APPENDIX C
PLANT-LEVEL FRAGILITY DATA

In the Safety/Risk Assessment, the plant-level seismic fragility has been modeled with a log-normal cumulative distribution function:

$$P_{CD}(a) = \Phi\left[\frac{\ln a - \mu}{\beta_C}\right] = \int_0^a \frac{1}{\sqrt{2\pi}\beta_C x} \exp\left[-\frac{(\ln x - \mu)^2}{2\beta_C^2}\right] dx \qquad \text{for } C_{50}, \beta_C > 0 \text{ and } \mu = \ln C_{50} \qquad \text{(C-1)}$$

where C_{50} denotes the median seismic capacity and β_C denotes composite logarithmic standard deviation. Seismic probabilistic risk assessments (PRAs) have typically used a log-normal function to model the seismic fragilities for individual structures and components, and this practice is reflected in Table 5-2-2.7(f) of the “Standard for Level 1 / Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, “ ASME/ANS-RA-Sa-2009. The assumption that the overall plant-level seismic fragility is reasonably modeled with a single log-normal function is discussed in Section 10-B.9 of the same standard.

The staff performed a confirmatory analysis of the reasonableness of the log-normal assumption by constructing probability plots of the plant-level fragility curves provided in Individual Plant Examination for External Events (IPEEE) submittals. A log-normal probability plot is constructed by observing that Equation (C-1) can be transformed into a linear equation:

$$y = mx + b \qquad \text{(C-2)}$$

where:

$$y = \Phi^{-1}[P_{CD}(a)]$$

$$x = \ln(a)$$

$$m = \frac{1}{\beta_C}$$

$$b = \frac{-\mu}{\beta_C}$$

If the log-normal assumption holds, then a plot of the plant-level fragility curve, as transformed, should appear as a straight line. Figures C.1 through C.4 provide log-normal probability plots for the plant-level seismic fragility curves for four plants and demonstrate the reasonableness of the log-normal assumption.

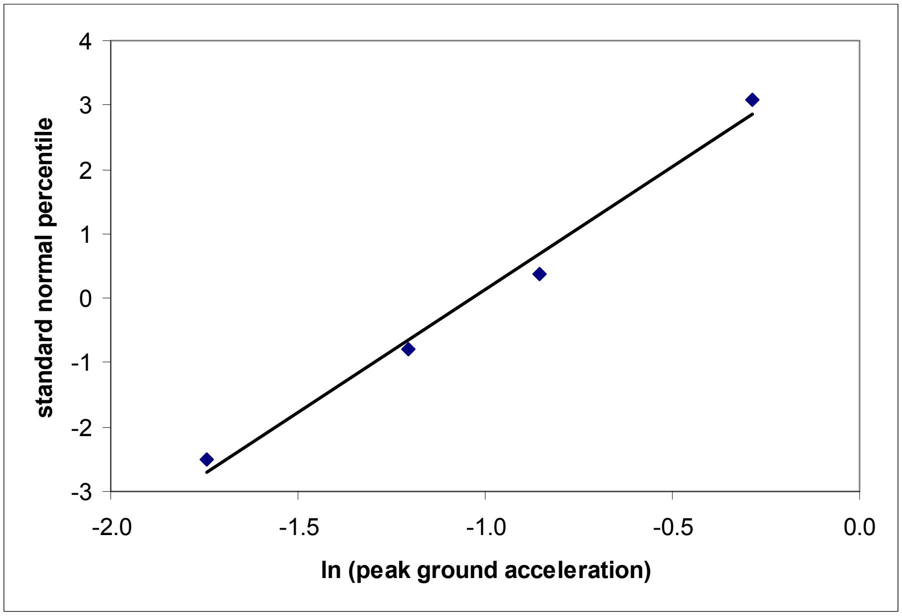

Figure C.1. Log-Normal Probability Plot of the Plant-Level Seismic Fragility Curve for Beaver Valley Unit 1.

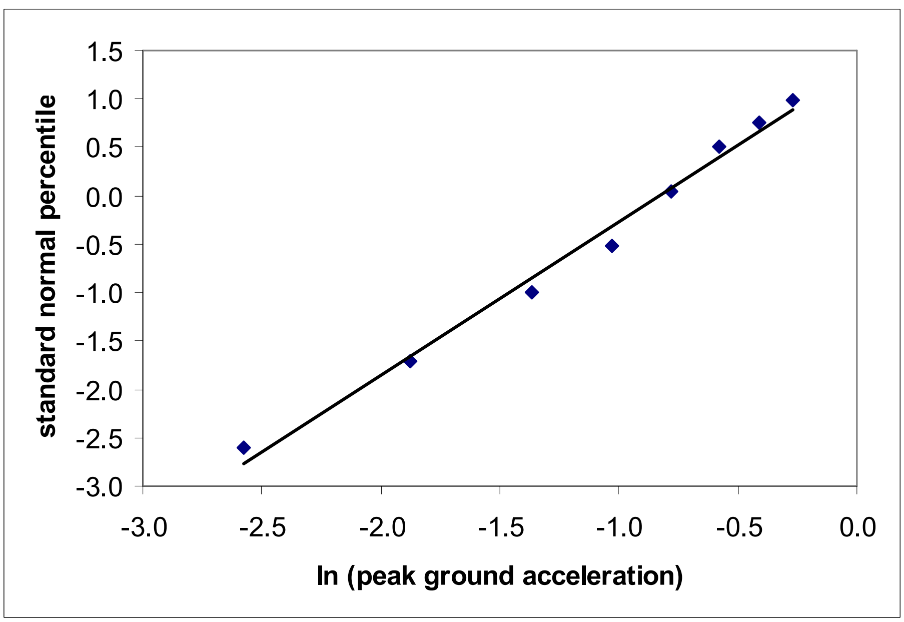

Figure C.2. Log-Normal Probability Plot of the Plant-Level Seismic Fragility Curve for Catawba Unit 1.

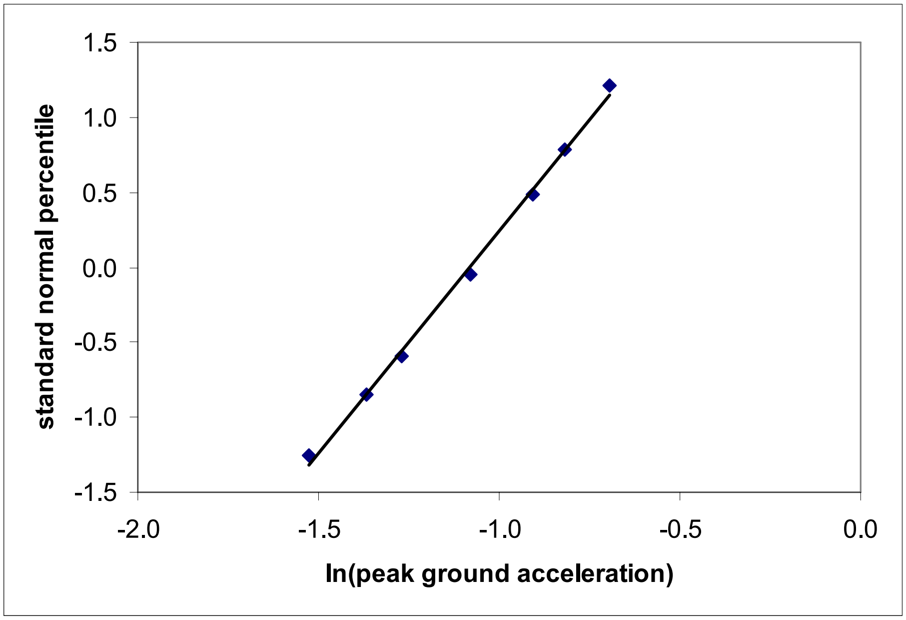

Figure C.3. Log-Normal Probability Plot of the Plant-Level Seismic Fragility Curve for Indian Point Unit 3.

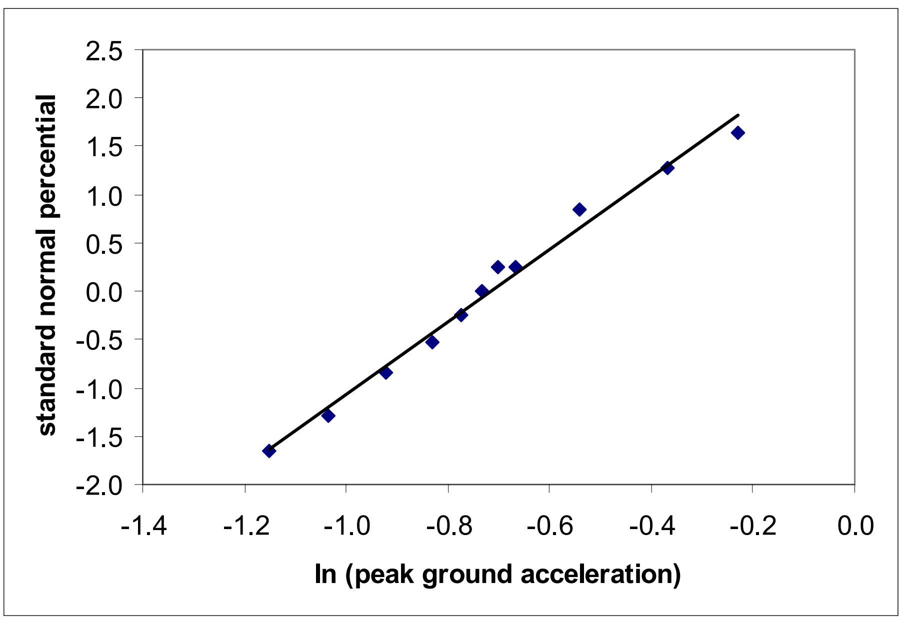

Figure C.4. Log-Normal Probability Plot of the Plant-Level Seismic Fragility Curve for Pilgrim.

Most of the available fragility information is expressed in terms of peak ground acceleration. In the Safety/Risk Assessment, this information was combined with information about the review-level response spectrum used in the IPEEE to develop fragility information at selected spectral frequencies (10 Hz, 5 Hz, and 1 Hz). The spectral ratio for a given spectral frequency, m_f, is defined as the ratio of the spectral ordinate on the review-level response spectrum corresponding to that spectral frequency to the spectral ordinate on the review-level response spectrum for the peak ground acceleration. Let *C* be a random variable that describes the plant's seismic capacity in terms of peak ground acceleration. Then, the cumulative distribution function of *C* is the peak ground acceleration (PGA)-based plant-level fragility, $P_{CD}(a)$. Thus, *C* is a log-normally distributed random variable with a median of C_{50} and a logarithmic standard deviation of β_C. Let C_f be a random variable that describes the plant's seismic capacity in terms of spectral frequency *f*. If $C_f = m_f C$, then C_f is also a log-normally distributed random variable with a median of $m_f C_{50}$ and a logarithmic standard deviation of β_C. Figure C.1 illustrates the relationships between C_f and *C*.

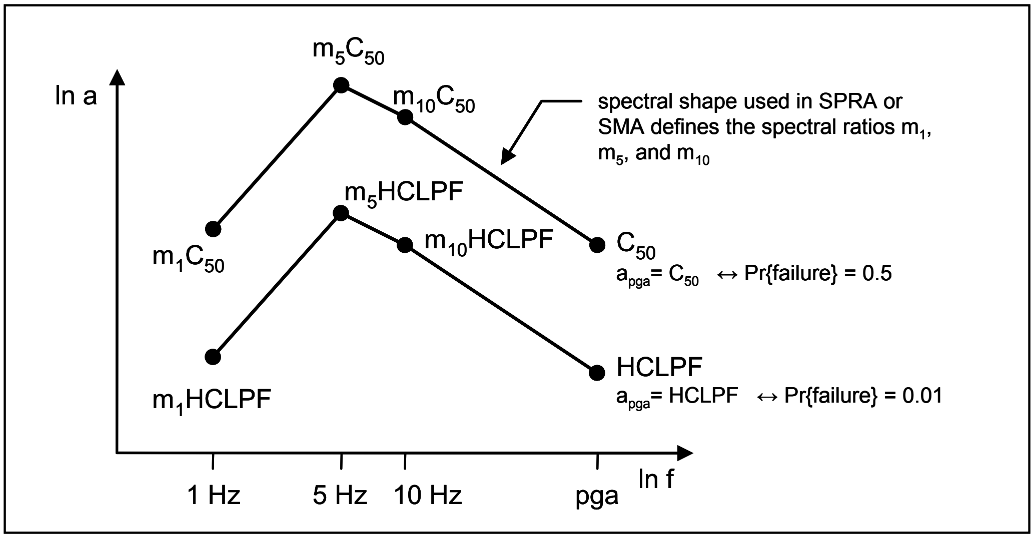

Figure C-1. The Definition of Spectral Fragility in Terms of the PGA-Based Fragility and the Review-Level Response Spectrum.

Parameters for the log-normal plant-level fragility curves were obtained by review of the IPEEE submittals. Table C.1 identifies the bases for establishing the plant-level fragility parameters from the available IPEEE information. Plant-level fragility curves (either in tabular or graphical form) were obtained for about two-thirds of the plants that performed a seismic PRA for the IPEEE (about one-third of all IPEEE submittals); if no plant-level fragility information was available, then the fragility parameters were back-calculated by matching reported seismic core-damage frequency (SCDFs) and using engineering judgment. The remaining two-thirds of plants performed a seismic margin analysis (SMA), which generated a plant-level high confidence of low probability of failure (HCLPF) value. The HCLPF is the peak ground acceleration that corresponds to a plant-level fragility of 0.01 (i.e., a 1-percent chance of core damage). The HCLPF is related to the median seismic capacity (C_{50}) as follows:

$$C_{50} = HCLPF \times \exp(2.3264\ \beta_C) \qquad \text{(C-3)}$$

Spectral ratios were obtained by review of the IPEEE submittals, which usually identified the specific spectral shape that was used (e.g., NUREG-0098). For some plants, the exact spectral shape could not be determined; in this case, several spectral shapes were postulated and carried through the entire analysis (i.e., SCDF estimates were made for each assumed spectral shape).

Table C.1. Bases for Establishing Plant-Level Fragility Curves Parameters From IPEEE Information.		
Basis	**Source**	**Parameters**
1a	SPRA	C_{50} and β_C determined by probability plot of the reported plant-level fragility curve
1b	SPRA	C_{50} found by matching the computed SCDF to the SCDF stated in the IPEEE for the specified hazard curve (EPRI, LLNL, or plant-specific). Assumed $\beta_C = 0.4$.
1c	SPRA	C_{50} and β_C determined by matching computed SCDFs to IPEEE SCDFs for a pair of hazard curves.
2	SMA (HCLPF < RLE)	C_{50} found by using the stated HCLPF Assumed $\beta_C = 0.4$.
3a	SMA (HCLPF = RLE)	C_{50} found by using the stated HCLPF/RLE Assumed $\beta_C = 0.4$ Note: The RLE is a lower bound on the actual HCLPF.
3b	SMA (HCLPF = RLE = SSE)	C_{50} found by using the stated HCLPF/RLE/SSE Assumed $\beta_C = 0.4$ Note: The SSE is a lower bound on the actual HCLPF; applies to reduced scope SMA plants.

Table C-2 lists the plant-level fragility parameters used in the Safety/Risk Assessment.

Table C-2. Plant-Level Fragility Data.									
			PGA Fragility			Spectral Ratios			
Plant	Docket Number	IPEEE Method	HCL PF	C_{50}	β_C	10 Hz	5 Hz	1 Hz	Basis
Arkansas Nuclear 1	05000313	0.3g full-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Arkansas Nuclear 2	05000368	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Beaver Valley 1	05000334	seismic PRA		0.36	0.26	1.71	1.54	0.68	1a
Beaver Valley 2	05000412	seismic PRA		0.53	0.34	1.71	1.54	0.68	1a
Braidwood 1	05000456	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Braidwood 2	05000457	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Browns Ferry 1	05000259	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Browns Ferry 2	05000260	0.3g focused-scope EPRI SMA	0.26	0.66	0.4	1.87	2.12	0.96	2
Browns Ferry 3	05000296	0.3g focused-scope EPRI SMA	0.26	0.66	0.4	1.87	2.12	0.96	2
Brunswick 1	05000325	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Brunswick 2	05000324	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Byron 1	05000454	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Byron 2	05000455	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Callaway	05000483	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Calvert Cliffs 1	05000317	seismic PRA		0.62	0.4	1.38	1.72	0.6	1b
Calvert Cliffs 2	05000318	seismic PRA		0.58	0.4	1.38	1.72	0.6	1b
Catawba 1	05000413	seismic PRA		0.44	0.63	1.87	2.12	0.96	1a
Catawba 2	05000414	seismic PRA		0.44	0.63	1.87	2.12	0.96	1a
Clinton (0098)	05000461	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Clinton(UHS)	05000461	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.67	1.81	0.59	3a
Comanche Peak 1	05000445	reduced-scope EPRI SMA; SSE=0.12g	0.12	0.30	0.4	2.26	2.56	1.28	3b
Comanche Peak 2	05000446	reduced-scope EPRI SMA; SSE=0.12g	0.12	0.30	0.4	2.26	2.56	1.28	3b
Cooper	05000298	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a

Table C-2. Plant-Level Fragility Data.									
			PGA Fragility			Spectral Ratios			
Plant	Docket Number	IPEEE Method	HCL PF	C_{50}	β_C	10 Hz	5 Hz	1 Hz	Basis
Crystal River 3	05000302	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.22	1.51	1.58	3b
D.C. Cook 1	05000315	seismic PRA		0.48	0.27	2.27	2.13	0.65	1a
D.C. Cook 2	05000316	seismic PRA		0.48	0.27	2.27	2.13	0.65	1a
Davis-Besse	05000346	reduced-scope EPRI SMA	0.26	0.66	0.4	1.87	2.12	0.96	2
Dresden 2	05000237	0.3g focused-scope EPRI SMA	0.2	0.51	0.4	1.87	2.12	0.96	2
Dresden 3	05000249	0.3g focused-scope EPRI SMA	0.2	0.51	0.4	1.87	2.12	0.96	2
Duane Arnold	05000331	reduced-scope EPRI SMA; SSE=0.12g	0.12	0.30	0.4	1.85	2.68	1.07	3b
Farley 1 (1st spectral ratios)	05000348	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.87	2.12	0.96	3b
Farley 1 (2nd spectral ratios)	05000348	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.85	2.12	1.32	3b
Farley 2 (1st spectral ratios)	05000364	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.87	2.12	0.96	3b
Farley 2 (2nd spectral ratios)	05000364	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.85	2.12	1.32	3b
Fermi 2	05000341	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
FitzPatrick	05000333	0.3g focused-scope NRC SMA	0.22	0.56	0.4	1.87	2.12	0.96	2
Fort Calhoun	05000285	0.3g focused-scope NRC SMA	0.25	0.63	0.4	1.85	2.12	1.32	2
Ginna	05000244	0.3g focused-scope EPRI SMA	0.2	0.51	0.4	2.14	2.42	1.36	2
Grand Gulf 1	05000416	reduced-scope EPRI SMA; SSE=0.15g	0.15	0.38	0.4	1.92	2.65	1.33	2
Harris 1	05000400	0.3g focused-scope EPRI SMA	0.29	0.74	0.4	1.87	2.12	0.96	2
Hatch 1	05000321	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Hatch 2	05000366	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Hope Creek 1	05000354	seismic PRA		1.66	0.70	1.97	2.27	0.98	1c
Indian Point 2	05000247	seismic PRA		0.68	0.4	1.62	1.23	0.41	1b
Indian Point 3	05000286	seismic PRA		0.34	0.34	1.56	1.61	0.81	1a
Kewaunee	05000305	seismic PRA		0.41	0.22	1.8	1.79	0.4	1a
La Salle 1 (0098)	05000373	seismic PRA		1.32	0.4	1.85	2.12	1.32	1b

Table C-2. Plant-Level Fragility Data.

Plant	Docket Number	IPEEE Method	PGA Fragility			Spectral Ratios			Basis
			HCLPF	C_{50}	β_C	10 Hz	5 Hz	1 Hz	
La Salle 1 (SSE)	05000373	seismic PRA		1.32	0.4	1.85	2.62	1.31	1b
La Salle 1 (UHS)	05000373	seismic PRA		1.32	0.4	1.67	1.83	0.923	1b
La Salle 2 (0098)	05000374	seismic PRA		1.32	0.4	1.85	2.12	1.32	1b
La Salle 2 (SSE)	05000374	seismic PRA		1.32	0.4	1.85	2.62	1.31	1b
La Salle 2 (UHS)	05000374	seismic PRA		1.32	0.4	1.67	1.83	0.923	1b
Limerick 1	05000352	reduced-scope EPRI SMA	0.15	0.38	0.4	2.59	2.47	1.18	3b
Limerick 2	05000353	reduced-scope EPRI SMA	0.15	0.38	0.4	2.59	2.47	1.18	3b
McGuire 1	05000369	seismic PRA		0.45	0.74	1.88	2.35	1.19	1a
McGuire 2	05000370	seismic PRA		0.45	0.74	1.88	2.35	1.19	1a
Millstone 2	05000336	0.3g focused-scope EPRI SMA	0.25	0.63	0.4	1.87	2.12	0.96	2
Millstone 3	05000423	seismic PRA		0.54	0.4	2.27	2.27	1.26	1b
Monticello	05000263	modified focused/expended reduced-scope EPRI SMA	0.12	0.30	0.4	2.29	2.69	1.12	3b
Nine Mile Point 1	05000220	0.3g focused-scope EPRI SMA	0.27	0.68	0.4	1.87	2.12	0.96	3b
Nine Mile Point 2	05000410	SPRA and focused-scope EPRI SMA	0.23	0.58	0.4	1.87	2.12	0.96	3b
North Anna 1 (1st spectral ratios)	05000338	0.3g focused-scope EPRI SMA	0.16	0.41	0.4	1.87	2.12	0.96	2
North Anna 1 (2nd spectral ratios)	05000338	0.3g focused-scope EPRI SMA	0.16	0.41	0.4	1.85	2.12	1.32	2
North Anna 2 (1st spectral ratios)	05000339	0.3g focused-scope EPRI SMA	0.16	0.41	0.4	1.87	2.12	0.96	2
North Anna 2 (2nd spectral ratios)	05000339	0.3g focused-scope EPRI SMA	0.16	0.41	0.4	1.85	2.12	1.32	2
Oconee 1	05000269	seismic PRA		0.62	0.32	1.66	1.32	0.35	1a
Oconee 2	05000270	seismic PRA		0.62	0.32	1.66	1.32	0.35	1a
Oconee 3	05000287	seismic PRA		0.62	0.32	1.66	1.32	0.35	1a

Table C-2. Plant-Level Fragility Data.									
	Docket Number		PGA Fragility			Spectral Ratios			
Plant		IPEEE Method	HCL PF	C_{50}	β_C	10 Hz	5 Hz	1 Hz	Basis
Oyster Creek	05000219	seismic PRA		0.57	0.36	2	1.78	0.796	1a
Palisades	05000255	seismic PRA		0.49	0.35	2.13	2.44	0.74	1a
Peach Bottom 2	05000277	modified focused-scope EPRI SMA	0.2	0.51	0.4	1.87	2.12	0.96	3b
Peach Bottom 3	05000278	modified focused-scope EPRI SMA	0.2	0.51	0.4	1.87	2.12	0.96	3b
Perry 1	05000440	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Pilgrim 1	05000293	seismic PRA		0.49	0.27	1.55	1.66	0.5	1a
Point Beach 1	05000266	seismic PRA		0.45	0.45	1.78	1.75	0.675	1a
Point Beach 2	05000301	seismic PRA		0.45	0.45	1.78	1.75	0.675	1a
Prairie Island 1	05000282	0.3g focused-scope EPRI SMA	0.28	0.71	0.4	1.85	2.12	1.32	2
Prairie Island 2	05000306	0.3g focused-scope EPRI SMA	0.28	0.71	0.4	1.85	2.12	1.32	2
Quad Cities 1	05000254	0.3g focused-scope EPRI SMA	0.09	0.23	0.4	1.87	2.12	0.96	2
Quad Cities 2	05000265	0.3g focused-scope EPRI SMA	0.09	0.23	0.4	1.87	2.12	0.96	2
River Bend 1	05000458	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	2.35	2.75	1.41	3b
Robinson 2	05000261	0.3g full-scope EPRI SMA	0.28	0.71	0.4	1.85	2.12	1.32	2
Saint Lucie 1 (s4)	05000335	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.18	1.5	0.8	3b
Saint Lucie 1 (s5)	05000335	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.18	1.5	0.8	3b
Saint Lucie 2 (s4)	05000389	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.18	1.5	0.8	3b
Saint Lucie 2 (s5)	05000389	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.18	1.5	0.8	3b
Salem 1	05000272	seismic PRA		1.31	0.84	1.97	2.27	0.68	1c
Salem 2	05000311	seismic PRA		1.31	0.84	1.97	2.27	0.68	1c
Seabrook 1	05000443	seismic PRA		0.90	0.52	2.223	2.42	1.36	1a
Sequoyah 1	05000327	0.3g full-scope EPRI SMA	0.27	0.68	0.4	1.87	2.12	0.96	2
Sequoyah 2	05000328	0.3g full-scope EPRI SMA	0.27	0.68	0.4	1.87	2.12	0.96	2
South Texas 1	05000498	seismic PRA		0.38	0.59	2.47	2.97	1.53	1a

Table C-2. Plant-Level Fragility Data.									
			PGA Fragility			Spectral Ratios			
Plant	Docket Number	IPEEE Method	HCL PF	C_{50}	β_C	10 Hz	5 Hz	1 Hz	Basis
South Texas 2	05000499	seismic PRA		0.38	0.59	2.47	2.97	1.53	1a
Summer	05000395	0.3g focused-scope EPRI SMA	0.22	0.56	0.4	1.87	2.12	0.96	2
Surry 1	05000280	seismic PRA		0.74	0.66	2.08	1.95	0.97	1a
Surry 2	05000281	seismic PRA		0.74	0.66	2.08	1.95	0.97	1a
Susquehanna 1	05000387	0.3g focused-scope EPRI SMA	0.21	0.53	0.4	1.87	2.12	0.96	2
Susquehanna 2	05000388	0.3g focused-scope EPRI SMA	0.21	0.53	0.4	1.87	2.12	0.96	2
Three Mile Island 1	05000289	seismic PRA		0.29	0.28	2.73	2.6	1.127	1a
Turkey Point 3	05000250	site-specific approach; SSE=0.15g	0.15	0.38	0.4	1.26	1.58	0.85	3b
Turkey Point 4	05000251	site-specific approach; SSE=0.15g	0.15	0.38	0.4	1.26	1.58	0.85	3b
Vermont Yankee	05000271	0.3g focused-scope EPRI SMA	0.25	0.63	0.4	1.87	2.12	0.96	2
Vogtle 1	05000424	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Vogtle 2	05000425	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Waterford 3	05000382	reduced-scope EPRI SMA; SSE=0.1g	0.1	0.25	0.4	1.72	2.4	1.19	3b
Watts Bar 1 (rock)	05000390	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.87	2.12	0.96	3a
Watts Bar 1 (soil)	05000390	0.3g focused-scope EPRI SMA	0.3	0.76	0.4	1.85	2.12	1.32	3a
Wolf Creek 1	05000482	reduced-scope EPRI SMA	0.2	0.51	0.4	1.83	2.25	0.32	3b