EGC ESP

Development of Risk-Based Seismic Design Criterion

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Risk-Based Approach Used to Establish Design-Basis Response Spectrum

- Develops a Risk-Consistent 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 Onset of Significant Inelastic Deformation (i.e., Conservative Surrogate for Unacceptable Seismic Performance)

Risk vs. Hazard Approach

- Risk-based approach integrates seismic hazard curve and SSC fragility curve
  - Hazard or demand curve from PSHA
  - Fragility curve defined by conservatism in structural capacity achieved by Standard Review Plan requirements
- Integration of two curves gives seismic risk: probability that demand exceeds capacity; i.e., unacceptable performance
  - Objective is to set Design Response Spectrum (DRS) to achieve mean 10^{-5} probability of unacceptable performance of SSC

Risk vs. Hazard Approach

- Benefits
  - Provides risk consistent safety evaluation (avoids risk differences as hazard slope changes by creating site-specific DRS)
  - Achieves seismic risk consistent with risk for population of existing plants
  - Achieves relative-risk seismic design based on existing PRAs, analogous to relative-hazard seismic designs achieved by RG 1.165

Four Required Steps

STEP #1: Define Target Seismic Risk Goal P_{FT} to Be Achieved by Seismic Design Criterion__

Preferably: Define in Terms of Mean Annual Frequency of Unacceptable Seismic Performance

Selected: P_{FT} = Mean 1x 10^{-5}/yr Against Onset of Significant Inelastic Behavior for Structures, Systems, or Components (SSCs)

Four Required Steps (cont.)

Basis:

1. Mean Seismic Core Damage Frequencies (CDF) Reported for Existing Nuclear Power Plants Average More Than Mean $1x10^{-5}$/yr
2. Onset of Significant Inelastic Behavior of an SSC is Generally Far Short of Failure
3. Core Damage Frequency is Typically Less Than Highest SSC Failure Frequency
4. Therefore, Seismic-Induced Core Damage Frequency Is Expected To Be Significantly Less Than Mean $1x10^{-5}$/yr

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

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

Four Required Steps (cont.)

STEP #2: Establish Seismic Hazard Exceedance Frequency H_D at Which Uniform Hazard Response Spectrum UHRS Is To Be Defined

$H_D = R_P * P_{FT}$

R_P = Probability Ratio

P_{FT} = Mean 1×10^{-5}/yr. Onset of Significant Inelastic Behavior

Preferably: $2 \leq R_P \leq 20$

Selected: $R_P = 10$

Result: H_D = Mean 1×10^{-4}

Four Required Steps (cont.)

STEP #3: Establish the Required Degree of Conservatism of Deterministic Seismic Acceptance Criterion

Requirement: Seismic Acceptance Criterion Defined by NUREG-0800 Standard Review Plan and Reg Guides

Premise: Seismic Demand and Structural Capacity Evaluations Have Sufficient Conservatism to Achieve Both of the Following:

1. Less Than about a 1% Probability of Unacceptable Performance for the Design Basis Earthquake Ground Motion, and
2. Less Than about a 10% Probability of Unacceptable Performance for a Ground Motion Equal to 150% of the Design Basis Earthquake Ground Motion

Four Required Steps (cont.)

Justification:

1. Past Seismic PRA and Seismic Margin Studies Have Shown that SSCs Designed to Standard Review Plan Requirements Achieve at Least these Levels of Conservatism

2. Additional Justifications for Above Premises are Presented in Reference Documents

Resulting Generic Seismic Fragility Curves

Definitions:

DRS = Design Basis Earthquake Response Spectrum (Uniform Risk Spectrum)

C_P = Seismic Capacity Corresponding to P Probability of Unacceptable Performance

$C_P = F_P * DRS$

F_P = Seismic Margin Factor Corresponding to P Probability of Unacceptable Performance

β = Logarithmic Standard Deviation of Fragility

Example:

$C_{1\%}$ = HCLPF Seismic Capacity Corresponding to 1% Probability of Unacceptable Performance

Result of Premised Conservatism

Minimum F_P Seismic Margins

β	$F_{1\%}$	$F_{5\%}$	$F_{10\%}$	$F_{50\%}$
0.30	1.10	1.35	1.50	2.20
0.40	1.00	1.31	1.52	2.54
0.50	1.00	1.41	1.69	3.20
0.60	1.00	1.50	1.87	4.04

*Minimum seismic margin; premise-design performed to Standard Review Plan and Regulatory Guides

Four Required Steps (cont.)

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

DRS = DF ∗ UHRS

DF = Design Factor

DF Function of:

- Probability Ratio R_P Defined in Step #2
- Seismic Margin Factor F_P Defined in Step #3
- Hazard Curve Slope Ratio A_R

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

A_R Differs at Each Natural Frequency

Four Required Steps (cont.)

STEP #4:

Recommend: For $R_P = (H_D/P_{FT}) = 10.0$

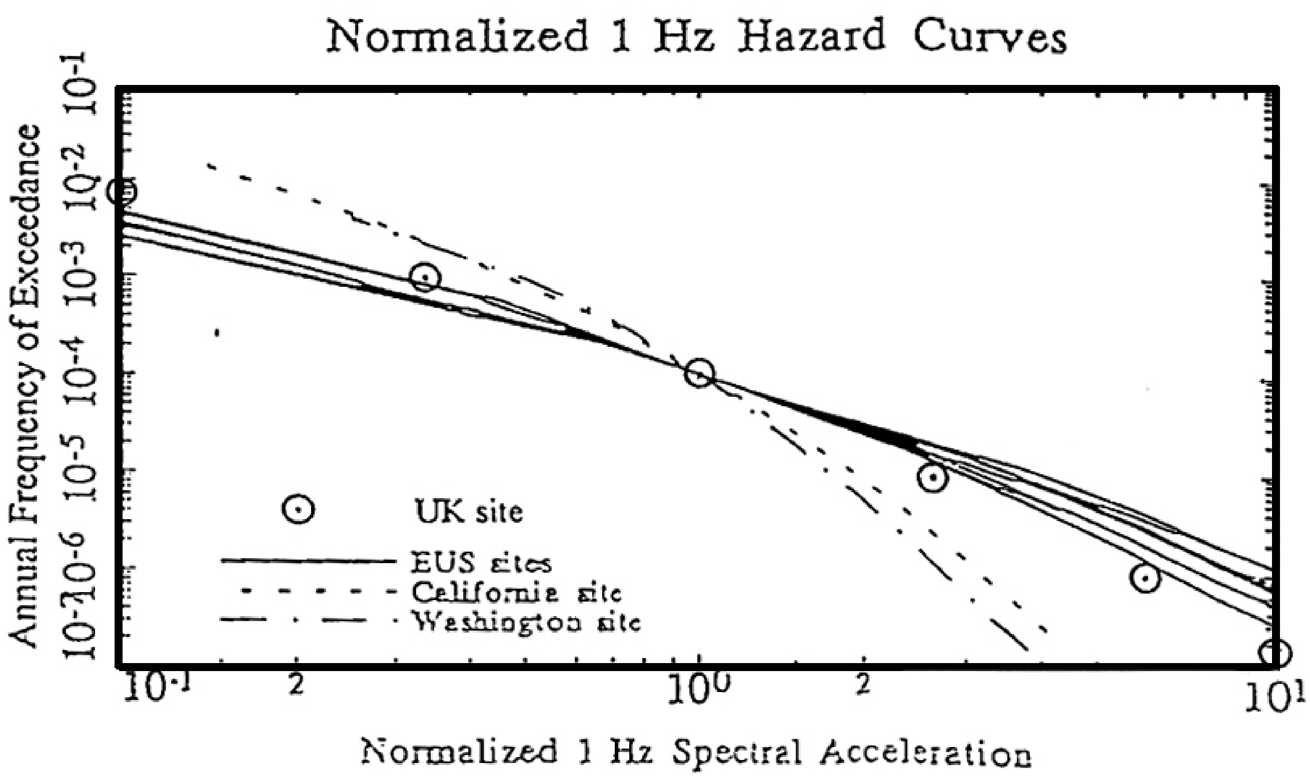
Equation 6:

$$DF = \text{Maximum}\ (DF_1, DF_2)$$

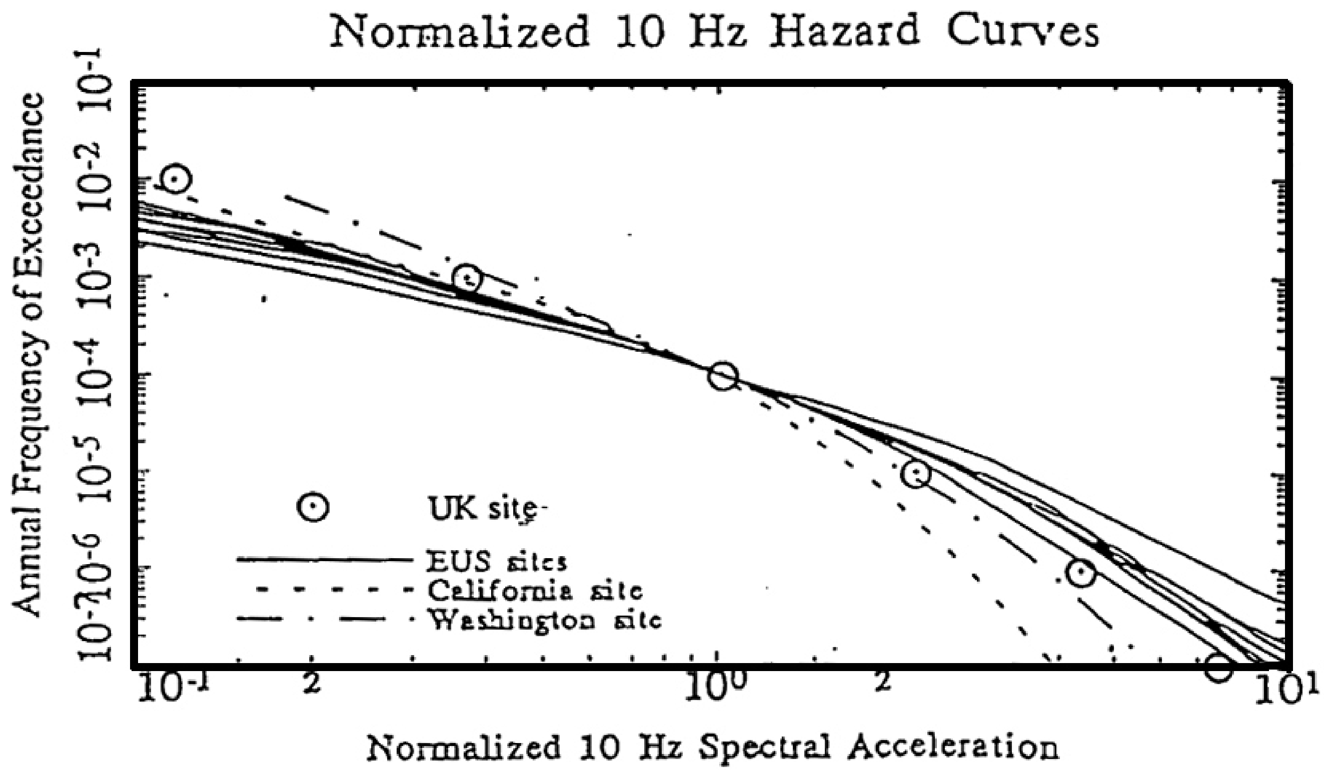
$$DF_1 = 1.0$$

$$DF_2 = 0.60\ A_R^{0.8}$$

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



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



For H_D = Mean $1x10^{-4}$

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	1
1.75	1
2	1.04
2.25	1.15
2.5	1.25
2.75	1.35
3	1.44
3.25	1.54
3.5	1.63
3.75	1.73

A_R	DF
4	1.82
4.25	1.91
4.5	2
4.75	2.09
5	2.17
5.25	2.26
5.5	2.35
5.75	2.43
6	2.52

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

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

$$f = 2.326 K_H \beta - \tfrac{1}{2}(K_H \beta)^2$$

Design Factor DF Values Required To Achieve A Probability Ratio $R_P = 10$

A_R	DF				DF
	$\beta = .3$	$\beta = .4$	$\beta = .5$	$\beta = .6$	Eqn (6)
1.5	0.88	0.93	0.95	1.03	1.0
1.75	0.96	0.96	0.91	0.91	1.0
2	1.05	1.03	0.95	0.9	1.04
2.25	1.16	1.11	1	0.93	1.15
2.5	1.27	1.21	1.07	0.97	1.25
2.75	1.38	1.3	1.14	1.03	1.35
3	1.50	1.4	1.22	1.08	1.44
3.25	1.61	1.5	1.3	1.14	1.54
3.5	1.73	1.6	1.38	1.21	1.63
3.75	1.84	1.7	1.46	1.27	1.73
4	1.96	1.8	1.54	1.34	1.82
4.25	2.07	1.9	1.62	1.4	1.91
4.5	2.19	2.01	1.7	1.47	2.0
4.75	2.30	2.11	1.79	1.54	2.09
5	2.42	2.21	1.87	1.6	2.17
5.25	2.54	2.31	1.95	1.67	2.26
5.5	2.65	2.42	2.04	1.74	2.35
5.75	2.77	2.52	2.12	1.8	2.43
6	2.88	2.62	2.2	1.87	2.52

Recommended Eqn. (6) DF Factors Are Conservatively Biased on Average

Individual SSC Seismic Risk R_{FC} Obtained Using Eqn. (6) Design Factors

(P_{FC} values shown should be multiplied times $0.1*H_D$)

A_R	P_{FC}			
	$\beta = .3$	$\beta = .4$	$\beta = .5$	$\beta = .6$
1.5	0.81	0.67	0.76	1.2
1.75	1.08	0.84	0.69	0.68
2	1.03	0.95	0.72	0.61
2.25	1.03	0.92	0.68	0.55
2.5	1.04	0.92	0.68	0.53
2.75	1.06	0.92	0.69	0.54
3	1.08	0.93	0.7	0.55
3.25	1.09	0.95	0.71	0.56
3.5	1.1	0.96	0.73	0.57
3.75	1.12	0.97	0.74	0.59
4	1.13	0.98	0.76	0.6
4.25	1.14	1	0.77	0.61
4.5	1.15	1.01	0.78	0.62
4.75	1.16	1.02	0.79	0.64
5	1.17	1.02	0.81	0.65
5.25	1.17	1.03	0.82	0.66
5.5	1.18	1.04	0.83	0.67
5.75	1.19	1.05	0.83	0.68
6	1.19	1.05	0.84	0.68

- **For $H_D = 1x10^{-4}$**

  $P_{FC} = 1.2 \times 10^{-5}$ to 0.53×10^{-5}

Demonstration Of Achieved P_F For Actual Hazard Curves 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

Individual SSC Seismic Risks P_{FC} Achieved for Representative Hazard Curves

Hazard Curve	UHRS SA_{UHRS}	A_R	DF	DRS SA_{DRS}	SSC Seismic Risk P_{FC} ($*10^{-5}$) $\beta = 0.30$	$\beta = 0.40$	$\beta = 0.50$	$\beta = 0.60$
EUS 1Hz	1.00	3.27	1.68	1.68	1.09	0.93	0.69	0.52
EUS 10 Hz	1.00	2.88	1.52	1.52	1.03	0.87	0.62	0.46
Calif 1 Hz	1.00	1.89	1.08	1.08	1.04	0.96	0.73	0.61
Calif 10 Hz	1.00	1.76	1.02	1.02	0.84	0.78	0.58	0.48

Other Options Exist For Achieving Performance Goal

P_{FT} = Mean $1x10^{-5}$/yr

Options

DF = Maximum (DF_1 , DF_2)

$DF_2 = 0.6 A_R^{\alpha}$

Mean H_D	R_P	DF_1	α
$2x10^{-4}$/yr	20	1.15	1.10
$1x10^{-4}$/yr	10	1.0	0.80
$5x10^{-5}$/yr	5	0.87	0.50
$4x10^{-5}$/yr	4	0.8	0.40
$2x10^{-5}$/yr	2	0.67	0.0

← Chosen ($1x10^{-4}$/yr row)

References

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