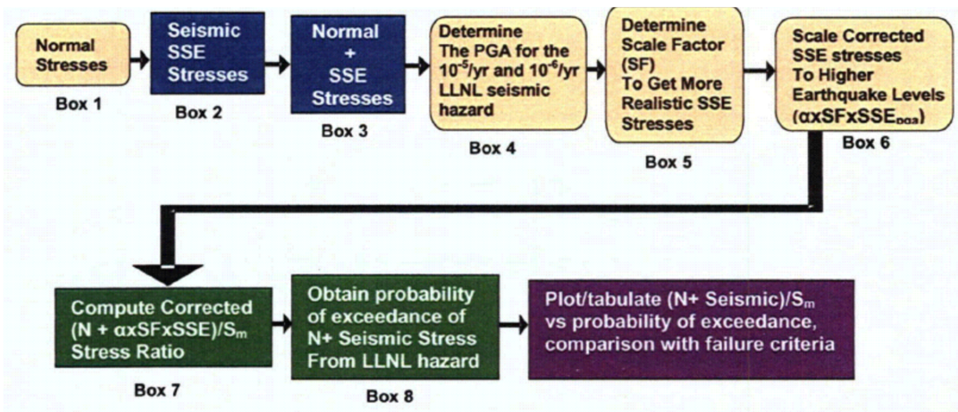

Figure 1. Approach and Key Steps for Unflawed Pipe Evaluation (Figure 4-2 of NUREG-1903)

The NUREG-1903 results show that failure probabilities for unflawed piping are significantly low compared to the 1E-05 per year frequency used as a basis to establish the TBS (see Figure 4-4 of NUREG-1903 for more details).

Since the use of the LLNL seismic hazard data in the original analysis, all U.S. NPP licensees re-evaluated and submitted their SHSRs in response to the 50.54(f) letter. The seismic hazard characterization of each NPP site, including spectral shapes and amplification functions, appears in NUREG/KM-0017, “Seismic Hazard Evaluations for U.S. Nuclear Power Plants: Near-Term Task Force Recommendation 2.1 Results,” issued December 2021 (NRC, 2021). To examine the impact of the hazard re-evaluation results on the TBS frequency criterion, the staff has revisited the results of the original seismic assessments performed for the 26 PWRs in NUREG-1903. Key input data needed for the analysis, such as the maximum normal stress, safe-shutdown earthquake (SSE) stress, and seismic scale factor for each plant, have been obtained from NUREG-1903. The seismic scale factor is an adjustment factor that is applied to the conservatively biased design-basis seismic stress to obtain a more realistic estimate of the seismic stress for use in the current analysis. For example, Table 1 gives such information for the cold leg discharge of Plant A.

Table 1. Key Analysis Information for Plant A

Plant	Piping Location	Maximum Normal Stress, N (ksi)	SSE (g)	Maximum SSE (ksi)	Seismic Scale Factor	S_m (ksi)
Plant A	Cold Leg Discharge	9.528	0.17	9.3	0.591	17

Additionally, two simplified assumptions have been made to facilitate the analysis:

(1) Conservative Design Stress Intensity Value (S_m): DG-1428, "Plant-Specific Applicability of Transition Break Size Specified in 10 CFR 50.46a," issued 2024 (NRC, 2024b), provides a table of design stress intensity values (or S_m table) for two representative materials (CF8A and A516) at three temperatures (500, 600, and 650 degrees Fahrenheit (°F)). The lowest S_m value is 18.4 kilopounds per square inch (ksi) for A516 at 650°F. Thus, a more conservative S_m of 17 ksi is assumed for all analysis cases. This is shown in the last column of Table 1.

(2) Conservative Failure Criterion: Table 4-7 of NUREG-1903 provides the stress values corresponding to 1 percent failure probability for components of interest. NUREG-1903 originally used $4.5S_m$ (nozzle girth-weld) as the bounding failure criterion, as reviews of piping stresses in instances of leak before break (LBB) suggest that the nozzle girth welds are typically the locations of highest stress. The current study conservatively uses the lowest stress value of $2.9S_m$ for boiling-water reactor (BWR) elbows for all PWR and BWR cases. Stress values corresponding to 50 percent failure probabilities are 1.4 times the stress values corresponding to 1 percent failure probability for straight pipe and elbows. This gives the 50 percent failure probability stress value of $1.4 \times 2.9S_m = 4.06S_m$.

Taken together, these conservative assumptions are intended to produce the highest exceedance frequency for each analysis case regardless of the type of material and location of critical failure. Table 2 provides the results of estimates of normalized stress ratios and probability of exceedance for peak ground acceleration (PGA) associated with Plant A, based on the information in Table 1 and obtained from NUREG/KM-0017, as shown graphically in Figure 2. The probability of exceedance of stresses corresponding to 1 percent failure probability is estimated to be 7.1E-07 by linear interpolation from Table 2, which is significantly less than the TBS criterion of 1E-05.

Table 2. Estimates of Normalized Stress Ratios and Probability of Exceedance for Plant A

PGA or Sa	Frequency of Exceedance	α = ACC./SSE_{PGA}	CORRECTED SEISMIC STRESSES, ksi $\alpha \times SF \times SSE$	(N+Seismic)/S_m VALUES
0.0261	1.000E-03	0.15	0.84	0.61
0.0284	9.189E-04	0.17	0.92	0.61
0.0300	8.600E-04	0.18	0.97	0.62
0.0317	7.986E-04	0.19	1.03	0.62
0.0335	7.381E-04	0.20	1.08	0.62
0.0354	6.807E-04	0.21	1.15	0.63
0.0373	6.271E-04	0.22	1.21	0.63
0.0394	5.775E-04	0.23	1.27	0.64
0.0417	5.315E-04	0.25	1.35	0.64
0.0440	4.889E-04	0.26	1.42	0.64
0.0465	4.494E-04	0.27	1.50	0.65

PGA or Sa	Frequency of Exceedance	α = ACC./SSE_{PGA}	CORRECTED SEISMIC STRESSES, ksi $\alpha \times SF \times SSE$	(N+Seismic)/S_m VALUES
0.0491	4.128E-04	0.29	1.59	0.65
0.0518	3.790E-04	0.30	1.68	0.66
0.0547	3.479E-04	0.32	1.77	0.66
0.0578	3.192E-04	0.34	1.87	0.67
0.0611	2.929E-04	0.36	1.98	0.68
0.0645	2.689E-04	0.38	2.09	0.68
0.0681	2.468E-04	0.40	2.20	0.69
0.0719	2.265E-04	0.42	2.33	0.70
0.0760	2.080E-04	0.45	2.46	0.71
0.0802	1.909E-04	0.47	2.59	0.71
0.0847	1.752E-04	0.50	2.74	0.72
0.0895	1.608E-04	0.53	2.90	0.73
0.0945	1.476E-04	0.56	3.06	0.74
0.0998	1.354E-04	0.59	3.23	0.75
0.1054	1.240E-04	0.62	3.41	0.76
0.1113	1.134E-04	0.65	3.60	0.77
0.1176	1.036E-04	0.69	3.80	0.78
0.1242	9.439E-05	0.73	4.02	0.80
0.1312	8.582E-05	0.77	4.24	0.81
0.1385	7.785E-05	0.81	4.48	0.82
0.1463	7.048E-05	0.86	4.73	0.84
0.1545	6.371E-05	0.91	5.00	0.85
0.1632	5.751E-05	0.96	5.28	0.87
0.1724	5.188E-05	1.01	5.58	0.89
0.1820	4.677E-05	1.07	5.89	0.91
0.1923	4.216E-05	1.13	6.22	0.93
0.2030	3.801E-05	1.19	6.57	0.95
0.2144	3.426E-05	1.26	6.94	0.97
0.2265	3.088E-05	1.33	7.33	0.99
0.2392	2.784E-05	1.41	7.74	1.02
0.2526	2.510E-05	1.49	8.17	1.04
0.2668	2.262E-05	1.57	8.63	1.07
0.2818	2.039E-05	1.66	9.12	1.10
0.2976	1.837E-05	1.75	9.63	1.13
0.3143	1.654E-05	1.85	10.17	1.16
0.3320	1.488E-05	1.95	10.74	1.19
0.3506	1.337E-05	2.06	11.34	1.23
0.3703	1.199E-05	2.18	11.98	1.27
0.3911	1.073E-05	2.30	12.65	1.30
0.4130	9.589E-06	2.43	13.36	1.35
0.4362	8.548E-06	2.57	14.11	1.39
0.4607	7.600E-06	2.71	14.90	1.44
0.4866	6.741E-06	2.86	15.74	1.49
0.5139	5.965E-06	3.02	16.63	1.54
0.5427	5.268E-06	3.19	17.56	1.59
0.5732	4.643E-06	3.37	18.54	1.65
0.6054	4.087E-06	3.56	19.59	1.71
0.6394	3.592E-06	3.76	20.69	1.78

PGA or Sa	Frequency of Exceedance	α = ACC./SSE_{PGA}	CORRECTED SEISMIC STRESSES, ksi $\alpha \times SF \times SSE$	(N+Seismic)/S_m VALUES
0.6753	3.155E-06	3.97	21.85	1.85
0.7132	2.768E-06	4.20	23.07	1.92
0.7532	2.428E-06	4.43	24.37	1.99
0.7955	2.127E-06	4.68	25.74	2.07
0.8402	1.863E-06	4.94	27.18	2.16
0.8873	1.630E-06	5.22	28.71	2.25
0.9371	1.425E-06	5.51	30.32	2.34
0.9898	1.243E-06	5.82	32.02	2.44
1.0453	1.083E-06	6.15	33.82	2.55
1.1040	9.419E-07	6.49	35.72	2.66
1.1660	8.172E-07	6.86	37.72	2.78
1.2314	7.073E-07	7.24	39.84	2.90
1.3006	6.104E-07	7.65	42.08	3.04
1.3736	5.253E-07	8.08	44.44	3.17
1.4507	4.508E-07	8.53	46.93	3.32
1.5322	3.856E-07	9.01	49.57	3.48
1.6182	3.288E-07	9.52	52.35	3.64
1.7090	2.795E-07	10.05	55.29	3.81
1.8050	2.369E-07	10.62	58.40	4.00
1.9063	2.000E-07	11.21	61.67	4.19
2.0133	1.683E-07	11.84	65.13	4.39
2.1264	1.410E-07	12.51	68.79	4.61
2.2457	1.177E-07	13.21	72.65	4.83
2.3718	9.764E-08	13.95	76.73	5.07
2.5050	8.057E-08	14.74	81.04	5.33
2.6456	6.605E-08	15.56	85.59	5.60
2.7941	5.374E-08	16.44	90.39	5.88
2.9510	4.336E-08	17.36	95.47	6.18
3.1167	3.465E-08	18.33	100.83	6.49
3.2916	2.741E-08	19.36	106.49	6.82
3.4764	2.142E-08	20.45	112.47	7.18
3.6716	1.653E-08	21.60	118.78	7.55
3.8777	1.258E-08	22.81	125.45	7.94
4.0954	9.425E-09	24.09	132.49	8.35
4.3254	6.948E-09	25.44	139.94	8.79
4.5682	5.032E-09	26.87	147.79	9.25
4.8246	3.577E-09	28.38	156.09	9.74
5.0955	2.491E-09	29.97	164.85	10.26
5.3816	1.699E-09	31.66	174.11	10.80
5.6837	1.134E-09	33.43	183.88	11.38
6.0028	7.390E-10	35.31	194.20	11.98

ACC. = acceleration

Sa = spectral acceleration

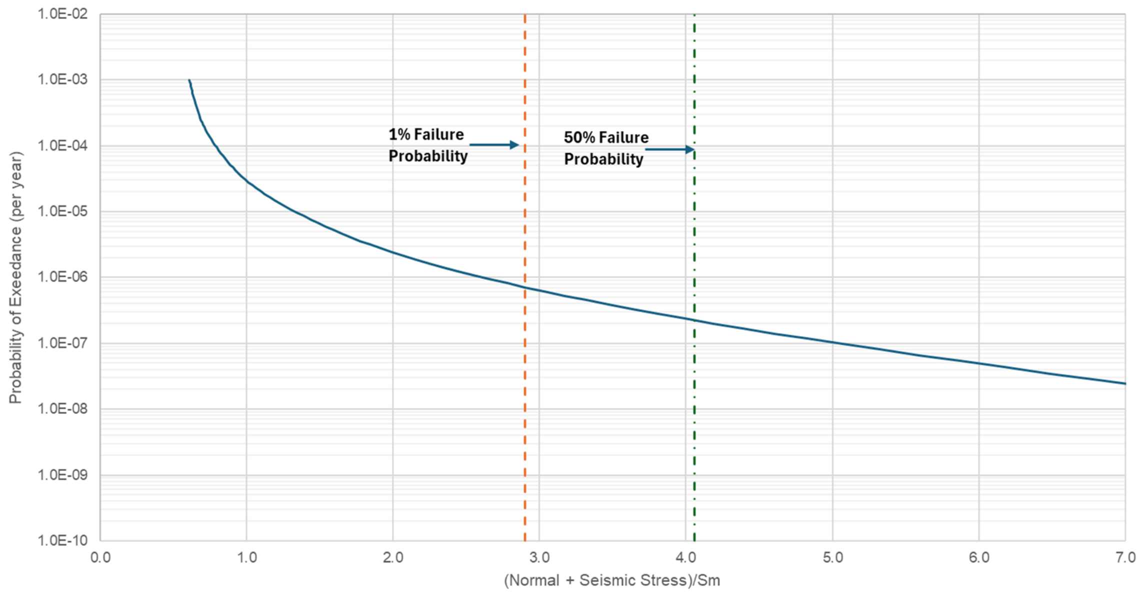

Figure 2. Probability of Exceedance Versus Maximum Normal + Seismic Stress in RCS Piping for Plant A

The same steps used for Plant A have been repeated for all the other PWRs that were originally considered in NUREG-1903, using their updated seismic hazard curves (NRC, 2021). Figure *3* provides a composite plot of the results of all the PWR plants considered in NUREG-1903.[1] As seen from Figure 3, the probabilities of exceedance corresponding to 1 percent probability of failure or high confidence of low probability of failure (HCLPF) are all below the TBS threshold, even if using the most conservative design stress intensity value and failure criterion.

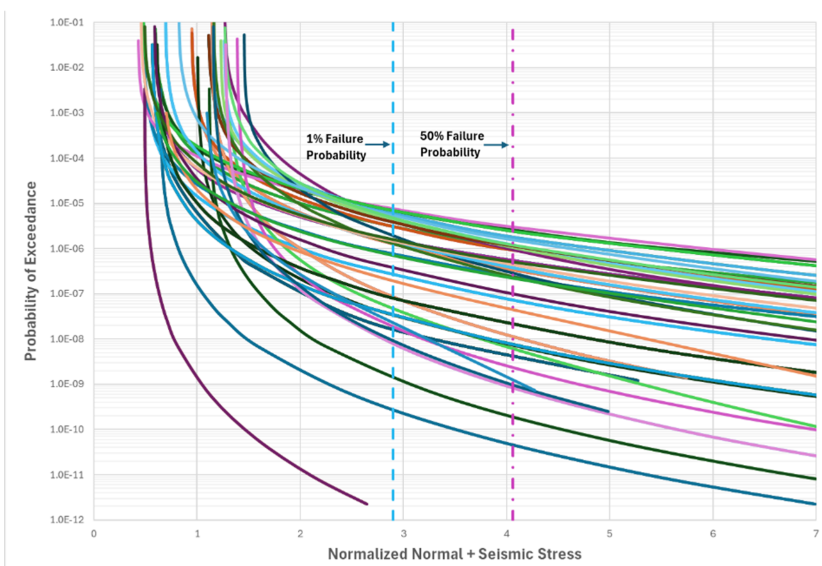

Figure 3. Probability of Exceedance Versus Maximum Normal + Seismic Stress in RCS Piping for 26 PWRs

In addition, to better determine whether seismic loading conditions significantly increase the probability of a break above the TBS in the current staff assessment, an unconditional piping

[1] The following plant sites were originally included in NUREG-1903 but are not included in the current study as they were permanently shut down: Big Rock Point, Crystal River, Haddam Neck, Kewaunee, La Crosse, Maine Yankee, Shoreham, Vermont Yankee, Yankee Rowe, and Zion.

failure probability has been obtained for each plant by using a representative mean large LOCA piping fragility curve that has the following parameter values from the Electric Power Research Institute (EPRI) report EPRI 3002000709, “Seismic Probabilistic Risk Assessment Implementation Guide,” issued December 2013 (EPRI, 2013):

- median capacity (A_m): 2.5g PGA
- randomness uncertainty, β_R: 0.3
- epistemic uncertainty, β_U: 0.4

This fragility function is shown graphically in Figure 4 and used for convolution with a site-specific mean hazard curve to compute the site-specific mean probability of unflawed piping failure for each plant.

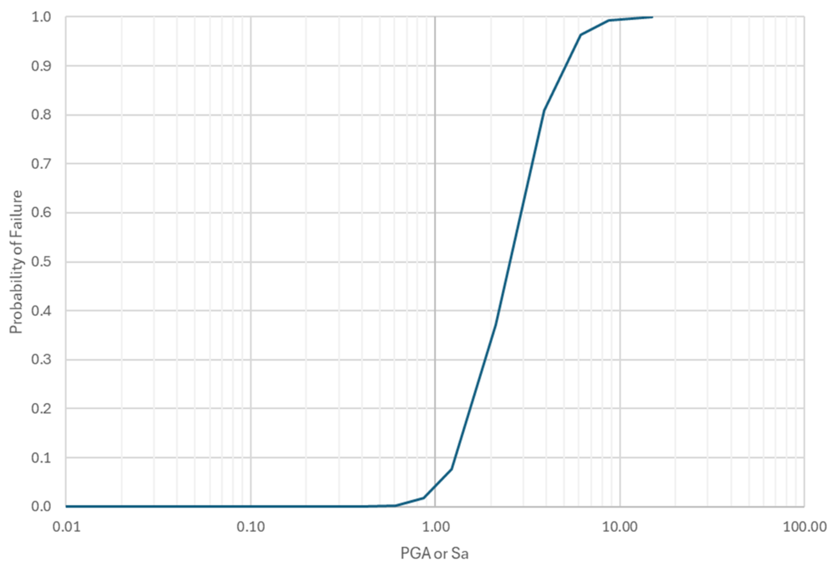

Figure 4. Representative Seismic Fragility Function for Large LOCA, A_m = 2.5g PGA and β_C = 0.5

In general, the seismic hazard curve is discretely defined as a seismic hazard vector or in tabular form for the mean value of PGA versus mean annual frequency of exceedance (MAFE). For example, Table 3 shows the seismic hazard vector for Plant B, and Figure 5 presents the same data graphically. As seen from Table 3, the hazard curve consists of a total of 19 seismic acceleration and frequency of exceedance pairs, with the accelerations ranging from 0.0005g to 10.0g.

Table 3. Mean Seismic Hazard Vector at PGA for Plant B

Seismic Acceleration (g)	MAFE
0.0005	7.640E-02
0.0010	5.910E-02
0.0050	1.770E-02
0.0100	9.120E-03
0.0150	5.980E-03
0.0300	2.550E-03
0.0500	1.180E-03
0.0750	5.950E-04
0.1000	3.570E-04
0.1500	1.670E-04

Seismic Acceleration (g)	MAFE
0.3000	4.310E-05
0.5000	1.500E-05
0.7500	6.080E-06
1.0000	3.040E-06
1.5000	1.040E-06
3.0000	1.260E-07
5.0000	2.140E-08
7.5000	4.600E-09
10.0000	1.430E-09

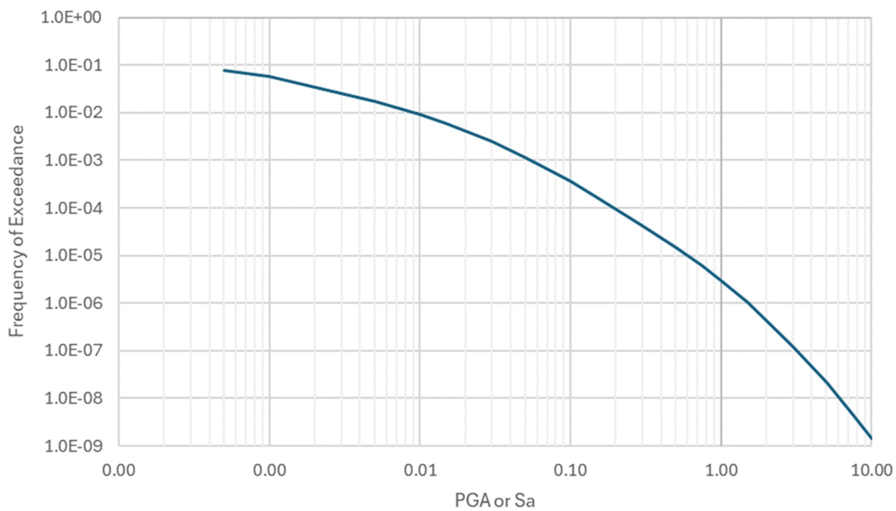

Figure 5. Mean Seismic Hazard Curve at PGA for Plant B

Given the large LOCA piping fragility and seismic hazard curve for each plant, the following steps are taken to compute the mean failure probability of unflawed piping:

(1) Step 1: The seismic acceleration range needs to be partitioned into N categories (bins) to define N discrete seismic event scenarios with increasing intensity. Typically, 5 to 10 seismic bins have been used in past and recent seismic probabilistic risk assessments. For the Plant B case above, Table 4 defines 19 seismic event categories (bins), based on the seismic acceleration data in Table 3. The seismic initiating frequency of each bin is calculated as the difference of the frequencies of two bin range limits. For example, the seismic initiating frequency for Bin 1, 1.730E-02, is obtained by subtracting 5.910E-02 at 0.0005g from 7.640E-02 at 0.0005g. The seismic frequencies for the remaining Bins 2 through 18 have been defined in the same way. For the last bin, Bin 19, which has no upper bound acceleration, the bin seismic frequency is simply the exceedance frequency at 10g.

(2) Step 2: For each bin, a mean acceleration is assigned in terms of the geometric average of the bin end point accelerations. For example, the mean acceleration for Bin 1 is obtained by √ (0.0005 x 0.0010) = 0.0007. For the last bin, Bin 19, which has no upper bound acceleration, the bin acceleration is arbitrarily set as 1.5 times 10g = 15g.

(3) Step 3: Then, a mean seismic failure probability for the given bin acceleration level is calculated using the following equation (EPRI, 2018):

$$P_f(A) = \Phi[\ln(A/A_m)/\beta_c] \tag{1}$$

where

Φ	=	is the standard normal cumulative distribution function
A	=	acceleration level of the seismic event
A_m	=	median of the component fragility (or median capacity)
β_c	=	composite variability, defined as $(\beta_r^2 + \beta_u^2)^{1/2}$
β_r	=	logarithmic standard deviation representing random uncertainty
β_u	=	logarithmic standard deviation representing systematic or modeling uncertainty

For example, the mean seismic failure probability for Bin 1 is calculated as follows:

$$P_f(0.0007) = \Phi[\ln(0.001/2.5)/(0.3^2 + 0.4^2)^{1/2}] = 2.511\text{E-}60$$

(4) Step 4: Next, a bin-specific seismic risk contribution is obtained by simply multiplying the bin seismic initiating frequency with the mean seismic failure probability obtained from the previous steps. For Bin 1, the bin seismic risk is obtained by 1.730E-02 x 2.511E-60 = 4.344E-62.

(5) Step 5: Steps 2 through 4 are repeated for all seismic hazard bins to compute bin-specific seismic risk contributions or piping failure probabilities (see Table 4 for details).

(6) Step 6: Finally, the obtained bin-specific piping failure probabilities are summed to obtain the overall mean piping failure probability. For Plant B, the overall piping failure probability is 6.746E-07 (see the bottom of Table 4). This is significantly less than the TBS frequency criterion.

Table 4. Seismic Hazard Bins and Risk Convolution for Plant B—Direct Piping Failure

Bin No.	Lower Acc., PGA	Upper Acc., PGA	Bin Acc.	Seismic Bin Frequency	Bin LOCA Fragility	Bin Seismic Risk, per year
1	0.0005	0.0010	0.0007	1.730E-02	2.511E-60	4.344E-62
2	0.0010	0.0050	0.0022	4.140E-02	4.521E-45	1.872E-46
3	0.0050	0.0100	0.0071	8.580E-03	4.163E-32	3.572E-34
4	0.0100	0.0150	0.0122	3.140E-03	9.975E-27	3.132E-29
5	0.0150	0.0300	0.0212	3.430E-03	7.222E-22	2.477E-24
6	0.0300	0.0500	0.0387	1.370E-03	3.879E-17	5.314E-20
7	0.0500	0.0750	0.0612	5.850E-04	5.919E-14	3.463E-17
8	0.0750	0.1000	0.0866	2.380E-04	8.754E-12	2.083E-15
9	0.1000	0.1500	0.1225	1.900E-04	8.083E-10	1.536E-13
10	0.1500	0.3000	0.2121	1.239E-04	4.035E-07	4.999E-11
11	0.3000	0.5000	0.3873	2.810E-05	9.585E-05	2.693E-09

Bin No.	Lower Acc., PGA	Upper Acc., PGA	Bin Acc.	Seismic Bin Frequency	Bin LOCA Fragility	Bin Seismic Risk, per year
12	0.5000	0.7500	0.6124	8.920E-06	2.451E-03	2.186E-08
13	0.7500	1.0000	0.8660	3.040E-06	1.699E-02	5.166E-08
14	1.0000	1.5000	1.2247	2.000E-06	7.677E-02	1.535E-07
15	1.5000	3.0000	2.1213	9.140E-07	3.713E-01	3.393E-07
16	3.0000	5.0000	3.8730	1.046E-07	8.093E-01	8.466E-08
17	5.0000	7.5000	6.1237	1.680E-08	9.634E-01	1.619E-08
18	7.5000	10.0000	8.6603	3.170E-09	9.935E-01	3.149E-09
19	10.0000	N/A	15.0000	1.430E-09	9.998E-01	1.430E-09
					∑ =	6.746E-07

The above steps have been implemented for all CEUS NPP sites that submitted their SHSRs. Table 5 provides the implementation results for those sites that were originally included in NUREG-1903. The results show that the unconditional failure probabilities of unflawed piping for the site considered herein are well below the TBS frequency criterion, with the maximum piping failure probability of 3.19E-6 for Plant XVIII in Table 5.[2] Therefore, there is a clear indication that unflawed piping generally has a very low probability of failure attributable to seismic loads, which is consistent with the conclusion of the original staff assessment in NUREG-1903 and the excellent performance experience of piping systems during strong, damaging earthquakes (NRC, 1985d). However, licensees need to verify this conclusion on a case-by-case basis, as the staff performed its assessment using the representative piping fragility and seismic fragility parameters such as seismic scale factors, and seismic loads estimates are highly site specific and dependent on plant configurations.

Table 5. Unflawed Piping Failure Probability for CEUS NPP Sites with SHSRs

No.	Site	Unflawed Piping Failure Probability, per year
1	I	3.29E-07
2	II	1.00E-07
3	III	1.09E-06
4	IV	2.74E-07
5	V	4.87E-07
6	VI	1.56E-07
7	VII	6.40E-07
8	VIII	2.10E-06
9	IX	4.47E-08
10	X	1.00E-06
11	XI	4.90E-09
12	XII	2.22E-07
13	XIII	8.03E-08
14	XIV	1.80E-06
15	XV	9.11E-07
16	XVI	2.35E-07

2 For a parallel comparison with the results of NUREG-1903, Table 5 only includes those sites that were originally included in NUREG-1903 and submitted their SHSRs in response to the 50.54(f) letter. Appendix A gives the results of those plants that were not originally included in NUREG-1903 but submitted their SHSRs.

No.	Site	Unflawed Piping Failure Probability, per year
17	XVII	1.73E-07
18	XVIII	3.19E-06
19	XIX	1.53E-06
20	XX	9.23E-08
21	XXI	4.36E-07
22	XXII	1.85E-06
23	XXIII	1.81E-07
24	XXIV	2.55E-06
25	XXV	6.60E-08
26	XXVI	2.30E-08
27	XXVII	1.95E-07
28	XXVIII	4.18E-08
29	XXIX	1.48E-06
30	XXX	9.37E-08
31	XXXI	2.61E-06
32	XXXII	1.19E-06
33	XXXIII	5.09E-08
34	XXXIV	5.56E-08
35	XXXV	8.64E-09
36	XXXVI	1.23E-06
37	XXXVII	3.44E-08
38	XXXVIII	3.82E-07
39	XXXIX	5.27E-09
40	XL	1.04E-06
41	XLI	6.75E-07

Note 1: The following plants were originally included in NUREG-1903 but were not included in the current study as they were permanently shut down:
Big Rock Point, Crystal River, Haddam Neck, Kewaunee, La Crosse, Maine Yankee, Shoreham, Vermont Yankee, Yankee Rowe, and Zion.

2.2 Flawed Piping Failure

For the direct flawed piping failure, NUREG-1903 used two approaches based on the "flaw exclusion" principle rather than the detailed probabilistic fracture mechanics approach. The first approach determined critical surface cracks (depths and lengths of circumferentially oriented surface flaws leading to piping failure) at the 1E-05 and 1E-06 seismic stresses, while the other approach was similar to an LBB analysis, but for critical circumferential through-wall cracks at the 1E-05 and 1E-06 seismic stresses. Figure 6 gives an overview of the process for determining code-allowable surface flaw sizes at design stresses, and critical flaw sizes for combined normal operational stresses and seismic stresses attributable to earthquake ground motion levels associated with the 1E-05 or 1E-06 annual probability of exceedance, respectively.

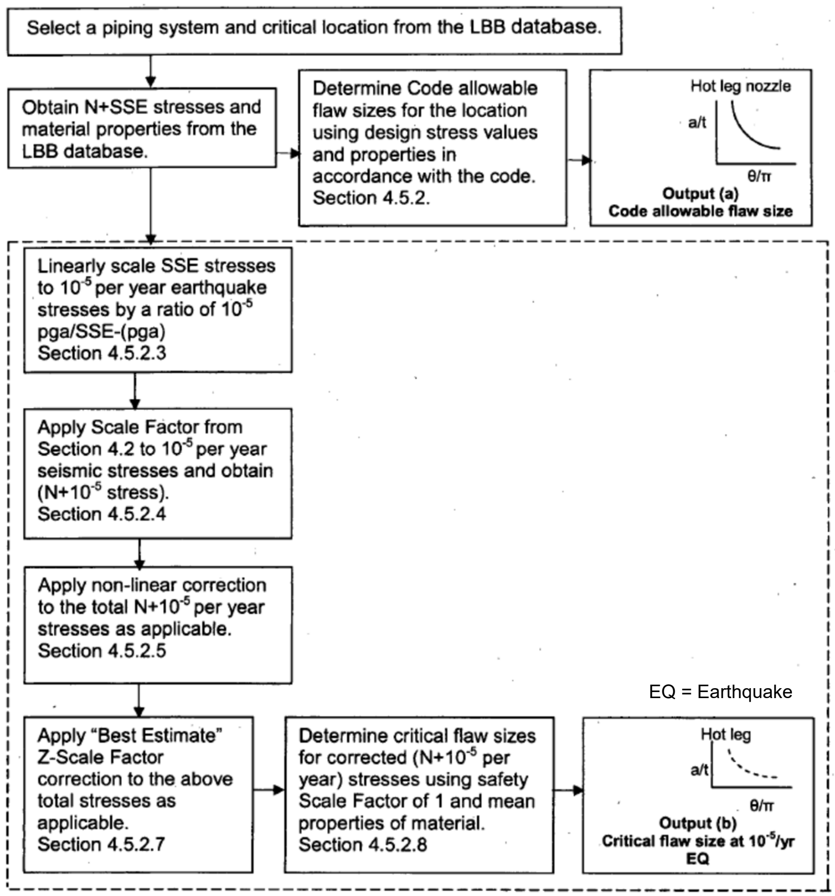

Figure 6. Critical Flaw Size Determination Procedure (Figure 4-6 of NUREG-1903)

The seismic stresses for the 1E-05 or 1E-06 annual probability of exceedance were obtained by linear scaling of the SSE stress times the ratio of the PGA for the 1E-05 or 1E-06 annual probability of exceedance seismic event to the PGA for the SSE obtained from the LLNL hazard curves. Then, the linearly scaled seismic stresses were multiplied by a seismic scale factor to obtain a more realistic estimate of the seismically induced inertial bending stress. Next, the normal stresses were added to this value to determine the total stresses. Finally, the elastically calculated stresses were converted to the corresponding nonlinear stresses by the elastic stress correction scale factor. The results of the two approaches demonstrate that the critical flaws associated with the stresses induced by the 1E-05 and 1E-06 probability of exceedance events are generally large, and, coupled with other mitigating aspects, the probabilities of pipe breaks larger than the TBS are likely to be less than the TBS frequency criterion.

As mentioned above, the staff used the LLNL hazard curves in the original NUREG-1903 study. Since then, all CEUS NPP licensees have re-evaluated their seismic hazards in response to the 50.54(f) letter. These updates are expected to affect the ratio of the PGA for the 1E-05 or 1E-06 annual probability of exceedance seismic event to the PGA for the SSE due to the seismic frequency changes and the seismic scale factor due to the shape differences between the ground motion response spectrum and design spectra used in the original design analysis. Nonetheless, it is most likely that the general conclusion obtained in NUREG-1903 would remain the same, as very large flaws need to be present to produce seismic-induced breaks even for very rare/large earthquakes. However, as the results are limited to those components considered in this study and the recent seismic hazard updates, licensees need to verify this conclusion on a case-by-case basis for its applicability to their plant sites by following the process shown in Figure 6, as well as the guidance provided in DG-1428.

2.3 Indirect Piping Failure

Indirect failures are pipe ruptures caused by failures of major components (e.g., reactor pressure vessel, steam generators, and reactor coolant pumps (RCPs)) or component supports as a result of an earthquake. In NUREG-1903, the NRC staff originally conducted a scoping evaluation of indirect failure for the two representative PWR nuclear steam supply system (NSSS) vendors: Combustion Engineering (CE) and Westinghouse. In this scoping study, the staff developed the plant-specific fragility function of the lowest capacity component for each plant, which is characterized by the fragility parameter values shown in **Table 6**.

Table 6. Fragility Parameter Values for the Two Representative CE and Westinghouse Plants

NSSS Vendor	Review Level Earthquake	Factor of Safety	Median Capacity	Composite Uncertainty
CE	0.15g	11.93	1.79g	0.62
Westinghouse	0.25g	7.52	1.88g	0.42

For each plant, the fragility function was convolved with the seismic hazard derived from the seismic hazard curves and uniform hazard spectrum in NUREG-1488, “Revised Livermore Seismic Hazard Estimates for Sixty-Nine Nuclear Power Plant Sites East of the Rocky Mountains,” issued April 1994 (NRC, 1994), to compute the unconditional mean probability of indirect piping failure. The convolution results showed that the mean probability of failure of the lowest capacity component support was 1.65E-6 per year for the CE plant and 7.6E-7 per year for the Westinghouse plant. Based on this, NUREG-1903 concluded that indirectly induced piping failure is unlikely to govern the combined failure of piping. However, the NRC staff noted that this conclusion is not necessarily bounding and may not be applicable to all sites, as the assessment used the outdated LLNL seismic hazard curves and the representative major component support fragilities in lieu of plant-specific component or support fragilities. In other words, once a plant-specific assessment is performed for each site, it is not guaranteed that the same conclusion made in NUREG-1903 may be obtained. More importantly, this is further complicated by the aforementioned recent seismic hazard re-evaluation results reported by all U.S. NPP licensees in response to the 50.54(f) letter. The assessment results documented in NUREG/KM-0017 show that some sites have experienced noticeable changes in both the seismic exceedance frequencies and ground motion response spectrum shapes relative to those of the prior assessments. Taken together, these changes are expected to affect seismic demand estimates that are used as key input to the fragility analysis of a key component itself or its support, as well as the resulting unconditional probability of indirectly induced piping failure. Therefore, it is essential for each plant to perform a plant-specific assessment of indirect piping failures using the most up-to-date seismic hazard information. To measure the potential impact of the updated seismic hazards on the TBS frequency criterion, the staff followed the same steps taken to compute the unconditional mean probability of direct piping failure in the previous section. To this end, the staff used the following conservative fragility parameter values selected from **Table 6**:

- median capacity (A_m): 1.79g PGA
- composite variability, β_C: 0.62
- HCLPF capacity: 1.79g Exp(-2.326 x 0.62) = 0.42g

Figure 7 shows this graphically as a solid line.

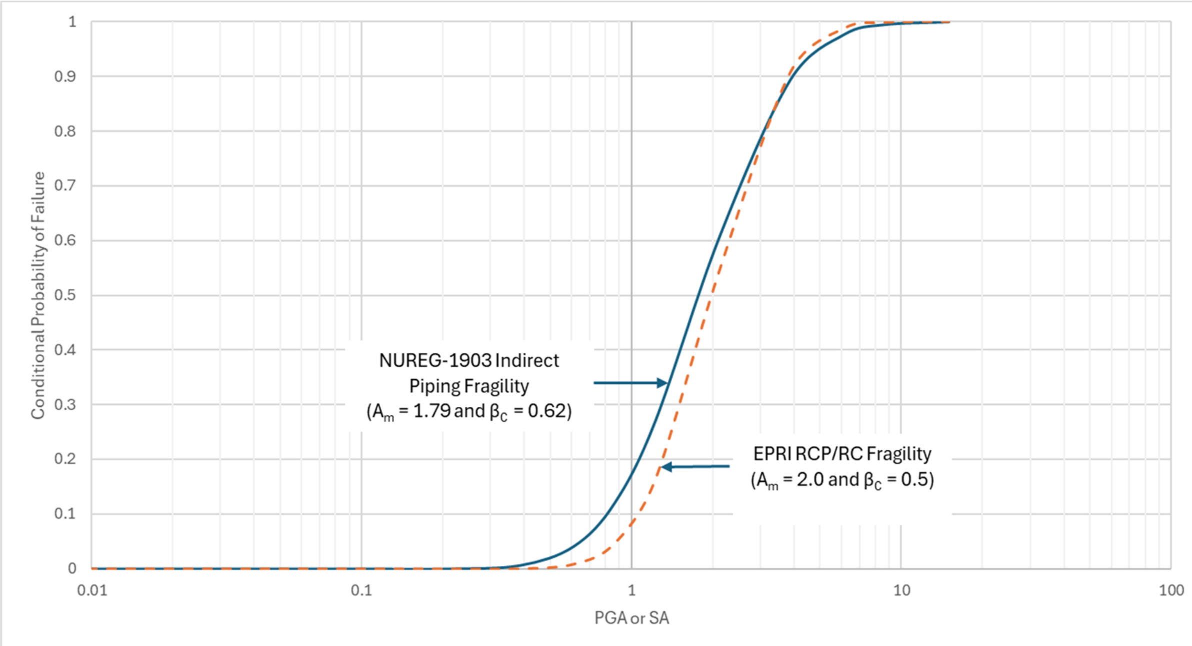

Figure 7. NUREG-1903 Representative Indirect Piping Failure Fragility Curve (A_m = 1.79g and β_C = 0.62) vs. EPRI RCP/RP Support Fragility (A_m = 2.0g and β_C = 0.5)

Although originally developed for PWR plants, this fragility function has been applied to both PWR and BWR plants in this study as it is slightly more conservative than the representative fragility function for support failure for RCPs for PWRs/recirculation pumps (RPs) for BWRs that was developed in EPRI report 3002000709. The EPRI RCP/RP support fragility has the following fragility parameter values:

- median capacity (A_m): 2.0g PGA
- composite variability, β_C: 0.5
- HCLPF capacity: 2.0g Exp(-2.326 x 0.5) = 0.62g

For comparison, this is also shown graphically in Figure 7 (dashed line). Figure 7 indicates that the NUREG-1903 fragility function selected for this study is slightly more conservative than the EPRI RCP/RP support fragility in terms of both the median and HCLPF capacities. Use of the NUREG-1903 fragility function provides additional assurance that the calculated unconditional indirect piping failure probabilities are conservative. As an illustration, Table 7 provides the bin-specific and overall mean failure probabilities calculated for Plant B. The calculational steps used to produce these values in Table 7 are based on the same steps used for Table 4, with the exception of using the RCP/RP support fragility as opposed to the large LOCA piping fragility. The unconditional mean probability of indirect piping failure is 2.179E-6, less than the TBS frequency criterion.

Table 7. Seismic Hazard Bins and Risk Convolution for Plant B—Indirect Piping Failure

Bin No.	Lower Acc., PGA	Upper Acc., PGA	Bin Acc.	Seismic Bin Frequency	Bin LOCA Fragility	Bin Seismic Risk, per year
1	0.0005	0.0010	0.001	1.730E-02	6.386E-37	1.105E-38
2	0.0010	0.0050	0.002	4.140E-02	2.078E-27	8.604E-29
3	0.0050	0.0100	0.007	8.580E-03	2.214E-19	1.899E-21
4	0.0100	0.0150	0.012	3.140E-03	4.501E-16	1.413E-18
5	0.0150	0.0300	0.021	3.430E-03	4.221E-13	1.448E-15
6	0.0300	0.0500	0.039	1.370E-03	3.148E-10	4.313E-13
7	0.0500	0.0750	0.061	5.850E-04	2.606E-08	1.525E-11
8	0.0750	0.1000	0.087	2.380E-04	5.174E-07	1.231E-10
9	0.1000	0.1500	0.122	1.900E-04	7.595E-06	1.443E-09
10	0.1500	0.3000	0.212	1.239E-04	2.909E-04	3.605E-08
11	0.3000	0.5000	0.387	2.810E-05	6.775E-03	1.904E-07
12	0.5000	0.7500	0.612	8.920E-06	4.181E-02	3.730E-07
13	0.7500	1.0000	0.866	3.040E-06	1.208E-01	3.672E-07
14	1.0000	1.5000	1.225	2.000E-06	2.702E-01	5.405E-07
15	1.5000	3.0000	2.121	9.140E-07	6.079E-01	5.556E-07
16	3.0000	5.0000	3.873	1.046E-07	8.934E-01	9.345E-08
17	5.0000	7.5000	6.124	1.680E-08	9.764E-01	1.640E-08
18	7.5000	10.0000	8.660	3.170E-09	9.945E-01	3.153E-09
19	10.0000	N/A	15.000	1.430E-09	9.997E-01	1.430E-09
					∑ =	2.179E-06

The same calculation is implemented for those CEUS NPP sites that were originally considered in NUREG-1903 and that submitted their SHSRs. Table 8[3] contains the results of these calculations. The results in Table 8 show that the unconditional mean probabilities of indirect piping failure for the sites considered herein are all below the TBS frequency criterion of 1E-05per year. However, it should be noted that the maximum piping failure probability can be as large as 9.2E-6 for Plant XVIII in Table 8, which is very close to the TBS criterion. One may argue that this estimate is conservatively biased due to the use of the conservative fragility parameter values selected from **Table 6**. Using a more refined estimate would likely decrease the indirect failure frequencies. However, this result cannot be verified without using a plant-specific fragility function in the analysis. More importantly, if other credible sources of indirect piping failure are considered, one cannot rule out the possibility that that the total or combined unconditional mean probability of all indirect piping failures exceeds the TBS frequency criterion. Therefore, each licensee needs to identify all credible indirect piping failure scenarios and associated systems, structures, and components applicable to their plants, based on plant-specific seismic considerations (e.g., seismic interactions identified by capacity walkdowns and review of relevant drawings). Then, each licensee needs to develop best estimate, plant-specific seismic fragility curves for all failure modes of the systems, structures, and components associated with the identified indirect piping failure scenarios. Next, each licensee needs to compute individual unconditional piping failure probabilities for the indirect piping

[3] For a parallel comparison with the results of NUREG-1903, Table 8 only includes those sites that were originally included in NUREG-1903 and that submitted their SHSRs in response to the 50.54(f) letter. Appendix B provides the results for those plants that were not originally included in NUREG-1903 but that submitted their SHSRs.

failure scenarios and combine them to obtain the total unconditional mean failure probability for comparison with the TBS frequency criterion. The licensees should also demonstrate that the combined results of the direct piping failure (i.e., flawed or unflawed) frequency and the indirect piping failure frequency are less than the TBS frequency criterion.

Table 8. Indirect Piping Failure Probability for CEUS NPP Sites with SHSRs Originally Assessed in NUREG-1903

No.	Site	Indirect Piping Failure Probability, per year
1	I	1.26E-06
2	II	5.50E-07
3	III	3.32E-06
4	IV	9.91E-07
5	V	1.75E-06
6	VI	6.61E-07
7	VII	2.00E-06
8	VIII	8.30E-06
9	IX	1.90E-07
10	X	3.04E-06
11	XI	3.09E-08
12	XII	7.78E-07
13	XIII	2.86E-07
14	XIV	5.07E-06
15	XV	2.66E-06
16	XVI	8.44E-07
17	XVII	5.96E-07
18	XVIII	9.20E-06
19	XIX	4.53E-06
20	XX	4.41E-07
21	XXI	1.82E-06
22	XXII	4.93E-06
23	XXIII	7.22E-07
24	XXIV	7.66E-06
25	XXV	3.12E-07
26	XXVI	8.54E-08
27	XXVII	6.52E-07
28	XXVIII	1.83E-07
29	XXIX	7.32E-06
30	XXX	4.02E-07
31	XXXI	7.49E-06
32	XXXII	3.97E-06
33	XXXIII	1.89E-07
34	XXXIV	1.65E-07
35	XXXV	4.36E-08
36	XXXVI	3.80E-06
37	XXXVII	1.48E-07
38	XXXVIII	1.30E-06
39	XXXIX	2.49E-08

No.	Site	Indirect Piping Failure Probability, per year
40	XL	3.65E-06
41	XLI	2.18E-06

3 Summary and Conclusions

To support the development of risk-informed emergency core cooling system requirements in 10 CFR 50.46, NUREG-1903 examined the effects of seismic loadings on the TBS frequency criterion of 1E-05 per year for three cases: direct unflawed piping failure, direct flawed piping failure, and indirect piping failure. The staff originally used the LLNL hazard curves in NUREG-1903. Since then, all CEUS NPP licensees have updated their seismic hazards in response to the 50.54(f) letter. As such, the current study has revisited the results of the original NUREG-1903 studies by applying the same analytical methodologies used in NUREG-1903 to the updated seismic hazard information.

For the unflawed piping failure case, the study has confirmed that the probabilities of exceedance corresponding to 1 percent probability of failure are all below the TBS frequency criterion. For the flawed piping failure case, given the existing insight that the critical flaws associated with stresses corresponding to 1E-05 and 1E-06 probability of exceedance seismic events are generally large, the probabilities of pipe breaks larger than the TBS are likely to be less than 1E-05 per year. However, as the applicability of the results is limited to those components considered in the study and the potential adverse impact of the recent seismic hazard updates on seismic demands, licensees need to verify this conclusion on a case-by-case basis to confirm its applicability to their plant sites. For the indirect piping failure case, this study shows that the unconditional mean probabilities of indirect piping failure for the sites considered herein are all below the TBS frequency criterion. However, additional verification is needed as this study has used the representative RCP/RP fragility only, and each licensee needs to identify and evaluate all credible indirect piping failure scenarios that may affect the TBS frequency criterion. Ultimately, the licensee needs to demonstrate that the overall unconditional mean piping probability of direct and indirect piping failures does not exceed the TBS frequency criterion in order to take advantage of less stringent emergency core cooling system requirements for LOCA break sizes larger than the TBS.

In summary, the results of the staff's updated seismic assessment confirm that seismic considerations are unlikely to affect selection of the TBS frequency criterion. This is consistent with the results of the original NUREG-1903 studies.

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Appendix A

Unconditional Mean Probability of Direct Piping Failure for Plant Sites Not Considered in NUREG-1903

No.	Site	Direct Piping Failure Probability, per year
1	XLII	3.36E-07
2	XLIII	1.52E-08
3	XLIV	3.45E-07
4	XLV	7.77E-08
5	XLVI	1.41E-07
6	XLVII	4.35E-07
7	XLVIII	6.37E-08
8	XLIX	1.72E-07
9	L	1.00E-07
10	LI	2.64E-08
11	LII	1.90E-08
12	LIII	9.82E-08
13	LIV	5.24E-07
14	LV	2.45E-07
15	LVI	7.00E-07
16	LVII	3.52E-08

Appendix B

Unconditional Mean Probability of Indirect Piping Failure for Plant Sites Not Considered in NUREG-1903

No.	Site	Indirect Piping Failure Probability, per year
1	XLII	1.43E-06
2	XLIII	5.52E-08
3	XLIV	1.37E-06
4	XLV	3.29E-07
5	XLVI	5.52E-07
6	XLVII	1.49E-06
7	XLVIII	2.12E-07
8	XLIX	7.82E-07
9	L	3.41E-07
10	LI	1.15E-07
11	LII	1.48E-07
12	LIII	4.74E-07
13	LIV	2.35E-06
14	LV	8.72E-07
15	LVI	6.38E-06
16	LVII	1.65E-07