Risk (Performance-Goal) Based Approach for Establishing the SSE Design Response Spectrum Aimed at Achieving a Seismic Core Damage Frequency Less than a Target Goal for Future Nuclear Power Plants

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Risk Based Approach Used To Establish SSE Design Basis Response Spectrum

- **Develops A Risk Consistent SSE Design Response Spectrum (DRS) As Opposed To A Relative Uniform Hazard Response Spectrum (UHRS) Based Upon Median Exceedance Frequency For 29 Sites**

- **Approach Implements Risk Consistent Regulatory Goals**

- **Conservatively Aimed At Achieving A Target Performance Goal for Seismic Core Damage Frequency (SCDF)**

Issues Which Must Be Addressed In Order to Develop a Performance-Goal Based SSE Design Response Spectrum

1. What Target Annual Probability of Seismic Induced Unacceptable Performance is Acceptable?
   - Policy Maker Decision
   - Can Be Based on Existing Precedence
2. What Minimum Seismic Margin is Achieved by Seismic Design Criteria?
   - A Question of How Much Deterministic Conservatism Exists in Design Criteria
3. Given the Decisions Made Under Issues 1 and 2, How Should the SSE Design Response Spectrum be Defined?

Step #1: Establish Target Performance Goal (Ingredient of Risk Informed Seismic Design)

- Performance Goals
  - Both Qualitative and Quantitative Performance Goals Should Be Established
- Qualitative Goals
  - What Constitutes Acceptable Performance?
  - Example: Avoidance of Seismic-Induced Core Damage (SCD)
- Quantitative Goal
  - What is a Target Acceptable Mean Annual Frequency P_{FT} of Seismic Induced Core Damage (SCDF)
  - Example: SCDF $P_{FT} \leq$ Mean $5x10^{-6}$/yr

Basis for Selecting SCDF Target Goal P_{FT}

- A goal for future nuclear power plants is that they should be safer than the average existing nuclear power plant.

- Example SCDF P_{FT}

$$\text{SCDF } P_{FT} = \text{mean } 5\text{x}10^{-6}/\text{yr}$$

- Proposed risk based approach works equally well if a different SCDF P_{FT} is selected

Mean Seismic CDF for Plants Performing Seismic PRA from Table 2.2 from NUREG 1742

Plant	Mean Seismic CDF (EPRI)	Plant	Mean Seismic CDF (EPRI)
South Texas Project 1 & 2	1.90E-07	Beaver Valley 1	1.29E-05
Nine Mile Point 2	2.50E-07	Indian Point 2	1.30E-05
La Salle 1 & 2	7.60E-07	Point Beach 1 & 2	1.40E-05
Hope Creek	1.06E-06	Catawba 1 & 2	1.60E-05
D.C. Cook 1 & 2	3.20E-06	San Onofre 2 & 3	1.70E-05
Salem 1 & 2	4.70E-06	Columbia (Washington Nuclear Project No. 2)	2.10E-05
Oyster Creek	4.74E-06	TMI 1	3.21E-05
Surry 1 & 2	8.20E-06	Oconee 1, 2, and 3	3.47E-05
Millstone 3	9.10E-06	Diablo Canyon 1 & 2	4.20E-05
Beaver Valley 2	1.03E-05	Pilgrim 1	5.80E-05
Kewaunee	1.10E-05	Indian Point 3	5.90E-05
McGuire 1 & 2	1.10E-05	Haddam Neck	2.30E-04
Seabrook	1.20E-05		

Median of Mean Seismic CDF Value (EPRI Results)	1.20E-05
Mean of Mean Seismic CDF Value (EPRI Results)	2.50E-05

* CDF Values reported are for EPRI hazard curves. LLNL hazard curves produced substantially higher CDF results

Step #2: Establish Acceptable Seismic Margin Goals

- Typically Seismic Margin Has been Defined in Terms of High-Confidence-Low-Probability-of-Failure (HCLPF) Capacity
- HCLPF Approximately Corresponds to 1% Conditional Probability of Unacceptable Performance Level on Composite (Mean) Fragility Curve
- An Acceptable HCLPF Capacity is Typically Established at Some Factor Greater than the Seismic Design Response Spectrum (DRS)
- Example: For ALWR Designs NRC Staff Established (SECY-93-087)

$F_{1\%}$ = (HCLPF/DRS) $\geq$ 1.67 for Seismic Core Damage

- Step #3: Establish Seismic Hazard Exceedance Frequency H at Which Uniform Hazard Response Spectrum UHRS Is To Be Defined

  $H = R_P * P_{FT}$

  R_P = Probability Ratio

  Preferably: $2 \leq R_P \leq 20$

- Example:

  Selected: $R_P = 10$

  Result: H = Mean 5×10^{-5}/yr for P_{FT} = Mean 5×10^{-6}/yr

- Selection of R_P is Fairly Arbitrary Since Accounted for in Step #4

STEP #4: Define Design-Basis Earthquake Response Spectrum (DRS)

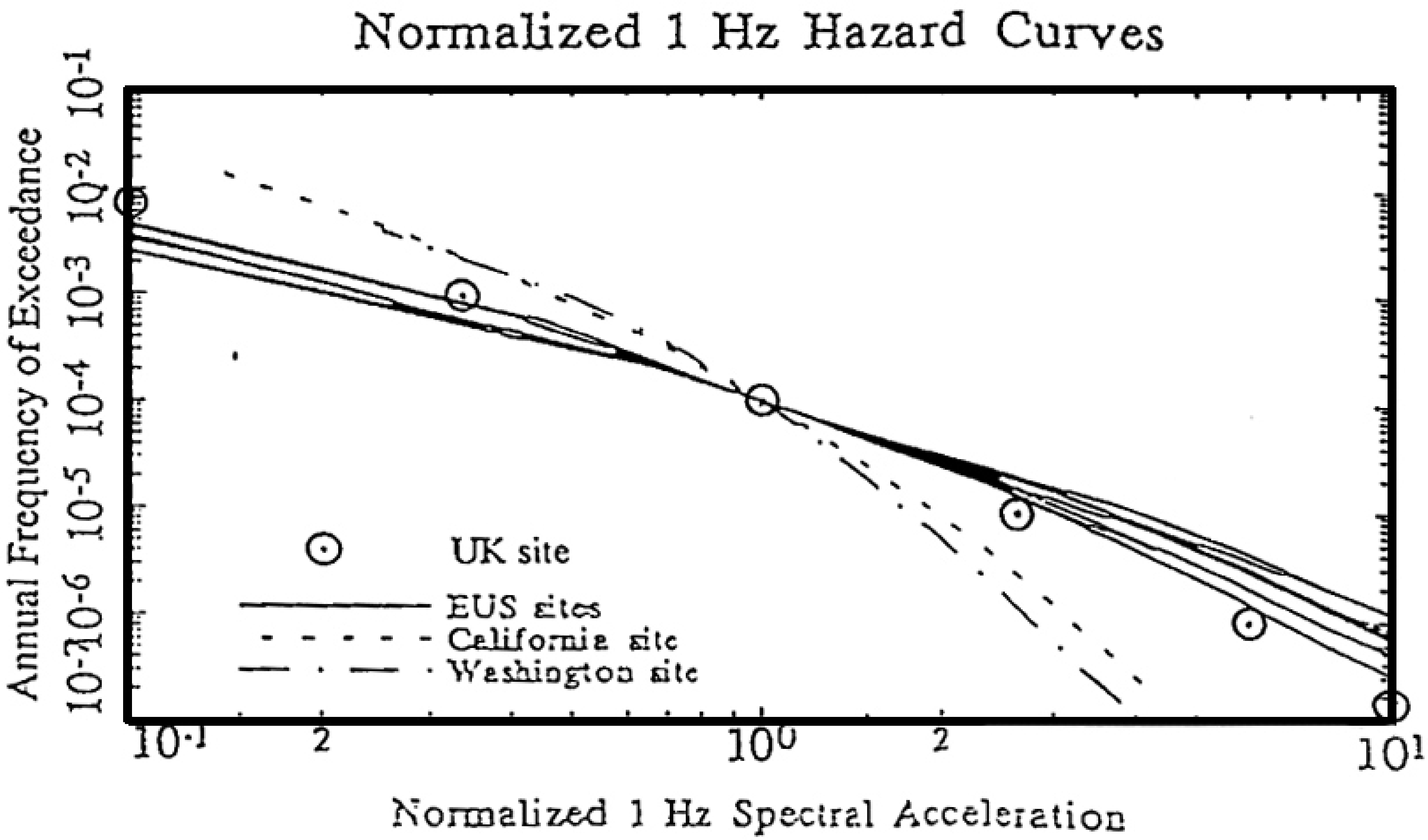
- DRS = DF $*$ UHRS

- DF = Design Factor

- DF Function of:
  - Probability Ratio RP Defined in Step #3
  - Seismic Margin Factor FP Defined in Step #2
  - Hazard Curve Slope Ratio AR

- AR = Ratio of Ground Motions Corresponding to Ten-Fold Reduction in Exceedance Frequency

Seismic Hazard Curves Normalized By the Spectral Acceleration Value Corresponding to a 10^{-4} Annual Probability



Summary of Proposed Risk Based Approach

- Establish Target SCDF goal P_{FT}:
  Example: SCDF P_{FT} = mean $5x10^{-6}$/yr

- Define UHRS Hazard Exceedance Frequency H
  $H = 10 * P_{FT}$ $(R_P=10)$
- Define Amplitude Ratio A_R by:

$$A_R = \frac{SA_{0.1H}}{SA_H}$$

- Define DF
  DF = Maximum (DF_1, DF_2)
  $DF_1 = 0.241 + 0.225\ A_R \geq 0.60$

  $DF_2 = 0.375\ A_R^{0.9}$

- Define SSE DRS
  DRS = DF* UHRS

For H_D = Mean $5x10^{-5}$

Calif. Site: A_R = 1.5 to 2.25
EUS Site: A_R = 2.25 to 4.0

Design Factors DF For Various Seismic Hazard Slope Factors A_R

A_R	DF
1.5	0.60
1.75	0.64
2	0.70
2.25	0.78
2.5	0.86
2.75	0.93
3	1.01
3.25	1.08
3.5	1.16
3.75	1.23

A_R	DF
4	1.31
4.25	1.38
4.5	1.45
4.75	1.52
5	1.60

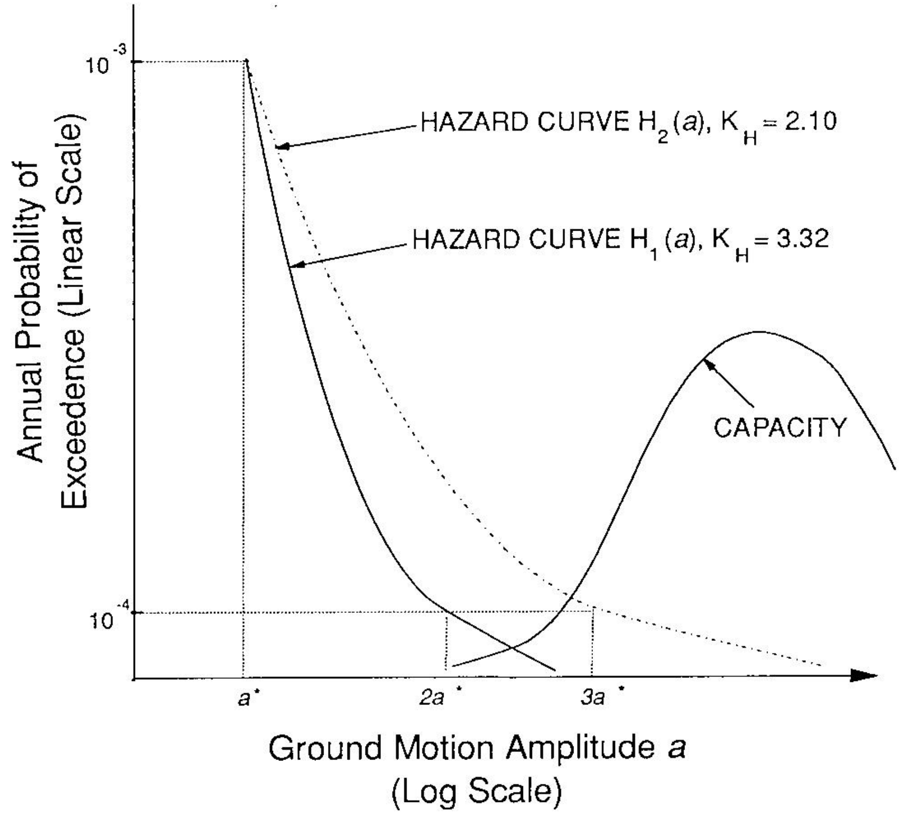


FIGURE 5

COMPARISON OF HAZARD CURVES WITH DIFFERENT SLOPES TO CAPACITY CURVE

Basis for Design Factor DF

- Approximate Hazard Curve By:

$$H_{(a)} = K_I a^{-K_H}$$

$$K_H = \frac{1}{\log(A_R)}$$

- Assume Lognormal Fragility Curve for SSC Defined By:

  $C_{1\%}$ = 1% Probability of Failure Capacity

  β = Logarithmic Standard Deviation

- Rigorous Closed Form Evaluation for Required DF

$$DF = \frac{\left[R_P e^{-f}\right]^{1/K_H}}{F_{1\%}}$$

$F_{1\%}$ = 1.667

f = $2.326K_H\beta - ½(KH\beta)^2$

Table 5.1
Design Factor DF Values Required to Achieve Probability Ratio R_P=10 for SCD HCLPF Seismic Margin Factor $F_{1\%}$=1.6667

A_R	Required DF				DF
	β = 0.30	β = 0.35	β =0.40	β = 0.45	Eqn (2.4)
1.50	0.578	0.565	0.559	0.562	0.579
1.75	0.629	0.599	0.576	0.559	0.635
2.00	0.694	0.652	0.617	0.590	0.700
2.25	0.763	0.712	0.668	0.632	0.778
2.50	0.836	0.775	0.723	0.679	0.855
2.75	0.910	0.840	0.781	0.729	0.932
3.00	0.984	0.907	0.840	0.781	1.008
3.25	1.060	0.974	0.899	0.834	1.083
3.50	1.135	1.041	0.959	0.888	1.158
3.75	1.211	1.109	1.020	0.942	1.232
4.00	1.287	1.177	1.081	0.997	1.306
4.25	1.363	1.245	1.142	1.052	1.379
4.50	1.440	1.314	1.204	1.107	1.452
4.75	1.516	1.382	1.265	1.162	1.524
5.00	1.592	1.451	1.327	1.217	1.596
5.25	1.669	1.519	1.388	1.273	1.668

Table 5.2
SCDF P_F Achieved by Proposed Risk Based Approach Defined in Section 2 When Target SCDF P_{FT}=5x10^{-6}/yr

A_R	SCDF P_F * 10^{-6}/yr			
	β = 0.30	β = 0.35	β = 0.40	β = 0.45
1.40	5.84	5.64	6.13	7.48
1.45	5.28	4.79	4.79	5.27
1.50	4.99	4.36	4.12	4.22
1.75	4.81	3.93	3.34	2.97
2.00	4.85	3.95	3.30	2.83
2.25	4.74	3.88	3.25	2.77
2.50	4.72	3.90	3.28	2.80
2.75	4.73	3.95	3.34	2.86
3.00	4.76	4.01	3.41	2.93
3.25	4.79	4.06	3.48	3.06
3.50	4.82	4.11	3.54	3.07
3.75	4.85	4.16	3.60	3.13
4.00	4.88	4.21	3.65	3.19
4.25	4.91	4.25	3.70	3.25
4.50	4.94	4.29	3.75	3.30
4.75	4.96	4.33	3.80	3.35
5.00	4.98	4.36	3.84	3.39
5.25	5.00	4.39	3.88	3.44
5.50	5.02	4.42	3.91	3.47
5.75	5.04	4.45	3.94	3.51
6.00	5.06	4.48	3.98	3.55
6.25	5.08	4.50	4.00	3.58
6.50	5.09	4.52	4.03	3.61

Demonstration That Proposed Approach Works for Actual Hazard Curves

- Central U.S. Soil Site Specific Hazard Curve
- Normalized Eastern U.S. and California Hazard Curves
- 28 CEUS Sites (Not Yet Done)

Table 6.1
Central U.S. Soil Site Specific Soil Hazard Curves

1 Hz		2.5 Hz		5 Hz		10 Hz	
SA (g)	H	SA (g)	H	SA (g)	H	SA (g)	H
0.00128	5.306E-02	0.00270	1.284E-01	0.00324	9.160E-02	0.00260	8.228E-02
0.00200	3.854E-02	0.00402	1.025E-01	0.00463	7.859E-02	0.00374	7.130E-02
0.00314	2.747E-02	0.00600	7.758E-02	0.00661	6.511E-02	0.00538	5.981E-02
0.00493	1.912E-02	0.00894	5.605E-02	0.00945	5.195E-02	0.00774	4.877E-02
0.00773	1.289E-02	0.01333	3.901E-02	0.01351	3.972E-02	0.01114	3.808E-02
0.01211	8.718E-03	0.01986	2.662E-02	0.01931	2.952E-02	0.01604	2.907E-02
0.01899	5.784E-03	0.02961	1.782E-02	0.02759	2.100E-02	0.02308	2.119E-02
0.02977	3.703E-03	0.04413	1.180E-02	0.03944	1.454E-02	0.03321	1.494E-02
0.04668	2.244E-03	0.06578	7.554E-03	0.05637	9.903E-03	0.04778	1.020E-02
0.07319	1.228E-03	0.09806	4.493E-03	0.08057	6.500E-03	0.06876	6.593E-03
0.11475	5.691E-04	0.14616	2.501E-03	0.11515	3.973E-03	0.09894	3.938E-03
0.17991	2.389E-04	0.21786	1.208E-03	0.16458	2.255E-03	0.14236	2.152E-03
0.28207	8.601E-05	0.32473	5.178E-04	0.23523	1.148E-03	0.20486	1.074E-03
0.44224	2.931E-05	0.48404	1.510E-04	0.33621	5.127E-04	0.29478	4.823E-04
0.69336	1.007E-05	0.72149	4.098E-05	0.48054	1.932E-04	0.42417	1.930E-04
1.08709	3.540E-06	1.07543	1.106E-05	0.68682	5.986E-05	0.61037	6.745E-05
1.70439	1.082E-06	1.60301	3.194E-06	0.98165	1.785E-05	0.87829	2.237E-05
2.67223	3.160E-07	2.38940	7.276E-07	1.40304	5.554E-06	1.26383	6.367E-06
4.18966	8.337E-08	3.56157	4.326E-08	2.00532	1.432E-06	1.81859	3.517E-07
6.56876	1.379E-08	5.30876	7.029E-09	2.86615	8.066E-08	2.61688	1.257E-07
10.29882	1.858E-09	7.91308	1.302E-09	4.09650	1.246E-08	3.76557	4.136E-08
16.14700	3.244E-10	11.79500	2.824E-10	5.85500	2.343E-09	5.41850	1.285E-08

Table 6.2
Computation of DRS Spectral Acceleration (SA_{DRS}) for Table 6.1 Hazard Curves

	1 Hz	2.5 Hz	5 Hz	10 Hz
$SA_{5x10^{-5}}$	0.354	0.679	0.724	0.674
$SA_{5x10^{-6}}$	0.937	1.388	1.442	1.303
A_R	2.65	2.04	1.99	1.93
DF	0.901	0.714	0.697	0.679
SA_{DRS}	0.319	0.485	0.505	0.457
$C_{1\%}$	0.531	0.808	0.842	0.762

Table 6.3:
Determination of SCDF (P_F) Using 5 Hz Hazard Curve from Table 6.1 and Logarithmic Standard Deviation β of 0.35

SA (g)	H $*10^{-6}$	ΔH $*10^{-6}$	$P_F(a)$	$P_F(a) \cdot \Delta H$ $*10^{-6}$
0.6	93.271			
		37.15	0.001	0.041
0.7	56.121			
		20.423	0.004	0.081
0.8	35.698			
		11.746	0.011	0.127
0.9	23.952			
		7.153	0.024	0.171
1.0	16.799			
		4.496	0.045	0.203
1.1	12.302			
		3.045	0.076	0.231
1.2	9.257			
		2.131	0.116	0.247
1.3	7.126			
		1.533	0.165	0.252
1.4	5.593			
		1.283	0.220	0.283
1.5	4.310			
		0.936	0.281	0.263
1.6	3.373			
		0.693	0.344	0.238
1.7	2.680			
		0.523	0.407	0.213
1.8	2.157			
		0.400	0.470	0.188

SA (g)	H $*10^{-6}$	ΔH $*10^{-6}$	$P_F(a)$	$P_F(a) \cdot \Delta H$ $*10^{-6}$
1.9	1.757			
		0.311	0.530	0.165
2.0	1.446			
		0.459	0.586	0.269
2.1	0.988			
		0.309	0.638	0.197
2.2	0.679			
		0.204	0.686	0.140
2.3	0.475			
		0.138	0.728	0.100
2.4	0.337			
		0.094	0.766	0.072
2.5	0.243			
		0.066	0.800	0.053
2.6	0.177			
		0.046	0.829	0.038
2.7	0.130			
		0.033	0.855	0.028
2.8	0.097			
		0.021	0.877	0.019
2.9	0.076			
		0.012	0.896	0.011
3.0	0.064			
		0.010	0.912	0.009
3.1	0.054			
		0.054	0.932	0.050

$$P_F = \Sigma = 3.689 \quad * 10^{-6}$$

Table 6.4
Seismic Core Damage Frequency SCDF for Table 6.1 Hazard Curves*

β	Section 2 Method SCDF $*$ $1x10^{-6}$/yr			
	1 Hz	2.5 Hz	5 Hz	10 Hz
0.30	4.68 (4.72)	4.74 (4.82)	4.66 (4.86)	4.60 (4.92)
0.35	3.87 (3.93)	3.82 (3.92)	3.70 (3.95)	3.58 (3.99)
0.40	3.24 (3.31)	3.16 (3.28)	3.03 (3.30)	2.93 (3.34)
0.45	2.75 (2.84)	2.68 (2.81)	2.57 (2.84)	2.49 (2.89)

* Values shown in ( ) are from Power Law Approximation Eqn. (5.11) for comparison with values obtained by rigorous numerical convolution.

Table 6.5: Typical Normalized Spectral Acceleration Hazard Curve Values

Hazard Exceedance Frequency $H_{(SA)}$	Eastern U.S.		California	
	1 Hz SA	10 Hz SA	1Hz SA	10 Hz SA
5×10^{-2}	0.014	0.018	0.087	0.046
2×10^{-2}	0.027	0.034	0.13	0.072
1×10^{-2}	0.045	0.055	0.175	0.100
5×10^{-3}	0.07	0.089	0.236	0.139
2×10^{-3}	0.143	0.169	0.351	0.215
1×10^{-3}	0.235	0.275	0.474	0.334
5×10^{-4}	0.383	0.424	0.629	0.511
2×10^{-4}	0.681	0.709	0.814	0.762
1×10^{-4}	1.00	1.0	1.0	1.0
5×10^{-5}	1.46	1.41	1.23	1.22
2×10^{-5}	2.35	2.13	1.61	1.51
1×10^{-5}	3.27	2.88	1.89	1.76
5×10^{-6}	4.38	3.65	2.2	2.05
2×10^{-6}	6.44	4.62	2.68	2.42
1×10^{-6}	8.59	5.43	3.1	2.72
5×10^{-7}	10.34	6.38	3.58	3.06
2×10^{-7}	13.21	7.9	4.24	3.56
1×10^{-7}	15.9	9.28	4.67	3.84

SA (1Hz) Hazard Curves for the Eleven Sites Normalized by the Acceleration Value Corresponding to 10^{-4} Annual Probability

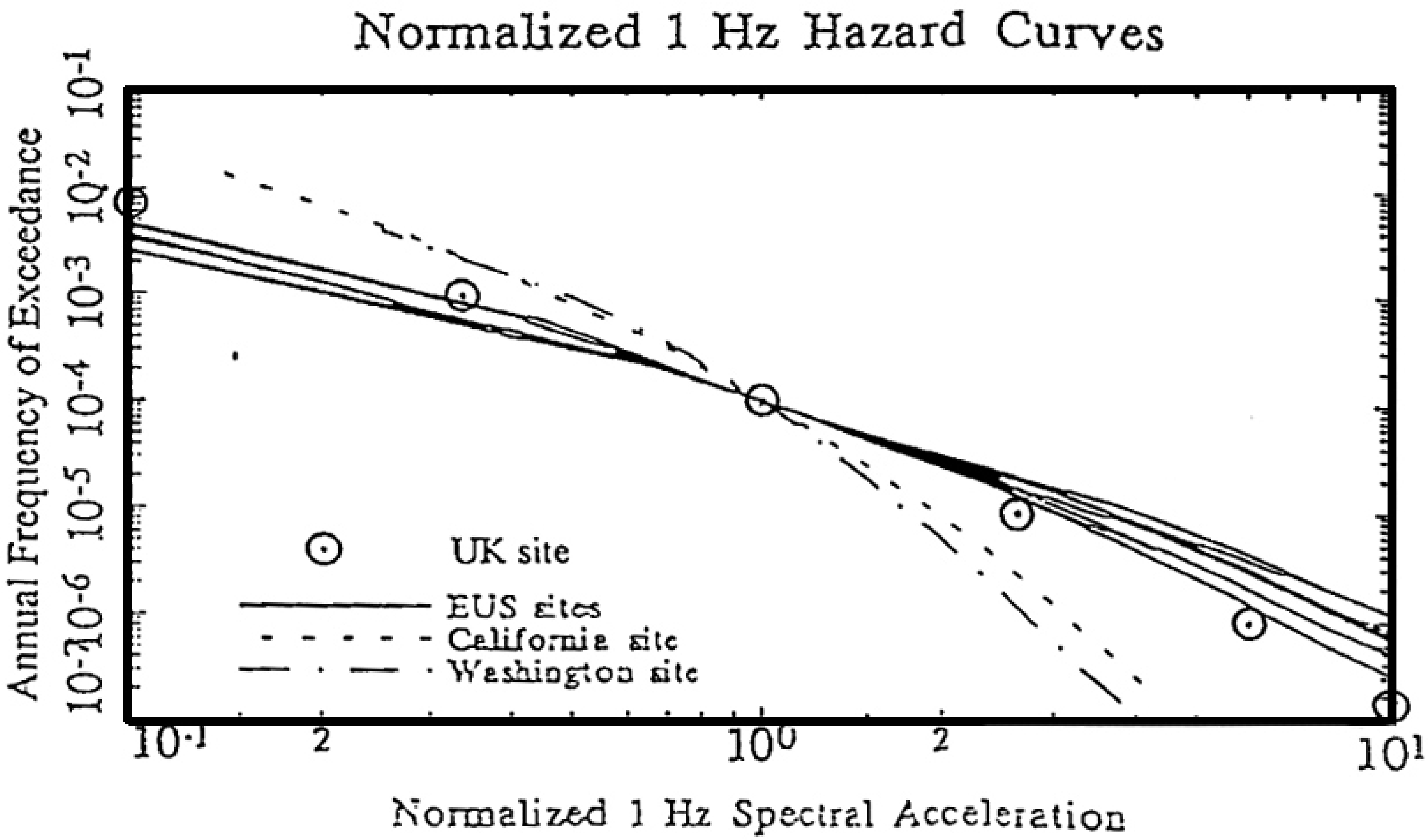


Table 6.6
Computation of DRS Spectral Acceleration SA_{DRS}
For Table 6.5 Hazard Curves

	EUS		Calif.	
	1 Hz	10 Hz	1 Hz	10 Hz
$SA_{5x10^{-5}}$	1.46	1.41	1.23	1.22
$SA_{5x10^{-6}}$	4.38	3.65	2.20	2.05
A_R	3.00	2.59	1.79	1.68
DF	1.008	0.883	0.643	0.619
SA_{DRS}	1.472	1.245	0.791	0.755
$C_{1\%}$	2.453	2.074	1.319	1.259

Table 6.7
Seismic Core Damage Frequency (SCDF) for DRS Defined by Section 2 Method and HCLPF Seismic Margin of 1.6667*

Hazard Curve	DRS SA_{DRS}	SCDF ($*10^{-6}$)			
		β=0.30	β=0.35	β=0.40	β=0.45
EUS 1Hz	1.472	4.81 (4.76)	3.98 (4.01)	3.33 (3.41)	2.81 (2.93
EUS 10 Hz	1.245	4.48 (4.72)	3.55 (3.92)	2.87 (3.30)	2.37 (2.82)
Calif 1 Hz	0.791	4.92 (4.84)	3.92 (3.94)	3.26 (3.34)	2.81 (2.94)
Calif 10 Hz	0.755	4.49 (4.77)	3.57 (3.92)	2.97 (3.39)	2.56 (3.07)

* Values shown in ( ) are from Power Law Approximation Eqn. (5.11) for comparison with values obtained by rigorous numerical convolution.

Recommendation

- Define Free Field SSE Design Response Spectrum DRS by SCDF Risk Based Approach Defined Herein
- However, Also Establish Lower Bound on SSE DRS by 0.10g PGA Reg. Guide 1.60 Response Spectrum
- Low Natural Spectral Accelerations Are Very Important Contributor to Damage of SSCs
- UHRS and DRS for many CEUS Sites Have Very Little Low Frequency Spectral Accelerations