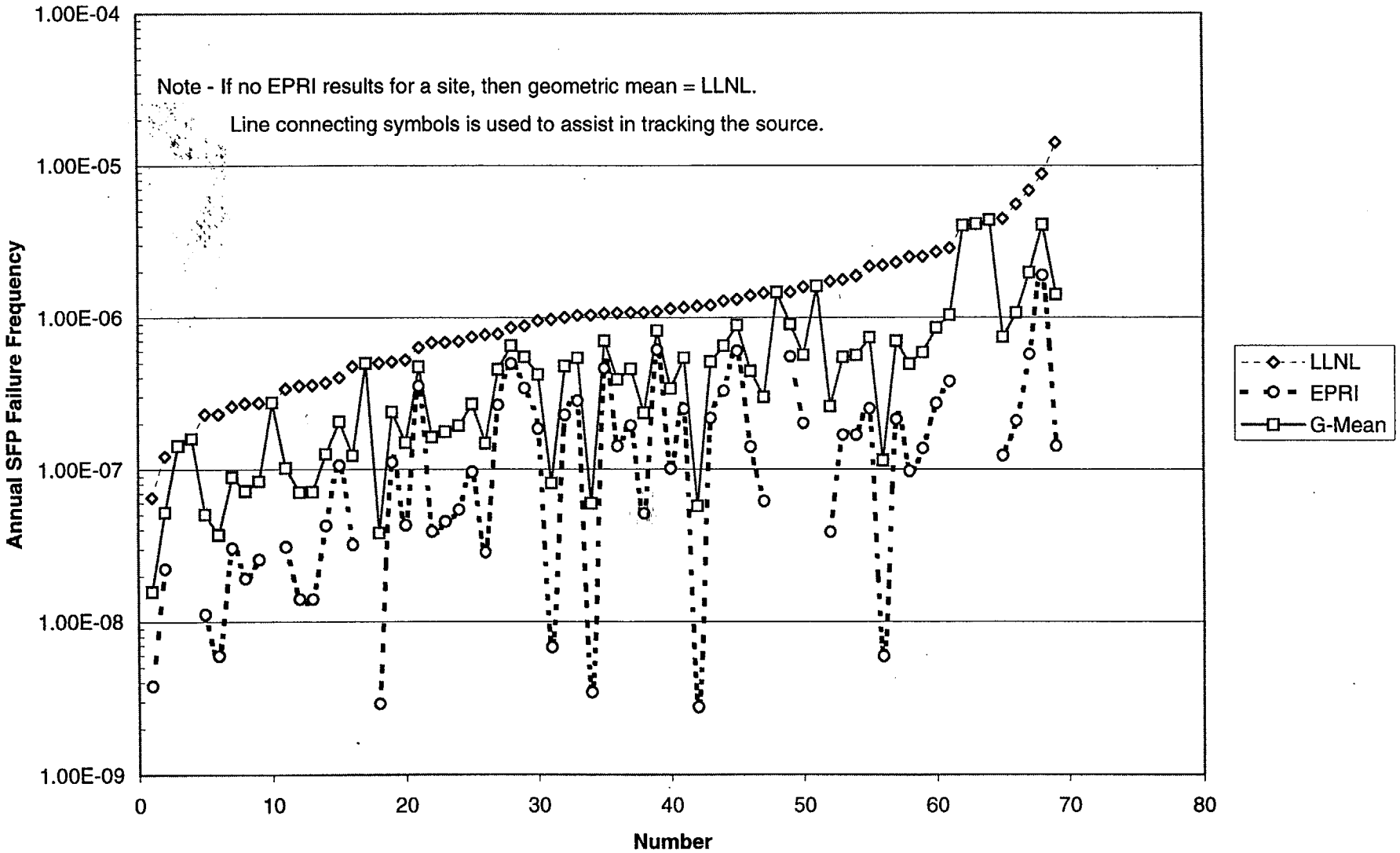
Site	srted	2.5hz	5hz	10hz	Max (2.5, 5, 10)	Max*0.5	EPRI	A-mean	G-mean	Accpt	B=1/P=2
58	1	9.12E-08	1.30E-07	7.10E-08	1.30E-07	6.51E-08	3.80E-09	3.45E-08	1.57E-08	3.00E-06	2
6	2	2.02E-07	2.44E-07	1.16E-07	2.44E-07	1.22E-07	2.22E-08	7.20E-08	5.20E-08	3.00E-06	2
61	3	2.22E-07	2.86E-07	1.61E-07	2.86E-07	1.43E-07		7.15E-08	1.43E-07	3.00E-06	1
68	4	2.34E-07	3.19E-07	1.81E-07	3.19E-07	1.59E-07		7.97E-08	1.59E-07	3.00E-06	2
30	5	3.20E-07	4.59E-07	2.61E-07	4.59E-07	2.30E-07	1.11E-08	1.20E-07	5.05E-08	3.00E-06	2
60	6	3.48E-07	4.61E-07	2.51E-07	4.61E-07	2.30E-07	5.96E-09	1.18E-07	3.71E-08	3.00E-06	2
2	7	4.23E-07	5.18E-07	2.44E-07	5.18E-07	2.59E-07	3.03E-08	1.45E-07	8.86E-08	3.00E-06	2
65	8	3.96E-07	5.41E-07	2.41E-07	5.41E-07	2.70E-07	1.91E-08	1.45E-07	7.19E-08	3.00E-06	1
3	9	4.04E-07	5.45E-07	2.69E-07	5.45E-07	2.72E-07	2.55E-08	1.49E-07	8.33E-08	3.00E-06	2
57	10	4.80E-07	5.48E-07	2.49E-07	5.48E-07	2.74E-07		1.37E-07	2.74E-07	3.00E-06	2
46	11	5.07E-07	6.74E-07	3.29E-07	6.74E-07	3.37E-07	3.08E-08	1.84E-07	1.02E-07	3.00E-06	1
11	12	5.24E-07	7.07E-07	3.63E-07	7.07E-07	3.53E-07	1.40E-08	1.84E-07	7.03E-08	3.00E-06	1
15	13	5.28E-07	7.14E-07	3.68E-07	7.14E-07	3.57E-07	1.40E-08	1.86E-07	7.07E-08	3.00E-06	1
51	14	5.71E-07	7.41E-07	3.88E-07	7.41E-07	3.71E-07	4.26E-08	2.07E-07	1.26E-07	3.00E-06	1
47	15	6.17E-07	8.00E-07	4.18E-07	8.00E-07	4.00E-07	1.06E-07	2.53E-07	2.06E-07	3.00E-06	1
42	16	7.60E-07	9.45E-07	4.85E-07	9.45E-07	4.73E-07	3.20E-08	2.52E-07	1.23E-07	3.00E-06	2
67	17	9.94E-07	9.40E-07	1.68E-07	9.94E-07	4.97E-07		2.49E-07	4.97E-07	3.00E-06	2
66	18	9.98E-07	7.16E-07	1.93E-07	9.98E-07	4.99E-07	2.90E-09	2.51E-07	3.80E-08	3.00E-06	2
33	19	8.50E-07	1.02E-06	5.15E-07	1.02E-06	5.10E-07	1.11E-07	3.11E-07	2.38E-07	3.00E-06	2
26	20	8.32E-07	1.05E-06	5.11E-07	1.05E-06	5.24E-07	4.29E-08	2.84E-07	1.50E-07	3.00E-06	1
34	21	1.02E-06	1.27E-06	6.24E-07	1.27E-06	6.33E-07	3.52E-07	4.92E-07	4.72E-07	3.00E-06	2
22	22	1.13E-06	1.36E-06	7.00E-07	1.36E-06	6.82E-07	3.89E-08	3.61E-07	1.63E-07	3.00E-06	1
45	23	1.08E-06	1.37E-06	6.85E-07	1.37E-06	6.85E-07	4.53E-08	3.65E-07	1.76E-07	3.00E-06	2
12	24	1.01E-06	1.39E-06	7.70E-07	1.39E-06	6.95E-07	5.41E-08	3.75E-07	1.94E-07	3.00E-06	2
56	25	1.18E-06	1.49E-06	7.93E-07	1.49E-06	7.43E-07	9.62E-08	4.20E-07	2.67E-07	3.00E-06	2
35	26	1.13E-06	1.54E-06	8.11E-07	1.54E-06	7.69E-07	2.86E-08	3.99E-07	1.48E-07	3.00E-06	2
29	27	1.17E-06	1.56E-06	9.36E-07	1.56E-06	7.78E-07	2.65E-07	5.21E-07	4.54E-07	3.00E-06	2
37	28	1.33E-06	1.71E-06	9.13E-07	1.71E-06	8.56E-07	4.95E-07	6.75E-07	6.51E-07	3.00E-06	2
7	29	1.36E-06	1.76E-06	9.54E-07	1.76E-06	8.79E-07	3.42E-07	6.11E-07	5.48E-07	3.00E-06	2
10	30	1.39E-06	1.90E-06	1.10E-06	1.90E-06	9.50E-07	1.85E-07	5.68E-07	4.19E-07	3.00E-06	2
5	31	1.94E-06	1.40E-06	4.35E-07	1.94E-06	9.68E-07	6.80E-09	4.88E-07	8.11E-08	3.00E-06	1
1	32	1.56E-06	2.00E-06	1.04E-06	2.00E-06	1.00E-06	2.27E-07	6.14E-07	4.76E-07	3.00E-06	1
52	33	6.09E-07	2.06E-06	1.16E-06	2.06E-06	1.03E-06	2.83E-07	6.57E-07	5.40E-07	3.00E-06	2
41	34	1.02E-06	1.32E-06	2.07E-06	2.07E-06	1.03E-06	3.45E-09	5.19E-07	5.97E-08	3.00E-06	1
48	35	6.36E-07	2.13E-06	1.16E-06	2.13E-06	1.06E-06	4.61E-07	7.62E-07	7.00E-07	3.00E-06	2
23	36	1.63E-06	2.14E-06	1.10E-06	2.14E-06	1.07E-06	1.42E-07	6.07E-07	3.90E-07	3.00E-06	2

Site	srted	2.5hz	5hz	10hz	Max (2.5, 5, 10)	Max*0.5	EPRI	A-mean	G-mean	Accpt	B=1/P=2
58	1	9.12E-08	1.30E-07	7.10E-08	1.30E-07	6.51E-08	3.80E-09	3.45E-08	1.57E-08	3.00E-06	2
6	2	2.02E-07	2.44E-07	1.16E-07	2.44E-07	1.22E-07	2.22E-08	7.20E-08	5.20E-08	3.00E-06	2
61	3	2.22E-07	2.86E-07	1.61E-07	2.86E-07	1.43E-07		7.15E-08	1.43E-07	3.00E-06	1
68	4	2.34E-07	3.19E-07	1.81E-07	3.19E-07	1.59E-07		7.97E-08	1.59E-07	3.00E-06	2
30	5	3.20E-07	4.59E-07	2.61E-07	4.59E-07	2.30E-07	1.11E-08	1.20E-07	5.05E-08	3.00E-06	2
60	6	3.48E-07	4.61E-07	2.51E-07	4.61E-07	2.30E-07	5.96E-09	1.18E-07	3.71E-08	3.00E-06	2
2	7	4.23E-07	5.18E-07	2.44E-07	5.18E-07	2.59E-07	3.03E-08	1.45E-07	8.86E-08	3.00E-06	2
65	8	3.96E-07	5.41E-07	2.41E-07	5.41E-07	2.70E-07	1.91E-08	1.45E-07	7.19E-08	3.00E-06	1
3	9	4.04E-07	5.45E-07	2.69E-07	5.45E-07	2.72E-07	2.55E-08	1.49E-07	8.33E-08	3.00E-06	2
57	10	4.80E-07	5.48E-07	2.49E-07	5.48E-07	2.74E-07		1.37E-07	2.74E-07	3.00E-06	2
46	11	5.07E-07	6.74E-07	3.29E-07	6.74E-07	3.37E-07	3.08E-08	1.84E-07	1.02E-07	3.00E-06	1
11	12	5.24E-07	7.07E-07	3.63E-07	7.07E-07	3.53E-07	1.40E-08	1.84E-07	7.03E-08	3.00E-06	1
15	13	5.28E-07	7.14E-07	3.68E-07	7.14E-07	3.57E-07	1.40E-08	1.86E-07	7.07E-08	3.00E-06	1
51	14	5.71E-07	7.41E-07	3.88E-07	7.41E-07	3.71E-07	4.26E-08	2.07E-07	1.26E-07	3.00E-06	1
47	15	6.17E-07	8.00E-07	4.18E-07	8.00E-07	4.00E-07	1.06E-07	2.53E-07	2.06E-07	3.00E-06	1
42	16	7.60E-07	9.45E-07	4.85E-07	9.45E-07	4.73E-07	3.20E-08	2.52E-07	1.23E-07	3.00E-06	2
67	17	9.94E-07	9.40E-07	1.68E-07	9.94E-07	4.97E-07		2.49E-07	4.97E-07	3.00E-06	2
66	18	9.98E-07	7.16E-07	1.93E-07	9.98E-07	4.99E-07	2.90E-09	2.51E-07	3.80E-08	3.00E-06	2
33	19	8.50E-07	1.02E-06	5.15E-07	1.02E-06	5.10E-07	1.11E-07	3.11E-07	2.38E-07	3.00E-06	2
26	20	8.32E-07	1.05E-06	5.11E-07	1.05E-06	5.24E-07	4.29E-08	2.84E-07	1.50E-07	3.00E-06	1
34	21	1.02E-06	1.27E-06	6.24E-07	1.27E-06	6.33E-07	3.52E-07	4.92E-07	4.72E-07	3.00E-06	2
22	22	1.13E-06	1.36E-06	7.00E-07	1.36E-06	6.82E-07	3.89E-08	3.61E-07	1.63E-07	3.00E-06	1
45	23	1.08E-06	1.37E-06	6.85E-07	1.37E-06	6.85E-07	4.53E-08	3.65E-07	1.76E-07	3.00E-06	2
12	24	1.01E-06	1.39E-06	7.70E-07	1.39E-06	6.95E-07	5.41E-08	3.75E-07	1.94E-07	3.00E-06	2
56	25	1.18E-06	1.49E-06	7.93E-07	1.49E-06	7.43E-07	9.62E-08	4.20E-07	2.67E-07	3.00E-06	2
35	26	1.13E-06	1.54E-06	8.11E-07	1.54E-06	7.69E-07	2.86E-08	3.99E-07	1.48E-07	3.00E-06	2
29	27	1.17E-06	1.56E-06	9.36E-07	1.56E-06	7.78E-07	2.65E-07	5.21E-07	4.54E-07	3.00E-06	2
37	28	1.33E-06	1.71E-06	9.13E-07	1.71E-06	8.56E-07	4.95E-07	6.75E-07	6.51E-07	3.00E-06	2
7	29	1.36E-06	1.76E-06	9.54E-07	1.76E-06	8.79E-07	3.42E-07	6.11E-07	5.48E-07	3.00E-06	2
10	30	1.39E-06	1.90E-06	1.10E-06	1.90E-06	9.50E-07	1.85E-07	5.68E-07	4.19E-07	3.00E-06	2
5	31	1.94E-06	1.40E-06	4.35E-07	1.94E-06	9.68E-07	6.80E-09	4.88E-07	8.11E-08	3.00E-06	1
1	32	1.56E-06	2.00E-06	1.04E-06	2.00E-06	1.00E-06	2.27E-07	6.14E-07	4.76E-07	3.00E-06	1
52	33	6.09E-07	2.06E-06	1.16E-06	2.06E-06	1.03E-06	2.83E-07	6.57E-07	5.40E-07	3.00E-06	2
41	34	1.02E-06	1.32E-06	2.07E-06	2.07E-06	1.03E-06	3.45E-09	5.19E-07	5.97E-08	3.00E-06	1
48	35	6.36E-07	2.13E-06	1.16E-06	2.13E-06	1.06E-06	4.61E-07	7.62E-07	7.00E-07	3.00E-06	2
23	36	1.63E-06	2.14E-06	1.10E-06	2.14E-06	1.07E-06	1.42E-07	6.07E-07	3.90E-07	3.00E-06	2

Comparison - LLNL/EPRI/GEOMETRIC MEAN

LLNL sorted from lowest to highest risk site



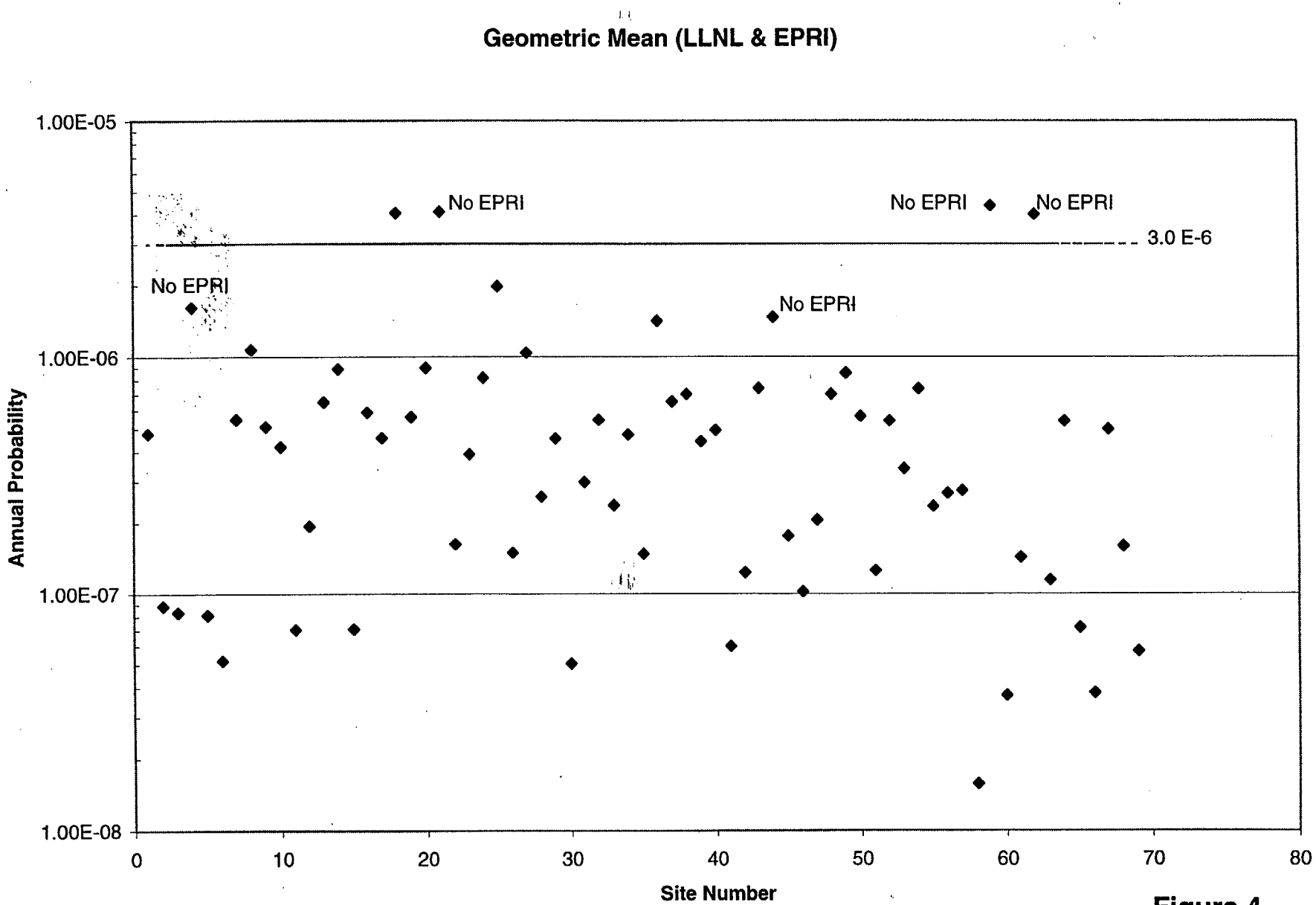
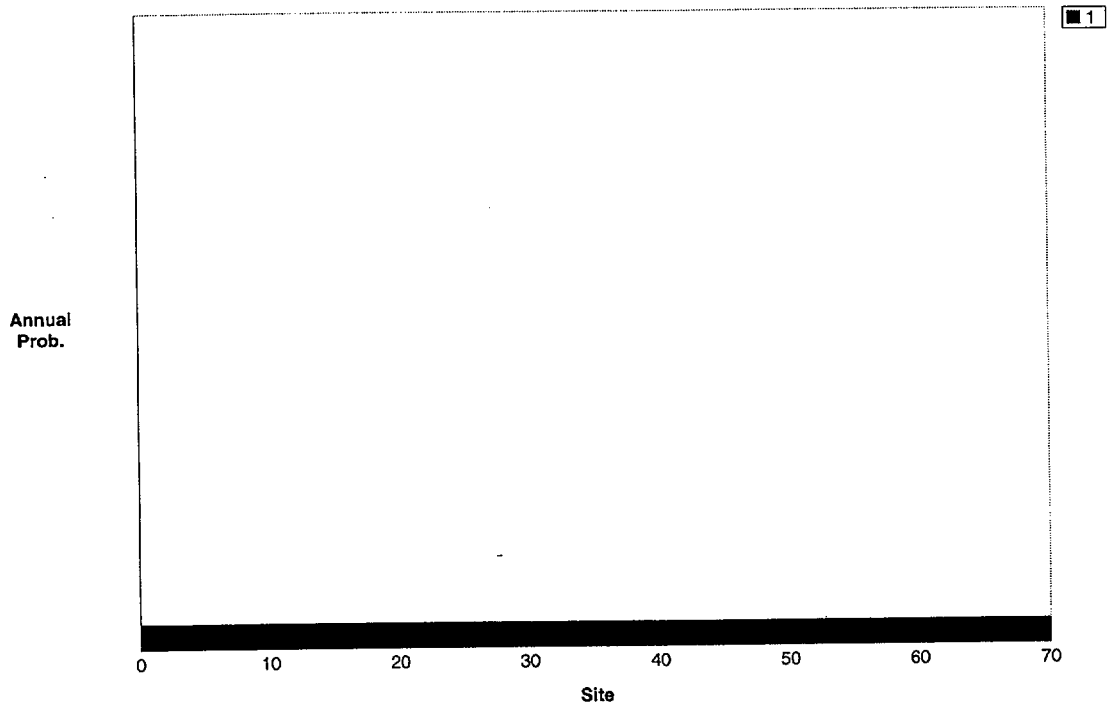

Geometric Mean (LLNL & EPRI)
1.00E-05
1.00E-06
1.00E-07
1.00E-08
Annual Probability
No EPRI
No EPRI
No EPRI
No EPRI
No EPRI
3.0 E-6
0
10
20
30
40
50
60
70
80
Site Number

Figure 4

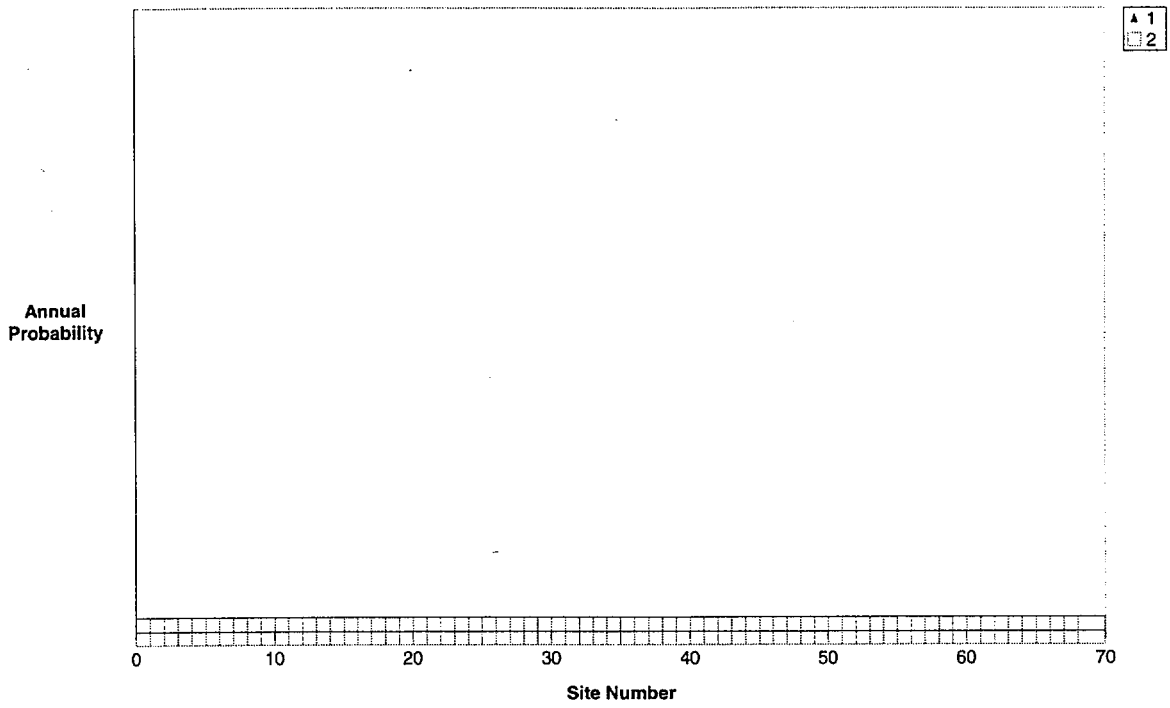
Site	srted	2.5hz	5hz	10hz	Max (2.5, 5, 10)	Max*0.5	EPRI	A-mean	G-mean	Accpt	B=1/P=2
58	1	9.12E-08	1.30E-07	7.10E-08	1.30E-07	6.51E-08	3.80E-09	3.45E-08	1.57E-08	3.00E-06	2
6	2	2.02E-07	2.44E-07	1.16E-07	2.44E-07	1.22E-07	2.22E-08	7.20E-08	5.20E-08	3.00E-06	2
61	3	2.22E-07	2.86E-07	1.61E-07	2.86E-07	1.43E-07		7.15E-08	1.43E-07	3.00E-06	1
68	4	2.34E-07	3.19E-07	1.81E-07	3.19E-07	1.59E-07		7.97E-08	1.59E-07	3.00E-06	2
30	5	3.20E-07	4.59E-07	2.61E-07	4.59E-07	2.30E-07	1.11E-08	1.20E-07	5.05E-08	3.00E-06	2
60	6	3.48E-07	4.61E-07	2.51E-07	4.61E-07	2.30E-07	5.96E-09	1.18E-07	3.71E-08	3.00E-06	2
2	7	4.23E-07	5.18E-07	2.44E-07	5.18E-07	2.59E-07	3.03E-08	1.45E-07	8.86E-08	3.00E-06	2
65	8	3.96E-07	5.41E-07	2.41E-07	5.41E-07	2.70E-07	1.91E-08	1.45E-07	7.19E-08	3.00E-06	1
3	9	4.04E-07	5.45E-07	2.69E-07	5.45E-07	2.72E-07	2.55E-08	1.49E-07	8.33E-08	3.00E-06	2
57	10	4.80E-07	5.48E-07	2.49E-07	5.48E-07	2.74E-07		1.37E-07	2.74E-07	3.00E-06	2
46	11	5.07E-07	6.74E-07	3.29E-07	6.74E-07	3.37E-07	3.08E-08	1.84E-07	1.02E-07	3.00E-06	1
11	12	5.24E-07	7.07E-07	3.63E-07	7.07E-07	3.53E-07	1.40E-08	1.84E-07	7.03E-08	3.00E-06	1
15	13	5.28E-07	7.14E-07	3.68E-07	7.14E-07	3.57E-07	1.40E-08	1.86E-07	7.07E-08	3.00E-06	1
51	14	5.71E-07	7.41E-07	3.88E-07	7.41E-07	3.71E-07	4.26E-08	2.07E-07	1.26E-07	3.00E-06	1
47	15	6.17E-07	8.00E-07	4.18E-07	8.00E-07	4.00E-07	1.06E-07	2.53E-07	2.06E-07	3.00E-06	1
42	16	7.60E-07	9.45E-07	4.85E-07	9.45E-07	4.73E-07	3.20E-08	2.52E-07	1.23E-07	3.00E-06	2
67	17	9.94E-07	9.40E-07	1.68E-07	9.94E-07	4.97E-07		2.49E-07	4.97E-07	3.00E-06	2
66	18	9.98E-07	7.16E-07	1.93E-07	9.98E-07	4.99E-07	2.90E-09	2.51E-07	3.80E-08	3.00E-06	2
33	19	8.50E-07	1.02E-06	5.15E-07	1.02E-06	5.10E-07	1.11E-07	3.11E-07	2.38E-07	3.00E-06	2
26	20	8.32E-07	1.05E-06	5.11E-07	1.05E-06	5.24E-07	4.29E-08	2.84E-07	1.50E-07	3.00E-06	1
34	21	1.02E-06	1.27E-06	6.24E-07	1.27E-06	6.33E-07	3.52E-07	4.92E-07	4.72E-07	3.00E-06	2
22	22	1.13E-06	1.36E-06	7.00E-07	1.36E-06	6.82E-07	3.89E-08	3.61E-07	1.63E-07	3.00E-06	1
45	23	1.08E-06	1.37E-06	6.85E-07	1.37E-06	6.85E-07	4.53E-08	3.65E-07	1.76E-07	3.00E-06	2
12	24	1.01E-06	1.39E-06	7.70E-07	1.39E-06	6.95E-07	5.41E-08	3.75E-07	1.94E-07	3.00E-06	2
56	25	1.18E-06	1.49E-06	7.93E-07	1.49E-06	7.43E-07	9.62E-08	4.20E-07	2.67E-07	3.00E-06	2
35	26	1.13E-06	1.54E-06	8.11E-07	1.54E-06	7.69E-07	2.86E-08	3.99E-07	1.48E-07	3.00E-06	2
29	27	1.17E-06	1.56E-06	9.36E-07	1.56E-06	7.78E-07	2.65E-07	5.21E-07	4.54E-07	3.00E-06	2
37	28	1.33E-06	1.71E-06	9.13E-07	1.71E-06	8.56E-07	4.95E-07	6.75E-07	6.51E-07	3.00E-06	2
7	29	1.36E-06	1.76E-06	9.54E-07	1.76E-06	8.79E-07	3.42E-07	6.11E-07	5.48E-07	3.00E-06	2
10	30	1.39E-06	1.90E-06	1.10E-06	1.90E-06	9.50E-07	1.85E-07	5.68E-07	4.19E-07	3.00E-06	2
5	31	1.94E-06	1.40E-06	4.35E-07	1.94E-06	9.68E-07	6.80E-09	4.88E-07	8.11E-08	3.00E-06	1
1	32	1.56E-06	2.00E-06	1.04E-06	2.00E-06	1.00E-06	2.27E-07	6.14E-07	4.76E-07	3.00E-06	1
52	33	6.09E-07	2.06E-06	1.16E-06	2.06E-06	1.03E-06	2.83E-07	6.57E-07	5.40E-07	3.00E-06	2
41	34	1.02E-06	1.32E-06	2.07E-06	2.07E-06	1.03E-06	3.45E-09	5.19E-07	5.97E-08	3.00E-06	1
48	35	6.36E-07	2.13E-06	1.16E-06	2.13E-06	1.06E-06	4.61E-07	7.62E-07	7.00E-07	3.00E-06	2
23	36	1.63E-06	2.14E-06	1.10E-06	2.14E-06	1.07E-06	1.42E-07	6.07E-07	3.90E-07	3.00E-06	2

17	37	1.65E-06	2.15E-06	1.09E-06	2.15E-06	1.08E-06	1.94E-07	6.35E-07	4.57E-07	3.00E-06	1
55	38	1.69E-06	2.15E-06	9.83E-07	2.15E-06	1.08E-06	5.13E-08	5.64E-07	2.35E-07	3.00E-06	2
24	39	1.59E-06	2.19E-06	1.25E-06	2.19E-06	1.10E-06	6.11E-07	8.54E-07	8.19E-07	3.00E-06	1
53	40	1.14E-06	2.29E-06	1.12E-06	2.29E-06	1.14E-06	1.01E-07	6.22E-07	3.40E-07	3.00E-06	2
64	41	6.10E-07	2.33E-06	1.75E-06	2.33E-06	1.16E-06	2.50E-07	7.07E-07	5.40E-07	3.00E-06	1
69	42	2.38E-06	1.37E-06	3.73E-07	2.38E-06	1.19E-06	2.75E-09	5.96E-07	5.72E-08	3.00E-06	2
9	43	1.71E-06	2.41E-06	1.34E-06	2.41E-06	1.21E-06	2.16E-07	7.11E-07	5.10E-07	3.00E-06	1
13	44	1.84E-06	2.57E-06	1.42E-06	2.57E-06	1.29E-06	3.27E-07	8.07E-07	6.48E-07	3.00E-06	2
14	45	1.88E-06	2.63E-06	1.41E-06	2.63E-06	1.32E-06	5.99E-07	9.58E-07	8.88E-07	3.00E-06	2
39	46	2.79E-06	1.84E-06	9.73E-07	2.79E-06	1.40E-06	1.40E-07	7.68E-07	4.42E-07	3.00E-06	2
31	47	1.79E-06	2.89E-06	5.35E-07	2.89E-06	1.45E-06	6.15E-08	7.53E-07	2.98E-07	3.00E-06	1
44	48	2.65E-06	2.79E-06	2.93E-06	2.93E-06	1.46E-06		7.32E-07	1.46E-06	3.00E-06	2
20	49	2.28E-06	2.94E-06	1.67E-06	2.94E-06	1.47E-06	5.50E-07	1.01E-06	9.00E-07	3.00E-06	2
50	50	1.84E-06	3.17E-06	1.25E-06	3.17E-06	1.59E-06	2.01E-07	8.94E-07	5.65E-07	3.00E-06	2
4	51	2.33E-06	3.22E-06	1.96E-06	3.22E-06	1.61E-06		8.06E-07	1.61E-06	3.00E-06	1
28	52	3.46E-06	2.43E-06	8.62E-07	3.46E-06	1.73E-06	3.86E-08	8.83E-07	2.58E-07	3.00E-06	2
32	53	3.54E-06	2.31E-06	1.06E-06	3.54E-06	1.77E-06	1.68E-07	9.70E-07	5.46E-07	3.00E-06	1
19	54	3.75E-06	2.23E-06	1.05E-06	3.75E-06	1.88E-06	1.68E-07	1.02E-06	5.61E-07	3.00E-06	2
54	55	2.37E-06	4.32E-06	2.64E-06	4.32E-06	2.16E-06	2.51E-07	1.21E-06	7.37E-07	3.00E-06	2
63	56	4.41E-06	2.75E-06	4.70E-07	4.41E-06	2.20E-06	5.91E-09	1.10E-06	1.14E-07	3.00E-06	1
38	57	3.42E-06	4.59E-06	2.35E-06	4.59E-06	2.29E-06	2.13E-07	1.25E-06	6.99E-07	3.00E-06	2
40	58	1.25E-06	5.01E-06	2.83E-06	5.01E-06	2.50E-06	9.71E-08	1.30E-06	4.93E-07	3.00E-06	2
16	59	5.02E-06	3.41E-06	1.00E-06	5.02E-06	2.51E-06	1.37E-07	1.32E-06	5.86E-07	3.00E-06	1
49	60	4.55E-06	5.39E-06	2.91E-06	5.39E-06	2.70E-06	2.71E-07	1.48E-06	8.55E-07	3.00E-06	1
27	61	2.30E-06	5.33E-06	5.70E-06	5.70E-06	2.85E-06	3.78E-07	1.61E-06	1.04E-06	3.00E-06	1
62	62	4.25E-06	7.43E-06	8.03E-06	8.03E-06	4.02E-06		2.01E-06	4.02E-06	3.00E-06	2
21	63	6.36E-06	8.23E-06	1.87E-06	8.23E-06	4.11E-06		2.06E-06	4.11E-06	3.00E-06	1
59	64	1.73E-06	8.73E-06	4.59E-06	8.73E-06	4.37E-06		2.18E-06	4.37E-06	3.00E-06	1
43	65	5.49E-06	8.90E-06	1.87E-06	8.90E-06	4.45E-06	1.23E-07	2.29E-06	7.40E-07	3.00E-06	1
8	66	1.11E-05	9.02E-06	2.43E-06	1.11E-05	5.54E-06	2.08E-07	2.87E-06	1.07E-06	3.00E-06	2
25	67	1.21E-05	1.37E-05	4.41E-06	1.37E-05	6.83E-06	5.71E-07	3.70E-06	1.98E-06	3.00E-06	2
18	68	9.05E-06	1.75E-05	1.08E-05	1.75E-05	8.74E-06	1.89E-06	5.32E-06	4.07E-06	3.00E-06	1
36	69	2.32E-05	2.81E-05	4.67E-06	2.81E-05	1.41E-05	1.42E-07	7.10E-06	1.41E-06	3.00E-06	2
					average of	1.66E-06	1.92E-07				
					column						

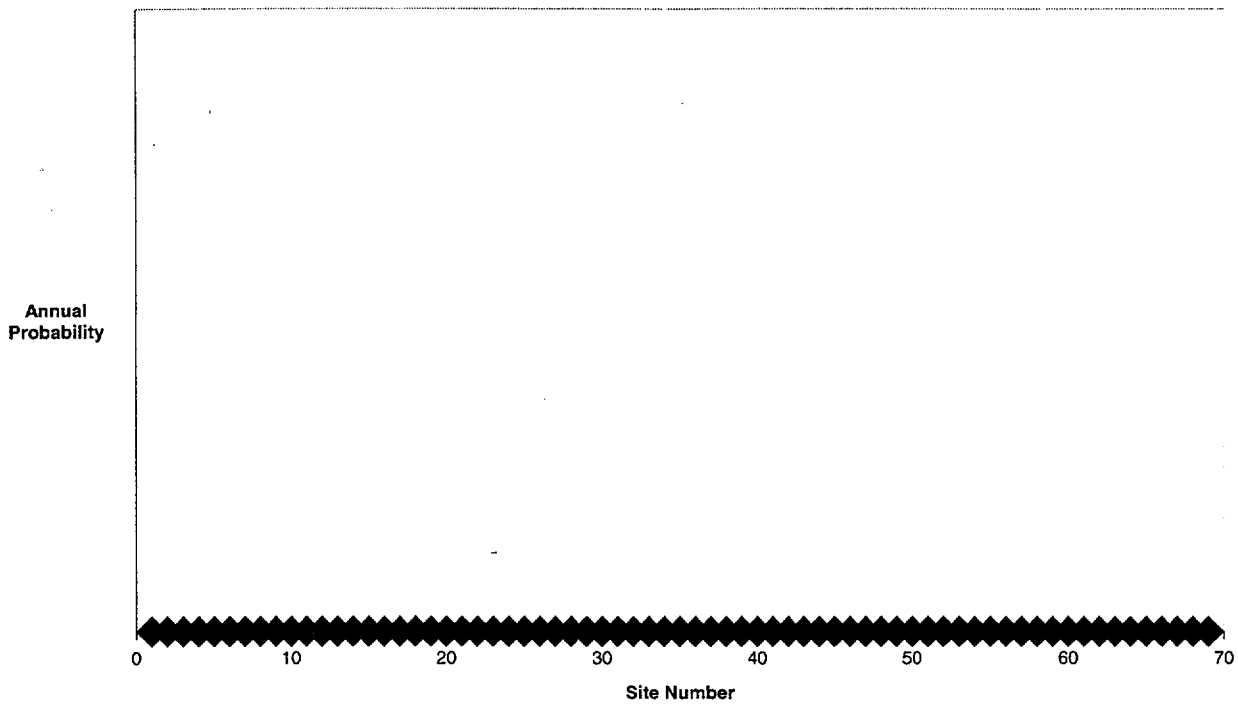
LLNL SFP Failure Frequency" Based on Kennedy Methodology



SFP Failure Frequency (LLNL-93 and EPRI-89)" Kennedy Methodology



Geometric Mean (LLNL & EPRI)" Kennedy Methodology



	LLNL	LLNL	LLNL	LLNL	LLNL		L+E	L+E	
Site #	2.5hz	5hz	10hz	Max (2.5, 5, 10)	Max*0.5	EPRI	Avg.	Geometric	
1	1.56E-06	2.00E-06	1.04E-06	2.00E-06	1.00E-06	2.27E-07	6.14E-07	3.73E-07	1.50E-06
2	4.23E-07	5.18E-07	2.44E-07	5.18E-07	2.59E-07	3.03E-08	1.45E-07	6.62E-08	1.50E-06
3	4.04E-07	5.45E-07	2.69E-07	5.45E-07	2.72E-07	2.55E-08	1.49E-07	6.16E-08	1.50E-06
4	2.33E-06	3.22E-06	1.96E-06	3.22E-06	1.61E-06		8.06E-07	8.06E-07	1.50E-06
5	1.94E-06	1.40E-06	4.35E-07	1.94E-06	9.68E-07	6.80E-09	4.88E-07	5.76E-08	1.50E-06
6	2.02E-07	2.44E-07	1.16E-07	2.44E-07	1.22E-07	2.22E-08	7.20E-08	4.00E-08	1.50E-06
7	1.36E-06	1.76E-06	9.54E-07	1.76E-06	8.79E-07	3.42E-07	6.11E-07	4.57E-07	1.50E-06
8	1.11E-05	9.02E-06	2.43E-06	1.11E-05	5.54E-06	2.08E-07	2.87E-06	7.73E-07	1.50E-06
9	1.71E-06	2.41E-06	1.34E-06	2.41E-06	1.21E-06	2.16E-07	7.11E-07	3.92E-07	1.50E-06
10	1.39E-06	1.90E-06	1.10E-06	1.90E-06	9.50E-07	1.85E-07	5.68E-07	3.24E-07	1.50E-06
11	5.24E-07	7.07E-07	3.63E-07	7.07E-07	3.53E-07	1.40E-08	1.84E-07	5.07E-08	1.50E-06
12	1.01E-06	1.39E-06	7.70E-07	1.39E-06	6.95E-07	5.41E-08	3.75E-07	1.42E-07	1.50E-06
13	1.84E-06	2.57E-06	1.42E-06	2.57E-06	1.29E-06	3.27E-07	8.07E-07	5.14E-07	1.50E-06
14	1.88E-06	2.63E-06	1.41E-06	2.63E-06	1.32E-06	5.99E-07	9.58E-07	7.58E-07	1.50E-06
15	5.28E-07	7.14E-07	3.68E-07	7.14E-07	3.57E-07	1.40E-08	1.86E-07	5.10E-08	1.50E-06
16	5.02E-06	3.41E-06	1.00E-06	5.02E-06	2.51E-06	1.37E-07	1.32E-06	4.26E-07	1.50E-06
17	1.65E-06	2.15E-06	1.09E-06	2.15E-06	1.08E-06	1.94E-07	6.35E-07	3.51E-07	1.50E-06
18	9.05E-06	1.75E-05	1.08E-05	1.75E-05	8.74E-06	1.89E-06	5.32E-06	3.17E-06	1.50E-06
19	3.75E-06	2.23E-06	1.05E-06	3.75E-06	1.88E-06	1.68E-07	1.02E-06	4.14E-07	1.50E-06
20	2.28E-06	2.94E-06	1.67E-06	2.94E-06	1.47E-06	5.50E-07	1.01E-06	7.46E-07	1.50E-06
21	6.36E-06	8.23E-06	1.87E-06	8.23E-06	4.11E-06		2.06E-06	2.06E-06	1.50E-06
22	1.13E-06	1.36E-06	7.00E-07	1.36E-06	6.82E-07	3.89E-08	3.61E-07	1.18E-07	1.50E-06
23	1.63E-06	2.14E-06	1.10E-06	2.14E-06	1.07E-06	1.42E-07	6.07E-07	2.94E-07	1.50E-06
24	1.59E-06	2.19E-06	1.25E-06	2.19E-06	1.10E-06	6.11E-07	8.54E-07	7.22E-07	1.50E-06
25	1.21E-05	1.37E-05	4.41E-06	1.37E-05	6.83E-06	5.71E-07	3.70E-06	1.45E-06	1.50E-06
26	8.32E-07	1.05E-06	5.11E-07	1.05E-06	5.24E-07	4.29E-08	2.84E-07	1.10E-07	1.50E-06
27	2.30E-06	5.33E-06	5.70E-06	5.70E-06	2.85E-06	3.78E-07	1.61E-06	7.81E-07	1.50E-06
28	3.46E-06	2.43E-06	8.62E-07	3.46E-06	1.73E-06	3.86E-08	8.83E-07	1.85E-07	1.50E-06
29	1.17E-06	1.56E-06	9.36E-07	1.56E-06	7.78E-07	2.65E-07	5.21E-07	3.72E-07	1.50E-06
30	3.20E-07	4.59E-07	2.61E-07	4.59E-07	2.30E-07	1.11E-08	1.20E-07	3.66E-08	1.50E-06
31	1.79E-06	2.89E-06	5.35E-07	2.89E-06	1.45E-06	6.15E-08	7.53E-07	2.15E-07	1.50E-06
32	3.54E-06	2.31E-06	1.06E-06	3.54E-06	1.77E-06	1.68E-07	9.70E-07	4.04E-07	1.50E-06
33	8.50E-07	1.02E-06	5.15E-07	1.02E-06	5.10E-07	1.11E-07	3.11E-07	1.86E-07	1.50E-06
34	1.02E-06	1.27E-06	6.24E-07	1.27E-06	6.33E-07	3.52E-07	4.92E-07	4.16E-07	1.50E-06
35	1.13E-06	1.54E-06	8.11E-07	1.54E-06	7.69E-07	2.86E-08	3.99E-07	1.07E-07	1.50E-06
36	2.32E-05	2.81E-05	4.67E-06	2.81E-05	1.41E-05	1.42E-07	7.10E-06	1.00E-06	1.50E-06
37	1.33E-06	1.71E-06	9.13E-07	1.71E-06	8.56E-07	4.95E-07	6.75E-07	5.78E-07	1.50E-06
38	3.42E-06	4.59E-06	2.35E-06	4.59E-06	2.29E-06	2.13E-07	1.25E-06	5.17E-07	1.50E-06
39	2.79E-06	1.84E-06	9.73E-07	2.79E-06	1.40E-06	1.40E-07	7.68E-07	3.28E-07	1.50E-06
40	1.25E-06	5.01E-06	2.83E-06	5.01E-06	2.50E-06	9.71E-08	1.30E-06	3.55E-07	1.50E-06
41	1.02E-06	1.32E-06	2.07E-06	2.07E-06	1.03E-06	3.45E-09	5.19E-07	4.23E-08	1.50E-06
42	7.60E-07	9.45E-07	4.85E-07	9.45E-07	4.73E-07	3.20E-08	2.52E-07	8.98E-08	1.50E-06
43	5.49E-06	8.90E-06	1.87E-06	8.90E-06	4.45E-06	1.23E-07	2.29E-06	5.30E-07	1.50E-06
44	2.65E-06	2.79E-06	2.93E-06	2.93E-06	1.46E-06		7.32E-07	7.32E-07	1.50E-06
45	1.08E-06	1.37E-06	6.85E-07	1.37E-06	6.85E-07	4.53E-08	3.65E-07	1.29E-07	1.50E-06
46	5.07E-07	6.74E-07	3.29E-07	6.74E-07	3.37E-07	3.08E-08	1.84E-07	7.53E-08	1.50E-06
47	6.17E-07	8.00E-07	4.18E-07	8.00E-07	4.00E-07	1.06E-07	2.53E-07	1.64E-07	1.50E-06
48	6.36E-07	2.13E-06	1.16E-06	2.13E-06	1.06E-06	4.61E-07	7.62E-07	5.93E-07	1.50E-06
49	4.55E-06	5.39E-06	2.91E-06	5.39E-06	2.70E-06	2.71E-07	1.48E-06	6.34E-07	1.50E-06
50	1.84E-06	3.17E-06	1.25E-06	3.17E-06	1.59E-06	2.01E-07	8.94E-07	4.24E-07	1.50E-06
51	5.71E-07	7.41E-07	3.88E-07	7.41E-07	3.71E-07	4.26E-08	2.07E-07	9.38E-08	1.50E-06
52	6.09E-07	2.06E-06	1.16E-06	2.06E-06	1.03E-06	2.83E-07	6.57E-07	4.31E-07	1.50E-06
53	1.14E-06	2.29E-06	1.12E-06	2.29E-06	1.14E-06	1.01E-07	6.22E-07	2.51E-07	1.50E-06
54	2.37E-06	4.32E-06	2.64E-06	4.32E-06	2.16E-06	2.51E-07	1.21E-06	5.50E-07	1.50E-06
55	1.69E-06	2.15E-06	9.83E-07	2.15E-06	1.08E-06	5.13E-08	5.64E-07	1.70E-07	1.50E-06
56	1.18E-06	1.49E-06	7.93E-07	1.49E-06	7.43E-07	9.62E-08	4.20E-07	2.01E-07	1.50E-06
57	4.80E-07	5.48E-07	2.49E-07	5.48E-07	2.74E-07		1.37E-07	1.37E-07	1.50E-06
58	9.12E-08	1.30E-07	7.10E-08	1.30E-07	6.51E-08	3.80E-09	3.45E-08	1.14E-08	1.50E-06
59	1.73E-06	8.73E-06	4.59E-06	8.73E-06	4.37E-06		2.18E-06	2.18E-06	1.50E-06
60	3.48E-07	4.61E-07	2.51E-07	4.61E-07	2.30E-07	5.96E-09	1.18E-07	2.65E-08	1.50E-06
61	2.22E-07	2.86E-07	1.61E-07	2.86E-07	1.43E-07		7.15E-08	7.15E-08	1.50E-06
62	4.25E-06	7.43E-06	8.03E-06	8.03E-06	4.02E-06		2.01E-06	2.01E-06	1.50E-06
63	4.41E-06	2.75E-06	4.70E-07	4.41E-06	2.20E-06	5.91E-09	1.10E-06	8.08E-08	1.50E-06
64	6.10E-07	2.33E-06	1.75E-06	2.33E-06	1.16E-06	2.50E-07	7.07E-07	4.20E-07	1.50E-06
65	3.96E-07	5.41E-07	2.41E-07	5.41E-07	2.70E-07	1.91E-08	1.45E-07	5.26E-08	1.50E-06
66	9.98E-07	7.16E-07	1.93E-07	9.98E-07	4.99E-07	2.90E-09	2.51E-07	2.70E-08	1.50E-06
67	9.94E-07	9.40E-07	1.68E-07	9.94E-07	4.97E-07		2.49E-07	2.49E-07	1.50E-06
68	2.34E-07	3.19E-07	1.81E-07	3.19E-07	1.59E-07		7.97E-08	7.97E-08	1.50E-06
69	2.38E-06	1.37E-06	3.73E-07	2.38E-06	1.19E-06	2.75E-09	5.96E-07	4.05E-08	1.50E-06

DRAFT

EPRI TECHNICAL REPORT

Evaluation of Spent Fuel Pool Seismic Failure Frequency in Support of Risk Informed Decommissioning Emergency Planning

Duke Engineering & Services.
A Duke Energy Company

EXECUTIVE SUMMARY

The overall objective of this effort is to perform a risk-informed evaluation whether inclusion of "beyond design basis accidents", particularly a Zircaloy oxidation reaction [fire] accident as the basis for Decommissioning Emergency Planning is warranted.

The annual probability of a Zircaloy cladding fire, resulting from the loss of water from the spent fuel pool, is estimated in NUREG-1353 [1] to have a mean value of 2×10^{-6} per reactor year for either the PWR or the BWR spent fuel pool. The Spent Fuel Pool (SFP) failure frequency due to seismic, used in NUREG-1353, is documented in NUREG/CR-5176 [5]. The annual frequency of seismic induced SFP failure documented in NUREG/CR-5176 was determined by convolving a family of seismic hazard curves with a family of fragility curves. The family of seismic hazard curves was developed based upon preliminary results which were subsequently published in LLNL 1989 [2]. The family of fragility curves was based on estimates of the seismic capacity of typical BWR and PWR spent fuel pools. Since publication of NUREG-1353 and NUREG/CR-5176, the LLNL seismic hazard results were updated in 1993 [3]. Industry also published seismic hazard results at 61 Nuclear Power Plant (NPP) sites in 1989 [4].

Using the methodology to calculate SFP failure frequency due to seismic described in NUREG/CR-5176, along with the NUREG-1353 assumptions, the NUREG-1353 SFP release values have been updated based upon use of the LLNL 1993 and EPRI 1989 seismic hazard results. Using the LLNL 1993 results the annual probability of a Zircaloy cladding fire, resulting from the loss of water from the spent fuel pool, is estimated to have a mean value of 5.6×10^{-7} per reactor year for either the PWR or the BWR spent fuel pool. Using the EPRI 1989 results the annual probability of a Zircaloy cladding fire, resulting from the loss of water from the SFP, is estimated to have a mean value of 1.8×10^{-7} per reactor year for either the PWR or the BWR spent fuel pool. On average, use of these updated seismic hazard curves results in a reduction in the SFP failure frequency across the population of plants by a factor of 8 when using LLNL 1993 and about 70 when using EPRI 1989.

The results of this analysis also meet the probabilistic acceptance criteria of Standard Review Plan (SRP) 2.2.3, "Evaluation of Potential Accidents." This SRP provides a basis for inclusion or exclusion of potential accidents into the plant design basis. For operating NPPs, emergency planning is required to ensure the continued protection of the public health and safety in areas around the nuclear facility in the event of a radiological emergency. Application of the SRP 2.2.3 criteria provides a basis for elimination of the requirements for off-site emergency planning at decommissioning NPPs.

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1.0 INTRODUCTION

The overall objective of this effort is to provide risk-informed evaluation whether inclusion of "beyond design basis accidents", particularly a Zircaloy oxidation reaction [fire] accident as the basis for Decommissioning Emergency Planning is warranted. This issue was satisfactorily resolved for all plants by NUREG-1353 in 1989. The conclusions remain valid today, because the decommissioning state does not adversely affect the results on which the conclusions were based. Since the publication of NUREG-1353, significant improvements have been made in the seismic hazard results on which the previous conclusions were based. In particular, recent work by both the regulator and the industry has reduced the calculated seismic hazard, which is the dominant contributor to the overall spent fuel pool release frequency.

The purpose of this document is to describe the methodology and results of the seismic technical analysis used to demonstrate the above conclusions are valid. NUREG-1353 "Regulatory Analysis for the Resolution of Generic Issue 82 Beyond Design Basis Accidents in Spent Fuel Pools", dated April 1989 is considered a valid framework for this analysis. Given the NUREG-1353 framework, the Spent Fuel Pool failure frequencies due to seismic was updated using more current seismic hazard results.

Table 4.7.1 of NUREG-1353 summarizes the frequency of spent fuel damage resulting from accident sequences which can result in the loss of water from the Spent Fuel Pool (SFP) either through drainage or boiling as a result of loss of cooling. As described in Reference 1, the seismic event contributes over 90% of the PWR spent fuel damage probability, and nearly 95% for the BWR. However, since publication of NUREG-1353, revisions have been made to the published seismic hazard results at those sites previously evaluated for SFP failure frequency. In particular, revisions to the Lawrence Livermore National Laboratory (LLNL) seismic hazard results at 69 Eastern United States (EUS) sites was published in 1993. In addition, Electric Power Research Institute (EPRI) hazard results are also available at 61 EUS sites.

NUREG-1353 is considered a valid framework to calculate release frequencies at these sites. SFP accident frequencies for other scenarios (Missiles, Aircraft crashes, etc.) as shown in Table 1.1, which is a verbatim copy of Table 4.7.1 in NUREG-1353, are considered valid for this analysis. Only the SFP failure frequency due to seismic is updated. The SFP failure frequencies due to seismic used in the NUREG-1353 analysis are from NUREG/CR-5176. Updates of the SFP failure frequency will be based on the methodology and inputs described in NUREG/CR-5176. Therefore, this analysis is in essence a NUREG-1353 analysis with new seismic hazard curves used to calculate spent fuel pool failure frequencies.

Using the 1989 and 1993 Lawrence Livermore National Laboratory (LLNL) seismic hazard results at 69 sites east of the Rocky Mountains, and the 1989 EPRI results at 61 sites east of the Rocky Mountains, the SFP failure frequency at each site is calculated. The reduction in SFP failure frequency due to the use of the 1993 LLNL results and the 1989 EPRI results is quantified. Given the NUREG-1353 framework, and the updated SFP failure frequencies, release frequencies are calculated for each of the 69 sites. The mean annual probability of a Zircaloy cladding fire, due to loss of water from the spent fuel pool, is also calculated.

Table 1.1: Summary of Accident Sequence Quantification from NUREG-1353

Table 4.7.1
Summary of SFP Accident Frequencies

Accident Sequence	PWR Frequency		BWR Frequency	
	Best Estimate (per R-year)	Upper Bound (per R-year)	Best Estimate (per R-year)	Upper Bound (per R-year)
Structural Failures				
1. Missiles	1.0 E-8	1.0 E-7	1.0 E-8	1.0 E-7
2. Aircraft crashes	6.0 E-9	2.0 E-8	6.0 E-9	2.0 E-8
3. Heavy Load Drop	3.1 E-8	3.1 E-7	3.1 E-8	3.1 E-7
Pneumatic Seal Failures	3.0 E-8	5.0 E-7	3.0 E-8(1)	5.0 E-7(1)
Inadvertent Drainage	1.2 E-8	1.0 E-7	1.2 E-8	1.0 E-7
Loss of Cooling/Make-up	6.0 E-8(2)	1.4 E-6	6.0 E-8(2)	1.4 E-6
TOTAL	1.5 E-7	2.4 E-6	1.5 E-7	2.4 E-6
Seismic Structural Failure	1.8 E-6		6.7 E-6	
Conditional Probability of Zircaloy Cladding Fire Given Loss of Water (High Density Storage Racks)	1.0		0.25	

NOTES:

1. BWRs do not, in general, use pneumatic refueling cavity seals, but other pneumatic seals are used in the transfer canal.
2. Includes beyond design basis seismic induced loss of cooling and make-up.

2.0 METHODOLOGY

2.1 SFP Failure Frequency Due to Seismic – NUREG/CR-5176

The methodology to calculate SFP failure frequency is described in NUREG/CR-5176. SFP failure frequency due to seismic is calculated by convolving the seismic hazard distribution with the seismic fragility of the SFP. The convolution process to numerically integrate the family of seismic hazard curves with the family of fragility curves is described in Reference 6.

2.1.1 Generation of the Family of Seismic Hazard Curves

The following assumptions and recommendations from Reference 5 were used to generate the family of seismic hazard curves for this analysis:

1. A lognormal distribution was assumed for the distribution of the uncertainty in probability of exceedance at each acceleration value. The parameters of the lognormal distribution (i.e., median and logarithmic standard deviation (β)) were calculated by using the 50th and 95th percentile values.
2. Given the median and the 95th percentile the logarithmic standard deviation (β) is calculated ($\beta = (\ln(x_{95}/x_{50})/1.64)$). β can also be calculated from the natural log of the ratio of the 85th percentile to the median. Given β, the probability of exceedance (X_n) can then be calculated at various percentiles ($X_n = x_{50} * e^{z\beta}$). Z is the standard normal variate.
3. Because it is possible to get probability of exceedance values greater than 1.0, the lognormal distribution is truncated at X_{99} (the 99 percentile). The lognormal distribution was normalized to get a new distribution with cutoff at X99.
4. The range of hazard represented by the truncated (lognormal) distribution at each acceleration was discretized into eleven discrete values of the hazard with subjective probabilities of 0.03, 0.05, 0.07, 0.12, 0.15, 0.16, 0.15, 0.12, 0.07, 0.05, and 0.03.

Figures 2.1, 2.2, and 2.3 show the family of hazard curves generated for the Vermont Yankee site based upon use of the above process. Figure 2.1 is based upon use of the 1989 LLNL results and an estimate of β based on use of the 95th percentile as described in (2) above. Figure 2.2 is based upon use of the 1993 LLNL results and an estimate of β based on use of the 85th percentile as described in (2) above. Figure 2.3 is based upon use of the 1989 EPRI results and an estimate of β based on use of the 85th percentile as described in (2) above. In Figures 2.2 and 2.3, β is estimated using the 85th percentile because 95th percentile results are not available. As can be seen, there is a significant reduction in the uncertainty between Figure 2.1 and Figures 2.2 and 2.3. At about 2 g, the uncertainty in Figure 2.1 ranges from about 5×10^{-5} to about 1×10^{-12}, whereas in Figure 2.2 the uncertainty ranges from about 4×10^{-6} to 2×10^{-11}. The Figure 2.3 results (EPRI) behave similar to the Figure 2.2 results.

Figure 2.4 compares estimates of β (logarithmic standard deviation) at each of the 69 sites using the LLNL 1989 results. As can be seen, β based upon use of the 95th percentile is equal to or lower than β based on use of the 85th percentile in all cases. Use of β based on 85th percentile estimates for the Vermont Yankee site would result in a wider uncertainty band than that shown in Figure 2.1. In terms of overall SFP seismic failure frequency, use of β values

based on the use of the 85th percentile would result in SFP failure frequencies about a factor of 2 higher than values calculated based on use of the 95th percentile. As described earlier, LLNL 1993 does not contain 95th percentile results. Therefore, LLNL 1993 SFP failure frequencies based on use of the 85th percentile to estimate β are in general about a factor of 2 higher in probability than SFP failure frequencies would be if 95th percentiles were available to estimate β.

2.1.2 Generation of the Family of Fragility Curves

In previous SFP failure frequency analyses by Brookhaven National Laboratory (BNL)[7], estimates of the seismic fragility of spent fuel pools were assigned by comparing with published PRAs. For the Millstone 1 BWR, the seismic fragility developed for the Oyster Creek reactor was judged appropriate for the Millstone 1 spent fuel pool. For the Ginna spent fuel pool, the fragility of the Zion plant auxiliary building shear walls was used.

In NUREG/CR-5176, one objective was to develop realistic estimates of the seismic capacity of typical BWR and PWR spent fuel pools. To accomplish this task, a detailed evaluation was performed of the Vermont Yankee (BWR) and Robinson (PWR) spent fuel pools. Structural drawings, the Final Safety Analysis Report (FSAR) and spent fuel pool reports (References 8 and 9) were reviewed. Based on this review, the seismic capacity of these two representative spent fuel pools, a BWR and a PWR, was determined. For BWRs, the SFP fragility is defined by:

The median fragility (x_{50})	= 1.4g
The random uncertainty β_R	= 0.26
The uncertainty in location β_U	= 0.39

For PWRs, the SFP fragility is defined by:

The median fragility (x_{50})	= 2.0g
The random uncertainty β_R	= 0.28
The uncertainty in location β_U	= 0.40

As described in Reference 6, the uncertainty in the median is described by the following equation:

$$\tilde{a}_i = A_m e^{\beta_U \zeta_i} \qquad (1)$$

where:

$\tilde{a}_i$ = uncertainty in the median,

A_m = the "median median" fragility (1.4 for BWR, 2.0 for PWR),

β_U = the lognormal standard deviation of the $\tilde{a}$ distribution, and

ζ_i = the standard normal variate.

Five curves, described by ζ_i values ranging from –1.28, -0.58, 0.0, 0.58, and 1.28, are used to define the uncertainty in median SFP fragilities. The basis for five fragility curves is described in Reference 10.

The desired discrete value for a fragility curve is then:

$$a = \tilde{a}_i \, e_\beta^{rZ} \qquad (2)$$

where:

a = acceleration value at a given failure frequency defined by Z,

$\tilde{a}_i$ = a median fragility,

β_r = the lognormal standard deviation of the random uncertainty about the median, and

Z = the standard normal variate.

Equations 1 and 2 can be combined such that the failure frequency at given accelerations (a), usually those which describe the hazard curve, can be readily calculated. The final equation is:

$$F_i(a) = N(\ln(a/A_m \, e_\beta^u \zeta^i)/\beta_r) \qquad (3)$$

$$F_i(a) = N(Z) \qquad (4)$$

where,

$F_i(a)$ = the fraction of earthquakes to fail the SFP at acceleration a, and

$N(Z)$ = the area under the normal curve up to point Z.

2.1.3 Calculation of the Release Frequency Given SFP Failure

The methodology to calculate the release frequency given SFP failure is described in NUREG-1353. Table 1.1 of this report is a duplicate of Table 4.7.1 of NUREG-1353. As can be seen in Table 1.1, the annual probability of a SFP failure for a PWR is described by the sum (1.5×10^{-7}) of the SFP failure frequencies associated with Structural Failures, Pneumatic Seal Failures, Inadvertent Drainage, and Loss of Cooling Make-up **plus** the Seismic Structural Failure. The annual probability of a release is the product of the annual SFP failure frequency and the conditional probability of Zircaloy cladding fire given loss of water. For PWRs, the conditional probability of the Zircaloy cladding fire is considered to be 1.0. Values less than 1.0 for a PWR are supported by Table 4.5.1 in NUREG-1353. For a BWR, the process is exactly the same with the exception that the conditional probability of Zircaloy cladding fire given loss of water is 0.25. Values less than 0.25 for a BWR are supported by Table 4.5.1 in NUREG-1353.

Using this approach, SFP seismic failure frequencies were calculated at each of the 69 sites using the LLNL results and at 61 sites using the EPRI results.

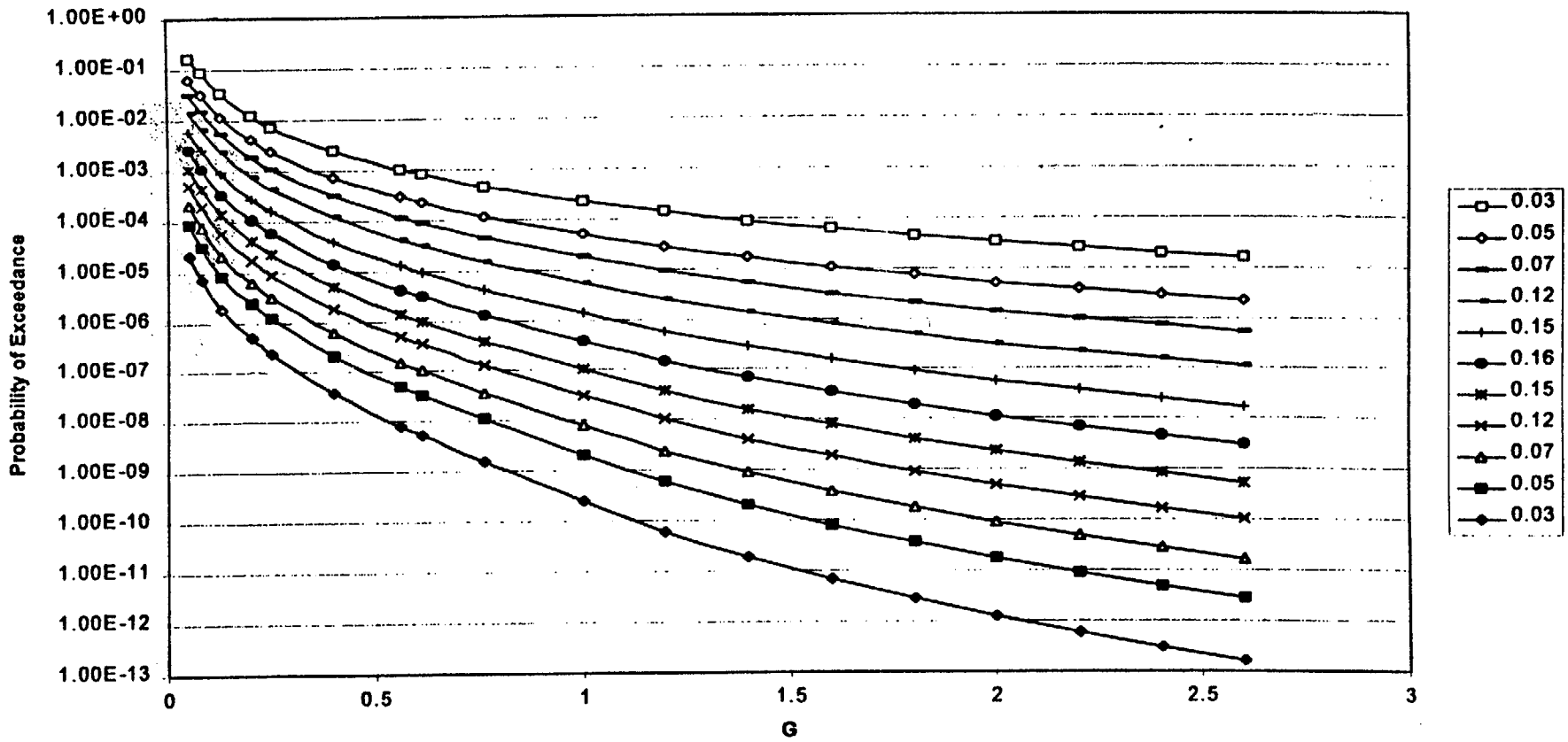

Figure 2.1 - Family of Hazard Curves for Vermont Yankee Based on Use of LLNL - 1989

Figure 2.1: Family of Hazard Curves for Vermont Yankee Based on Use of LLNL - 1989

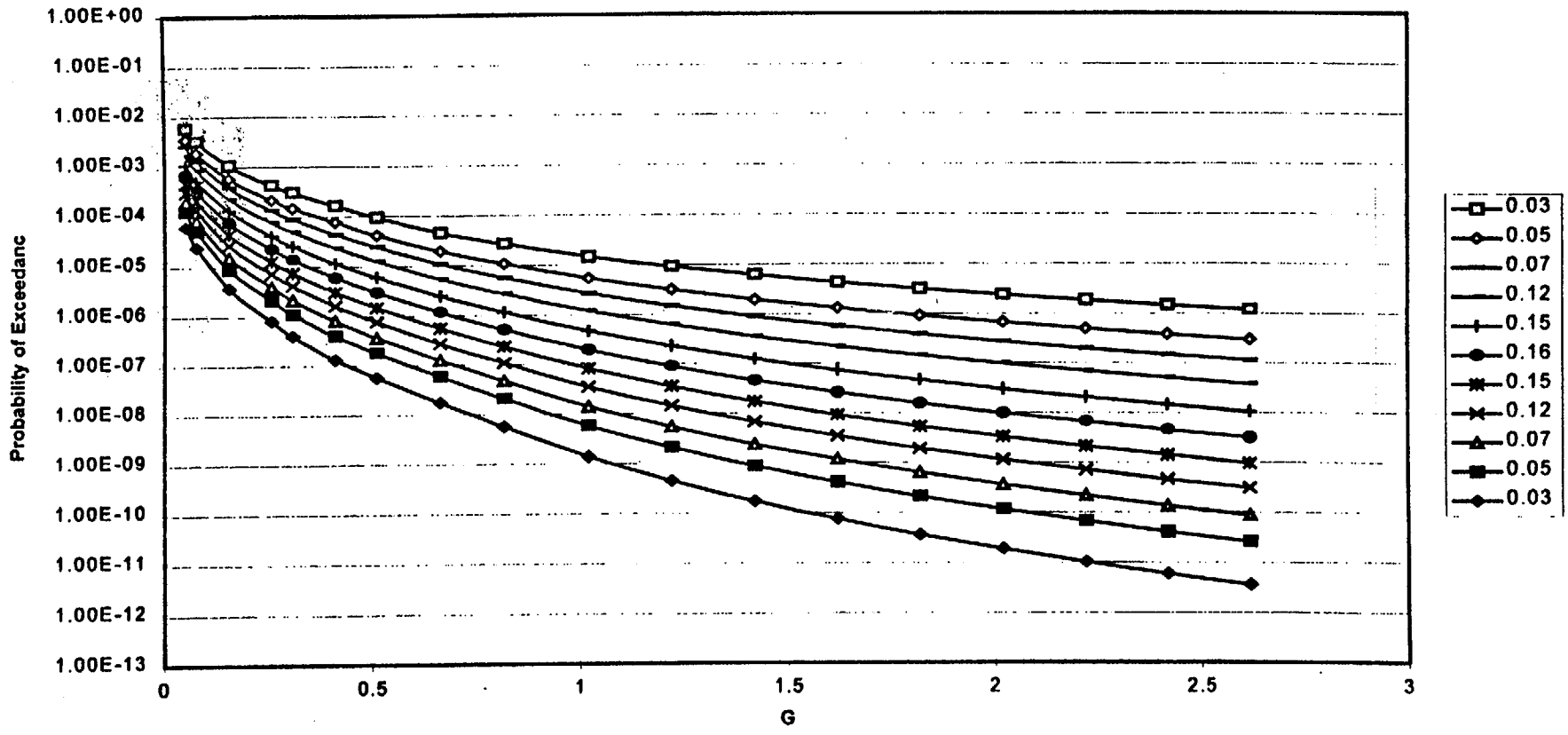

Figure 2.2 - Family of Hazard Curves for Vermont Yankee Based on Use of LLNL - 1993

Figure 2.2: Family of Hazard Curves for Vermont Yankee Based on Use of LLNL - 1993

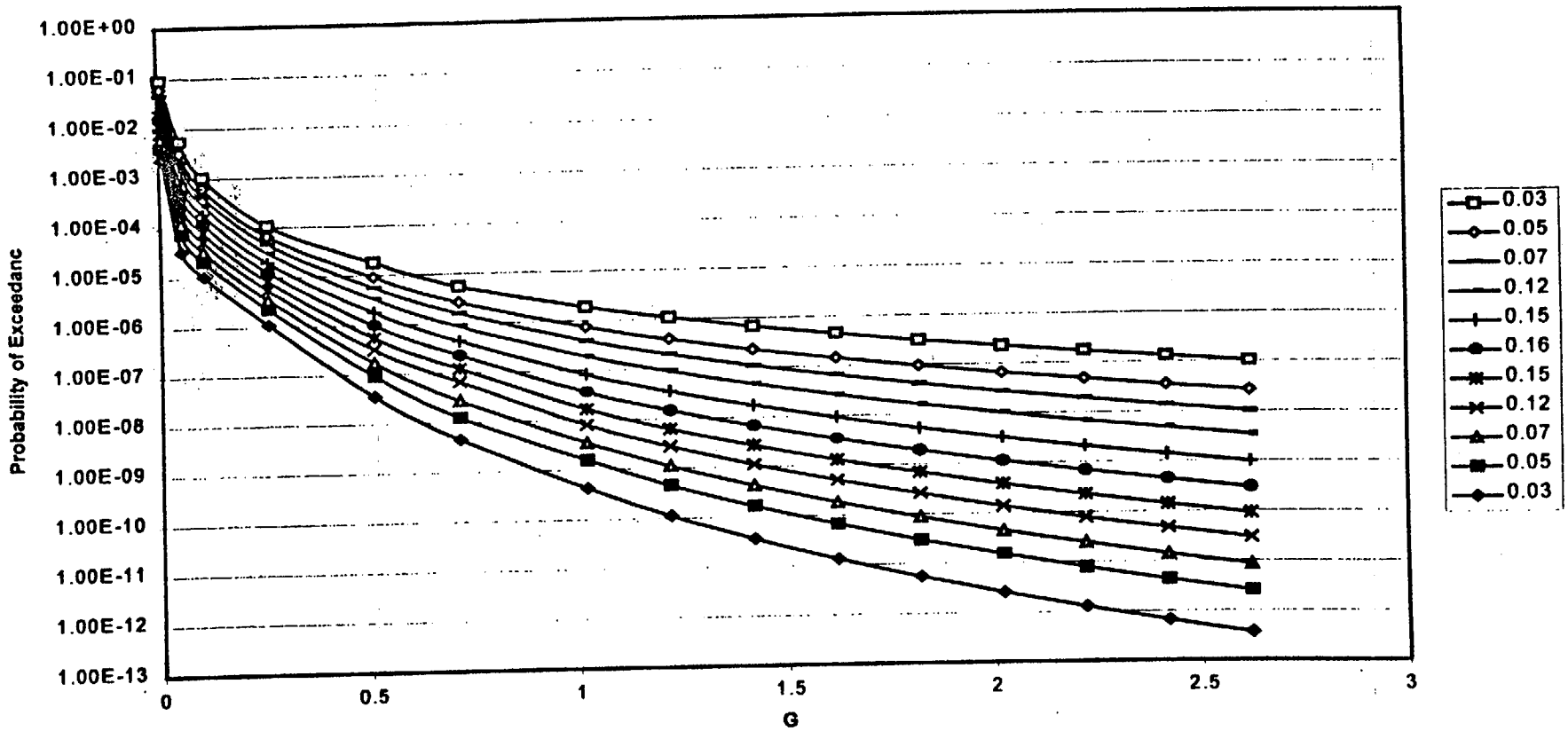

Figure 2.3 - Family of Hazard Curves for Vermont Yankee Based on Use of EPRI - 1989

Figure 2.3: Family of Hazard Curves for Vermont Yankee Based on Use of EPRI - 1989

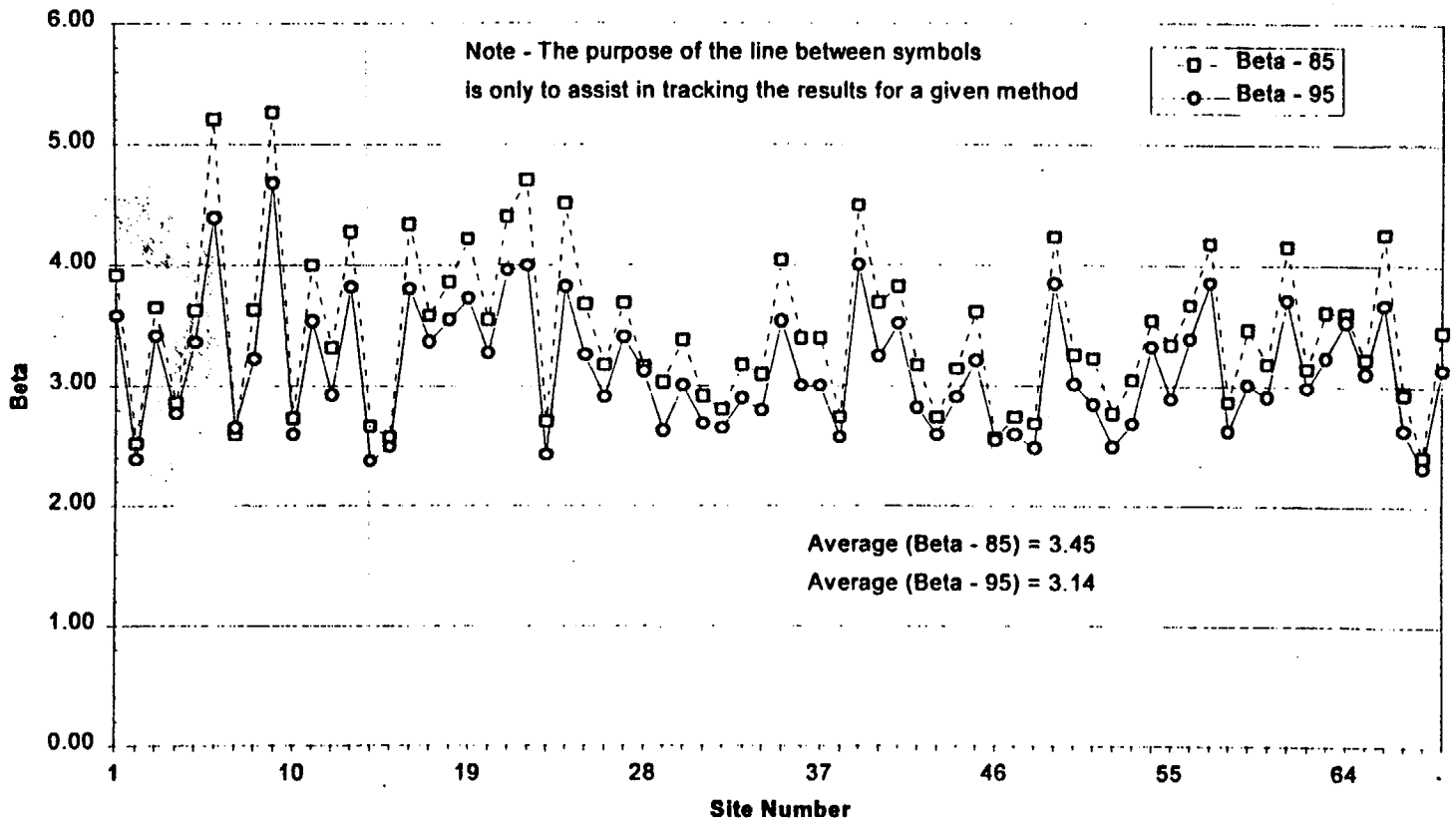

Figure 2.4 - Comparison of Alternative Methods to Calculate Beta

Figure 2.4: Comparison of Alternative Methods to Calculate Beta

3.0 RESULTS

Based on the methodology described in Section 2 the annual probability of a SFP failure due to seismic was calculated. The SFP failure frequency was calculated based on reproduction of the LLNL 1989 results, and use of the LLNL 1993 results, and the EPRI 1989 results. The annual probability of a release based upon the alternative SFP failure frequencies was also calculated.

Table 3.1 provides the overall results of the analysis. The site numbers in Table 3.1 are ordered the same as the Nuclear Power Plants (NPPs) listed in Table A.1 of NUREG-1353 with the exception that no western US NPPs were included in this analysis. Column 2 contains the code specifying the plant at the site to be either a BWR or a PWR. Column 3 presents the SFP failure frequency based on use of the LLNL 1989 results and estimates of β based on the natural log of the ratio between the 85th percentile and the 50th percentile. Column 4 presents the SFP failure frequency based on use of the LLNL 1989 results and estimates of β based on the natural log of the ratio between the 95th percentile and the 50th percentile divided by 1.64. The column 4 SFP failure frequencies are on average about a factor of 2 lower than the column 3 SFP failure frequencies. Column 5 presents the SFP failure frequency based on use of the LLNL 1993 results and estimates of β based on the natural log of the ratio between the 85th percentile and the 50th percentile. Column 6 presents the SFP failure frequency based on use of the EPRI 1989 results and estimates of β based on the natural log of the ratio between the 85th percentile and the 50th percentile. Column 7 quantifies the reduction in SFP failure frequency based upon use of the 1993 LLNL results. Column 7 is the ratio of the LLNL 1989 (Column 4) and LLNL 1993 (column 5) SFP failure frequencies. Column 8 quantifies the reduction in SFP failure frequency based upon use of the 1989 EPRI results. Column 8 is the ratio of the LLNL 1989 (column 4) and EPRI 1993 (column 5) SFP failure frequencies. Columns 9, 10, and 11 are the overall SFP release frequencies at each site.

As shown in Table 3.1, the average reduction in SFP failure frequency across the population of EUS sites was about a factor of 8 when the LLNL 1993 results were used and over a factor of 70 when the EPRI 1989 results were used relative to the SFP failure frequency when the 1989 LLNL results were used. At some sites the SFP failure frequency increased slightly when the LLNL 1993 results were used. This was due to use of the 85th percentile to estimate the logarithmic standard deviation β from the LLNL 1993 results.

Figure 3.1 is a plot of the annual probability of a release at the population of EUS sites based on the LLNL 1993 results and the EPRI 1989 results. As can be seen, all NPPs are on the order of 10^{-6} or less based upon the LLNL 1993 results with an overall mean annual probability of 5.6×10^{-7}. Two plants are slightly above the figure of merit (2.0×10^{-6}) presented in NUREG-1353. All NPPs are less than 10^{-6} based on the EPRI 1989 results (overall mean = 1.8×10^{-7}). In general there is excellent agreement between the LLNL and EPRI release frequency results with the exception of those LLNL NPP results that exceed 10^{-6}. All NPPs that exceed 10^{-6} based on LLNL seismic hazard results are soil sites.

Table 3.1: Spent Fuel Pool Analysis

1	2	3	4	5	6	7	8	9	10	11
Site	BWR=1	LLNL - 89	LLNL - 89	LLNL - 93	EPRI - 89	Ratio	Ratio	Release	Release	Release
	PWR=2	Beta=x85/x50	Beta=x95/x50	Beta=x85/x50	Beta=x85/x50	L89/L93	L89/E89	Frequency	Frequency	Frequency
								LLNL-89	LLNL-93	EPRI - 89
1	2	1.10E-05	5.80E-06	3.60E-07	3.70E-08	16.1	156.8	5.95E-06	5.10E-07	1.87E-07
2	2	1.40E-06	1.10E-06	1.10E-06	1.20E-08	1.0	91.7	1.25E-06	1.25E-06	1.62E-07
3	2	1.00E-05	7.20E-06	3.70E-07	8.60E-08	19.5	83.7	7.35E-06	5.20E-07	2.36E-07
4	1	1.60E-06	1.40E-06	9.60E-07	4.40E-09	1.5	318.2	3.88E-07	2.78E-07	3.86E-08
5	2	2.00E-06	1.10E-06	1.20E-07	2.50E-08	9.2	44.0	1.25E-06	2.70E-07	1.75E-07
6	1	9.10E-05	2.00E-05	5.80E-07	8.40E-08	34.5	238.1	5.04E-06	1.83E-07	5.85E-08
7	1	7.30E-06	8.00E-06	3.20E-06	4.80E-07	2.5	16.7	2.04E-06	8.38E-07	1.58E-07
8	2	1.90E-06	8.10E-07	1.80E-07	1.90E-08	4.5	42.6	9.60E-07	3.30E-07	1.69E-07
9	2	1.80E-05	6.50E-06	7.10E-08		91.5		6.65E-06	2.21E-07	
10	2	4.10E-07	3.30E-07	3.90E-07	1.90E-08	0.8	17.4	4.80E-07	5.40E-07	1.69E-07
11	2	5.60E-06	2.30E-06	2.30E-07	1.40E-07	10.0	16.4	2.45E-06	3.80E-07	2.90E-07
12	1	1.30E-05	6.80E-06	2.20E-06	5.80E-08	3.1	117.2	1.74E-06	5.88E-07	5.20E-08
13	2	9.90E-07	3.80E-07	2.80E-08	2.80E-09	13.6	135.7	5.30E-07	1.78E-07	1.53E-07
14	2	1.10E-06	6.50E-07	5.80E-07		1.1		8.00E-07	7.30E-07	
15	1	6.00E-06	5.40E-06	4.90E-06		1.1		1.39E-06	1.26E-06	
16	2	2.20E-06	6.60E-07	8.70E-08	2.80E-09	7.6	235.7	8.10E-07	2.37E-07	1.53E-07
17	2	2.10E-06	1.40E-06	3.50E-07	3.20E-08	4.0	43.8	1.55E-06	5.00E-07	1.82E-07
18	1	7.40E-06	4.30E-06	5.20E-07	8.10E-08	8.3	53.1	1.11E-06	1.68E-07	5.78E-08
19	1	4.10E-06	1.80E-06	1.10E-07		16.4		4.88E-07	6.50E-08	

Table 3.1: Spent Fuel Pool Analysis

1	2	3	4	5	6	7	8	9	10	11
Site	BWR=1	LLNL - 89	LLNL - 89	LLNL - 93	EPRI - 89	Ratio	Ratio	Release	Release	Release
	PWR=2	Beta=x85/x50	Beta=x95/x50	Beta=x85/x50	Beta=x85/x50	L89/L93	L89/E89	Frequency	Frequency	Frequency
20	1	3.90E-06	2.50E-06	3.80E-07	1.40E-07	6.6	17.9	6.63E-07	1.33E-07	7.25E-08
21	2	4.40E-06	1.70E-06	9.70E-08	3.70E-09	17.5	459.5	1.85E-06	2.47E-07	1.54E-07
22	1	1.90E-05	5.50E-06	2.20E-07	4.50E-08	25.0	122.2	1.41E-06	9.25E-08	4.88E-08
23	2	1.80E-06	1.10E-06	1.30E-06		0.8		1.25E-06	1.45E-06	
24	2	7.50E-06	1.80E-06	1.30E-07	3.60E-08	13.8	50.0	1.95E-06	2.80E-07	1.86E-07
25	1	1.90E-06	9.90E-07	3.50E-07	6.20E-09	2.8	159.7	2.85E-07	1.25E-07	3.91E-08
26	2	3.10E-06	2.00E-06	3.80E-07	1.90E-07	5.3	10.5	2.15E-06	5.30E-07	3.40E-07
27	2	2.20E-06	1.30E-06	1.20E-07	3.10E-08	10.8	41.9	1.45E-06	2.70E-07	1.81E-07
28	1	2.30E-06	2.20E-06	1.10E-06	1.20E-07	2.0	18.3	5.88E-07	3.13E-07	6.75E-08
29	1	2.80E-06	1.50E-06	1.80E-06	2.50E-07	0.8	6.0	4.13E-07	4.88E-07	1.00E-07
30	2	6.10E-06	2.90E-06	4.90E-07	3.00E-07	5.9	9.7	3.05E-06	6.40E-07	4.50E-07
31	2	6.10E-07	3.90E-07	4.70E-07	9.60E-08	0.8	4.1	5.40E-07	6.20E-07	2.46E-07
32	1			1.30E-06					3.63E-07	
33	1	5.70E-06	4.50E-06	2.50E-06	2.10E-07	1.8	21.4	1.16E-06	6.63E-07	9.00E-08
34	1	9.80E-06	6.40E-06	1.20E-06	4.10E-07	5.3	15.6	1.64E-06	3.38E-07	1.40E-07
35	2	5.50E-06	3.50E-06	4.90E-07	1.10E-07	7.1	31.8	3.65E-06	6.40E-07	2.60E-07
36	2	7.10E-06	2.30E-06	1.50E-07	5.60E-08	15.3	41.1	2.45E-06	3.00E-07	2.06E-07
37	1	1.10E-05	6.20E-06	1.00E-06	5.40E-07	6.2	11.5	1.59E-06	2.88E-07	1.73E-07
38	2	3.90E-06	1.90E-06	3.40E-07	1.60E-07	5.6	11.9	2.05E-06	4.90E-07	3.10E-07
39	1	2.40E-06	1.90E-06	1.40E-06	1.90E-07	1.4	10.0	5.13E-07	3.88E-07	8.50E-08
40	1	1.40E-05	5.60E-06	2.30E-07	4.50E-08	24.3	124.4	1.44E-06	9.50E-08	4.88E-08

Table 3.1: Spent Fuel Pool Analysis

1	2	3	4	5	6	7	8	9	10	11
Site	BWR=1	LLNL - 89	LLNL - 89	LLNL - 93	EPRI - 89	Ratio	Ratio	Release	Release	Release
	PWR=2	Beta=x85/x50	Beta=x95/x50	Beta=x85/x50	Beta=x85/x50	L89/L93	L89/E89	Frequency	Frequency	Frequency
41	2	4.50E-06	1.80E-06	2.50E-07	2.00E-07	7.2	9.0	1.95E-06	4.00E-07	3.50E-07
42	2	8.10E-06	4.30E-06	3.00E-07	1.90E-07	14.3	22.6	4.45E-06	4.50E-07	3.40E-07
43	1	2.60E-06	1.50E-06	2.00E-06	2.50E-07	0.8	6.0	4.13E-07	5.38E-07	1.00E-07
44	2	9.20E-07	7.10E-07	4.60E-07	4.50E-08	1.5	15.8	8.60E-07	6.10E-07	1.95E-07
45	1	1.10E-05	7.50E-06	1.20E-06	4.50E-07	6.3	16.7	1.91E-06	3.38E-07	1.50E-07
46	1	4.50E-06	2.40E-06	3.70E-07	1.00E-07	6.5	24.0	6.38E-07	1.30E-07	6.25E-08
47	1	2.20E-05	2.20E-05	1.20E-05	1.10E-06	1.8	20.0	5.54E-06	3.04E-06	3.13E-07
48	2	7.00E-07	5.20E-07	4.10E-07	7.00E-08	1.3	7.4	6.70E-07	5.60E-07	2.20E-07
49	2	7.50E-07	5.40E-07	5.80E-07	2.10E-08	0.9	25.7	6.90E-07	7.30E-07	1.71E-07
50	1	5.50E-06	2.90E-06	2.70E-07	1.00E-07	10.7	29.0	7.63E-07	1.05E-07	6.25E-08
51	2	2.20E-06	1.30E-06	1.60E-06	6.60E-08	0.8	19.7	1.45E-06	1.75E-06	2.16E-07
52	1	1.10E-06	6.60E-07	3.10E-07	6.40E-09	2.1	103.1	2.03E-07	1.15E-07	3.91E-08
53	2	6.70E-07	4.20E-07	6.60E-07	7.60E-08	0.6	5.5	5.70E-07	8.10E-07	2.26E-07
54	2	8.40E-06	4.80E-06	8.40E-07	3.00E-07	5.7	16.0	4.95E-06	9.90E-07	4.50E-07
55	2	1.00E-05	6.90E-06	4.10E-07	3.50E-07	16.8	19.7	7.05E-06	5.60E-07	5.00E-07
56	2	2.10E-07	9.90E-08	2.20E-07	9.60E-10	0.5	103.1	2.49E-07	3.70E-07	1.51E-07
57	2	4.50E-07	2.30E-07	2.70E-07		0.9		3.80E-07	4.20E-07	
58	2	1.00E-05	4.90E-06	3.40E-07	1.00E-07	14.4	49.0	5.05E-06	4.90E-07	2.50E-07
59	2	4.20E-07	2.80E-07	4.60E-07	4.40E-08	0.6	6.4	4.30E-07	6.10E-07	1.94E-07
60	1	9.60E-06	4.60E-06	7.90E-07	9.90E-08	5.8	46.5	1.19E-06	2.35E-07	6.23E-08
61	2	3.90E-06	2.20E-06	3.40E-07	1.10E-07	6.5	20.0	2.35E-06	4.90E-07	2.60E-07

Table 3.1: Spent Fuel Pool Analysis

1	2	3	4	5	6	7	8	9	10	11
Site	BWR=1	LLNL - 89	LLNL - 89	LLNL - 93	EPRI - 89	Ratio	Ratio	Release	Release	Release
	PWR=2	Beta=x85/x50	Beta=x95/x50	Beta=x85/x50	Beta=x85/x50	L89/L93	L89/E89	Frequency	Frequency	Frequency
62	2	1.40E-06	5.00E-07	9.80E-08		5.1		6.50E-07	2.48E-07	
63	2	2.20E-06	1.50E-06	1.40E-06	6.00E-08	1.1	25.0	1.65E-06	1.55E-06	2.10E-07
64	1	1.50E-05	7.70E-06	8.40E-07	1.40E-07	9.2	55.0	1.96E-06	2.48E-07	7.25E-08
65	2	6.30E-07	5.10E-07	3.00E-07	5.30E-10	1.7	962.3	6.60E-07	4.50E-07	1.51E-07
66	2	6.60E-06	5.70E-06	4.00E-07	2.00E-07	14.3	28.5	5.85E-06	5.50E-07	3.50E-07
67	2	2.10E-06	6.60E-07	5.30E-08	2.00E-08	12.5	33.0	8.10E-07	2.03E-07	1.70E-07
68	2	4.80E-06	2.90E-06	2.50E-06	6.60E-08	1.2	43.9	3.05E-06	2.65E-06	2.16E-07
69	2	9.10E-07	7.50E-07	1.10E-06	5.00E-08	0.7	15.0	9.00E-07	1.25E-06	2.00E-07
	Average	6.52E-06	3.28E-06	9.07E-07	1.35E-07	8.2	73.9	1.91E-06	5.61E-07	1.82E-07

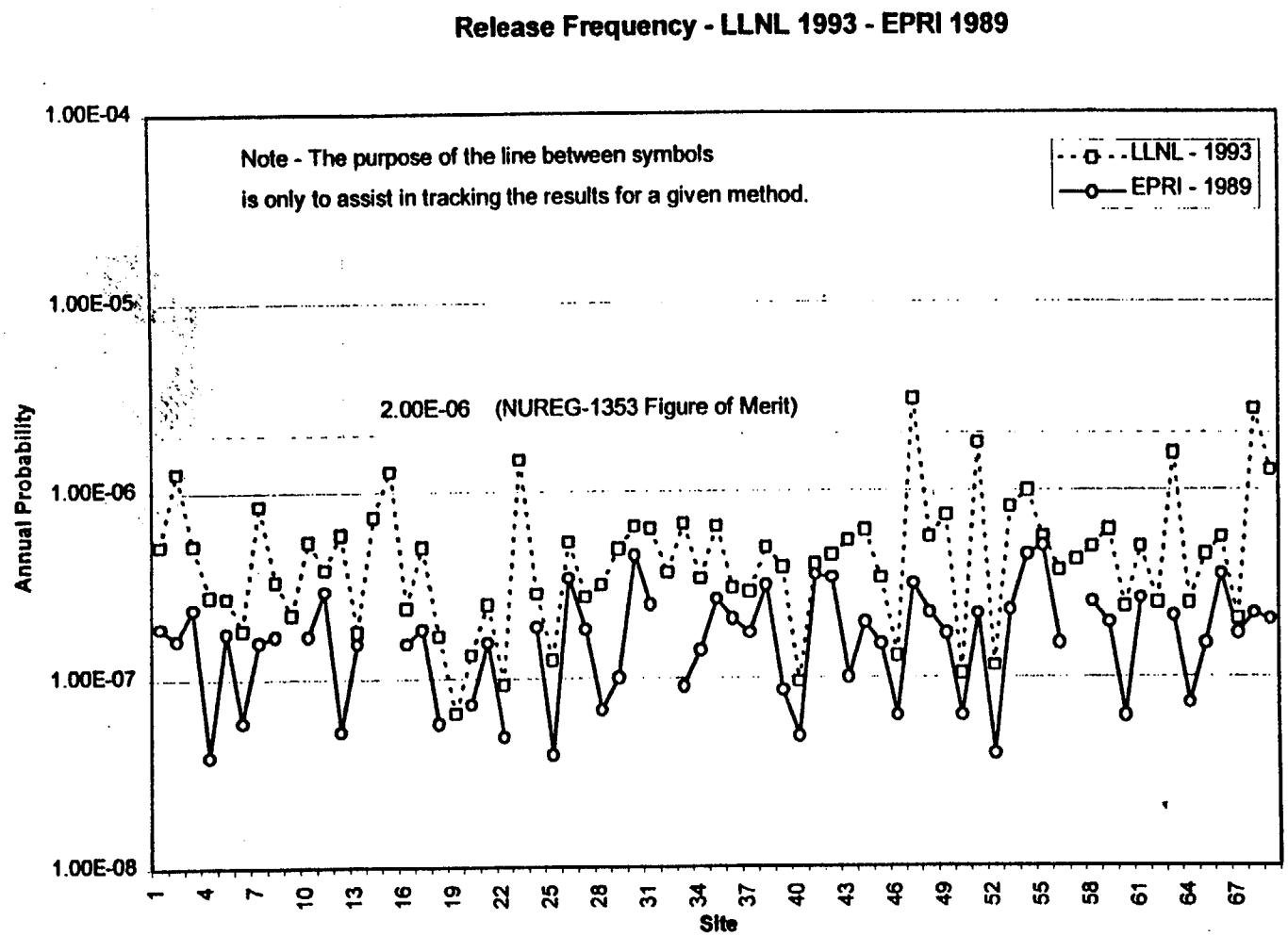

Figure 3.1 Comparison of SFP Release Frequencies with the NUREG-1353 Figure of Merit

Figure 3.1: Comparison of SFP Release Frequencies with the NUREG-1353 Figure of Merit

4.0 CONCLUSIONS

The following key results are derived from NUREG-1353:

- The annual probability of a Zircaloy cladding fire, resulting from the loss of water from the spent fuel pool, is estimated to have a mean value of 2×10^{-6} per reactor year for either the PWR or the BWR spent fuel pool.
- The seismic event is the dominant contributor to the annual probability of a Zircaloy cladding fire resulting from the loss of water from the spent fuel pool.
- The risk due to beyond design basis accidents in spent fuel pools, while not negligible, are sufficiently low such that no further risk reductions were warranted.

The SFP failure frequency due to seismic and used in NUREG-1353 is documented in NUREG/CR-5176. Since publication of NUREG-1353 and NUREG/CR-5176 the LLNL seismic hazard results have been updated. Industry also published seismic hazard results at 61 NPP sites.

Using the methodology to calculate SFP failure frequency due to seismic described in NUREG/CR-5176, along with the NUREG-1353 assumptions, the NUREG-1353 SFP release values have been updated based upon use of the LLNL 1993 and EPRI 1989 seismic hazard results. The average reduction in SFP failure frequency across the population of EUS sites was about a factor of 8 when the LLNL 1993 results were used and over a factor of 70 when the EPRI 1989 results were used relative to the SFP failure frequency using the 1989 LLNL results. Using the LLNL 1993 results, the annual probability of a Zircaloy cladding fire, resulting from the loss of water from the spent fuel pool, is estimated to have a mean value of 5.6×10^{-7} per reactor year for either the PWR or the BWR spent fuel pool. Using the EPRI 1989 results, the annual probability of a Zircaloy cladding fire, resulting from the loss of water from the spent fuel pool, is estimated to have a mean value of 1.8×10^{-7} per reactor year for either the PWR or the BWR spent fuel pool. These results indicate that the mean risk due to beyond design basis accidents in spent fuel pools across the population of EUS sites is essentially negligible.

In addition, NUREG-1353 states that the high confidence low probability of failure (HCLPF) value for SFPs is estimated to be in the 0.5 to 0.65 g range, about three times the safe shutdown earthquake (SSE) peak ground acceleration values for typical EUS NPPs. The SFP median capacity is estimated to be in the 1.4 to 2.0 g range. 10 CFR Part 100, Appendix III.(c) defines an SSE as:

> "that earthquake which is based upon an evaluation of the maximum earthquake potential considering regional and local geology and seismology, and specific characteristics of local subsurface material. It is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional. These structures, systems, and components are those necessary to assure: (1) the integrity of the reactor coolant pressure boundary, (2) the capability to shutdown the reactor and maintain it in a safe shut down condition, or (3) the capability to prevent or mitigate the consequences of accidents which could result in potential off-site exposures comparable to the guideline exposures of 10 CFR Part 100."

The results of this analysis also meet the probabilistic criteria of SRP 2.2.3, "Evaluation of Potential Accidents." This SRP provides a basis for inclusion or exclusion of potential accidents into the plant design basis. For operating NPPs, emergency planning is required to ensure the continued protection of the public health and safety in areas around the nuclear facility in the event of a radiological emergency. Application of the SRP 2.2.3 criteria provides a basis for elimination of the requirements for off-site emergency planning at decommissioning NPPs, as explained below.

The probabilistic acceptance criteria for exclusion of accidents, in SRP 2.2.3, is as follows: "Accordingly, the expected rate of occurrence of potential exposures in excess of 10 CFR Part 100 guidelines of approximately 10^{-6} per year is acceptable if, when combined with reasonable qualitative arguments, the realistic probability can be shown to be lower." As can be seen in Figure 3.1, the LLNL 1993 mean results are on the order of 10^{-6}. The results of this analysis are conservative for the following reasons:

1. Loss of cooling/makeup is less probable for decommissioning plants because of fewer potential challenges to the fuel pool cooling/makeup system, as well as increased simplicity/reliability of the system.
2. Complete loss of SFP water is assumed given the seismic failure in NUREG-1353, however only a partial loss may actually result.
3. The conditional probability of Zircaloy cladding fire given loss of water for operating PWRs and BWRs has been assumed to be guaranteed and 0.25 respectively (bounding values). Decommissioning PWRs and BWRs, experience spent fuel decay which immediately and continuously reduces this probability.

Based on the results of this analysis, it is concluded that the probabilistic acceptance criteria for exclusion of potential accidents which could result in radiological release in excess of the 10 CFR Part 100 guidelines is conservatively met and therefore, the need for off-site emergency planning for decommissioning plants is eliminated.

5.0

6.0 REFERENCES

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