Risk-based seismic isolation of nuclear facilities

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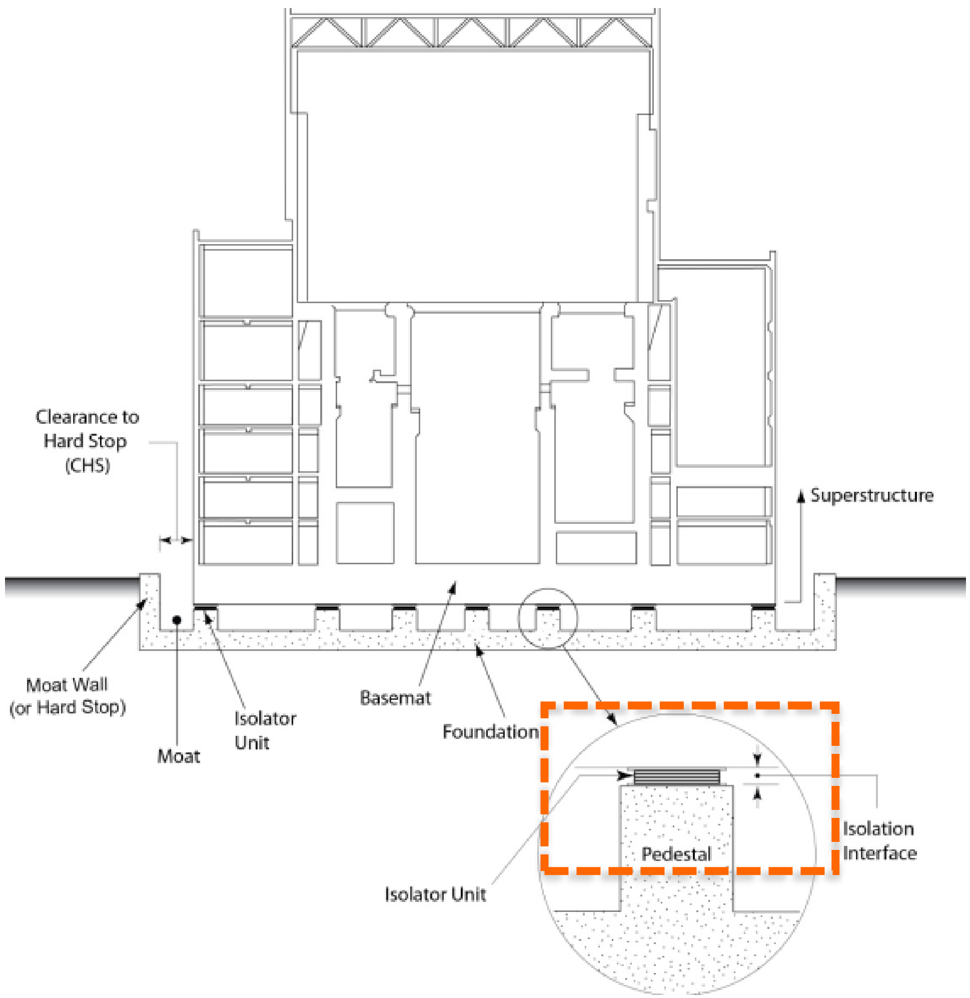
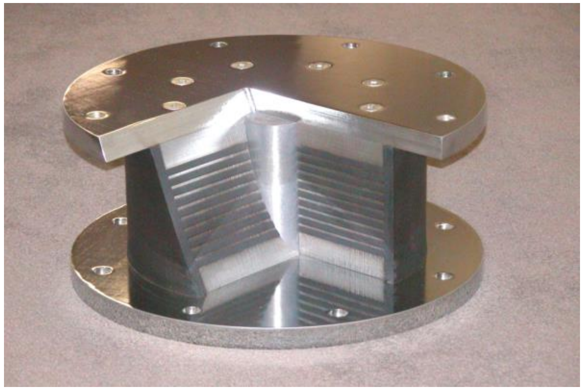
EARTHQUAKE ENGINEERING TO EXTREME EVENTS

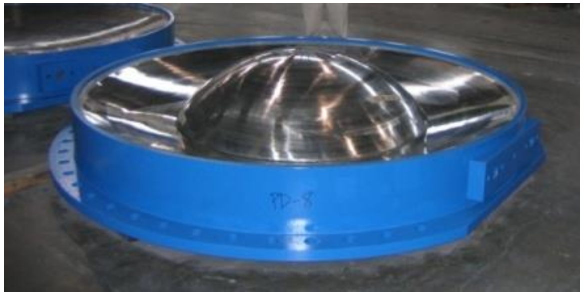
Outline

- Regulatory guidance for seismic isolation
  - Performance expectations
  - DOE and NRC commonalities
  - US seismic isolation hardware
- Risk calculations in DOE and NRC space
- On-going nuclear-related studies

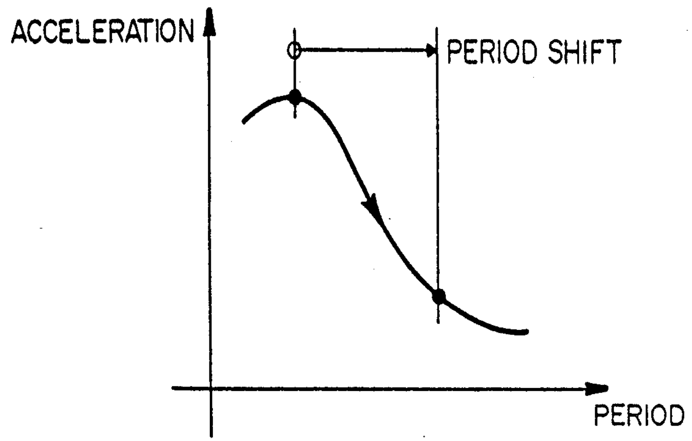
Regulatory guidance for isolation

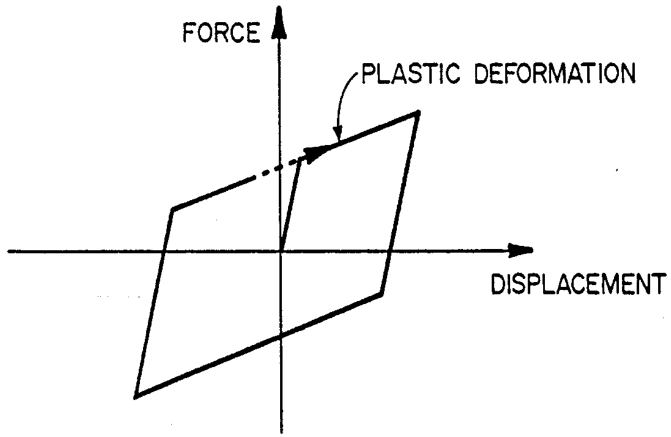


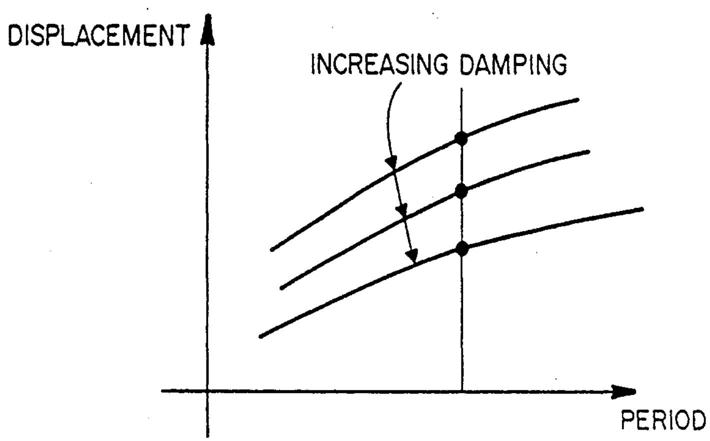


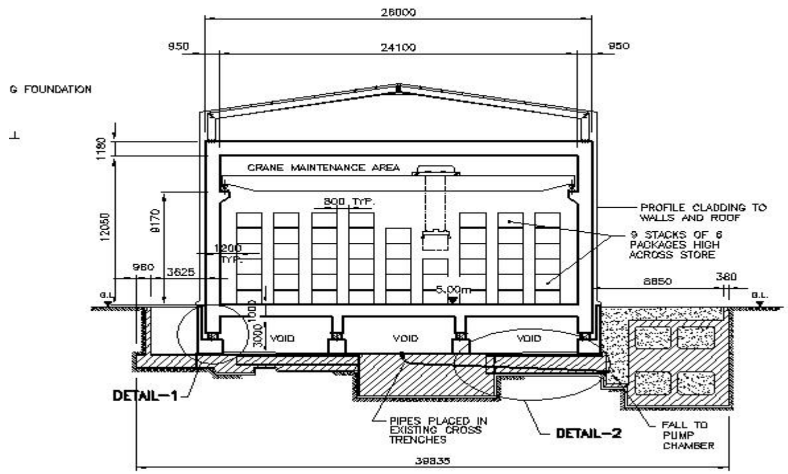


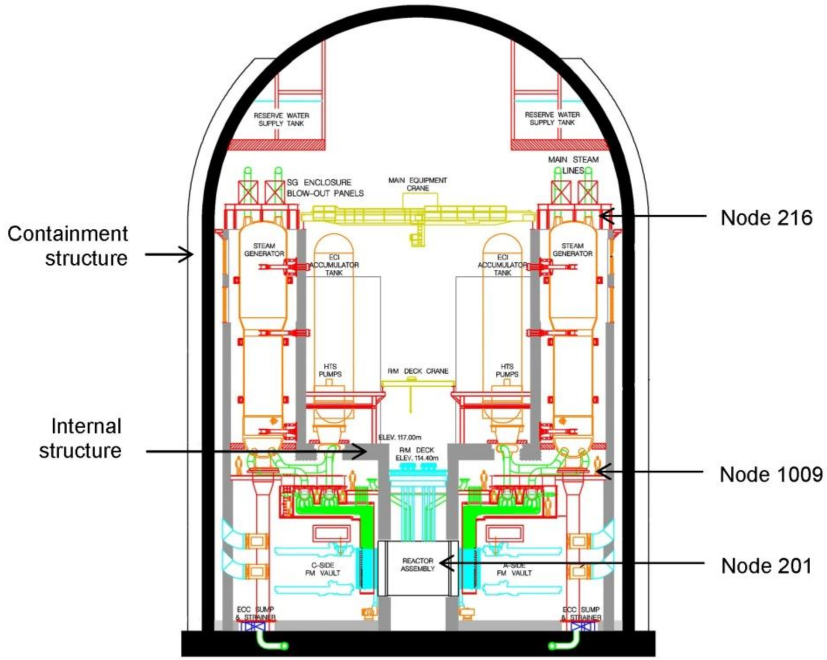
Seismic isolation

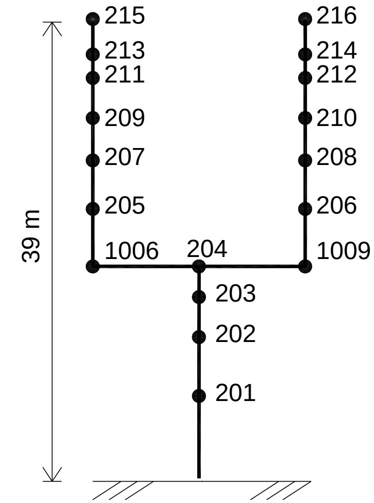









Containment structure
Internal structure
Node 216
Node 1009
Node 201


215
213
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1009
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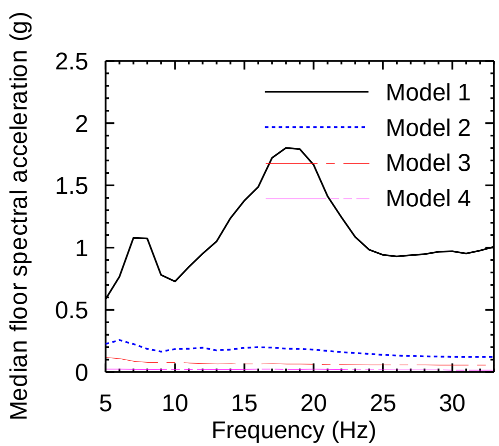
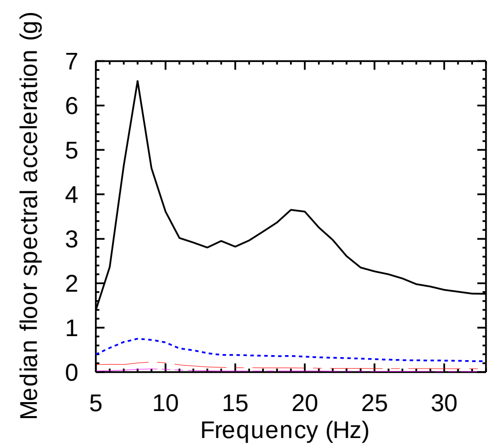

Median floor spectral acceleration (g)
Frequency (Hz)
Model 1
Model 2
Model 3
Model 4

201


Median floor spectral acceleration (g)
Frequency (Hz)

216

Regulatory guidance for isolation

- ASCE 4-14, Chapter 12: analysis, design, testing
- ASCE 43-**, Chapter 10: design, testing
- Seismic isolation NUREG
- Horizontal isolation only
- *Surface*-mounted nuclear facilities
- Prequalified seismic isolators: LRB, LDRB, FPB
- DOE and NRC provisions applicable in principle to
  - Components and systems
  - Deeply embedded facilities
  - Small modular reactors
  - Three-dimensional isolation systems
- Prequalification of alternate systems

Regulatory guidance for isolation

- Performance expectations of ASCE 43, SDC 5
  - FOSID at MAFE = E-5
  - DBE = DF * UHS at E-4 = GMRS
  - 1% NEP for 100% DBE shaking
  - 10% NEP for 150% DBE shaking
- Analyzable for beyond design basis loadings
  - Definitions differ for DOE and NRC applications
- Reliable numerical models of isolators
  - Validated by full-scale dynamic testing
- Modeling and analysis of isolated structures
- Prototype and production testing

Regulatory guidance for isolation

- Fully coupled, nonlinear time-domain
  - Soil (LB, BE, UB), isolators, SSCs
  - ABAQUS, LS-DYNA, NRC ESSI
  - Used for all types of isolators
  - 3D soil domain, domain reduction method
  - Apply ground motions at boundary of model
- Full coupled, frequency domain
  - LDR bearings
- Multi-step
  - Frequency domain analysis to compute SIDRS; equivalent linear models of isolators
  - Ground motions matched to SIDRS
  - Nonlinear analysis of isolated superstructure

Regulatory guidance for isolation

- Performance statements
  - Isolators suffer no damage in the DBE
    - Confirm by testing all isolators
  - Isolated facility impacts surrounding structure
    - 1% NEP for DBE shaking; 10% NEP for BDBE shaking
  - Isolators sustain gravity and earthquake induced axial loads at 90%-ile BDBE displacement
    - Confirm by prototype testing
  - Safety-critical umbilical lines sustain 90%-ile BDBE displacement with 90% confidence
    - Confirm by testing and/or analysis

Regulatory guidance for isolation

- Prototype tests
  - 3 minimum of every type and size
  - Dynamic tests to interrogate isolator behavior
    - Design basis and beyond design basis
    - Clearance to the stop (CS)
    - Cycles consistent with EDB shaking demands
  - Damage acceptable for CS tests
- Production tests
  - Isolators identical to prototype isolators
  - QA/QC testing of all isolators
  - Static or dynamic tests
    - Design basis loadings
  - No damage acceptable for design basis tests
- ASME-NQA-1 quality program, or equivalent

		Isolation system			Superstructure	Other SSCs	Umbilical lines	Hard Stop or Moat
Hazard	Use	Isolation system displacement	Performance	Acceptance criteria	Performance	Performance		
DBE Response spectrum per Chapter 2	Production testing of isolators. Design loads for isolated superstructure. In-structure response spectra (ISRS).	Mean and 80th percentile isolation system displacements.	No damage to the isolation system for DBE shaking.	Production testing of each isolator for the 80th percentile isolation system displacement and corresponding axial force. Isolators damaged by testing cannot be used for construction.	Conform to consensus materials standards for 80th percentile demands. Greater than 99% probability that component capacities will not be exceeded. Greater than 99% probability that the superstructure will not contact the moat.[1]	Conform to ASME standards for 80th percentile demands; adjust ISRS per Section 6.2.3. Greater than 99% probability that component capacities will not be exceeded.	-	-
BDBE 150% of DBE	Prototype testing of isolators. Selecting moat width (or Clearance to Stop).	90th percentile isolation system displacement.[2]	Greater than 90% probability of the isolation system surviving BDBE shaking without loss of gravity-load capacity.	Prototype testing of a sufficient[3] number of isolators for the CS displacement and the corresponding axial force. Isolator damage is acceptable but load-carrying capacity is maintained.	Greater than 90% probability that the superstructure will not contact the moat. Achieved by setting the moat width equal to or greater than the 90th percentile displacement. Greater than 90% probability that component capacities will not be exceeded.	Greater than 90% probability that component capacities will not be exceeded.	Greater than 90% confidence that all safety-related umbilical lines and their connections, shall remain functional for the CS displacement by testing, analysis or a combination of both.	Clearance to Stop (CS) or moat width equal to or greater than the 90th percentile displacement. Damage to the moat is acceptable in the event of contact.

1. Can be achieved by satisfying the requirement for BDBE shaking.

2. 90th percentile BDBE displacements may be calculated by multiplying the mean DBE displacement by a factor of 3.

3. The number of prototype isolators to be tested shall be sufficient to provide the required 90+% confidence.

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Table 8-1. Performance and design expectations for seismically isolated nuclear power plants[1]

Ground motion levels	Isolation system: Isolation unit and system design and performance criteria	Isolation system: Approach to demonstrating acceptable performance of isolator unit	Superstructure design and performance	Umbilical line design and performance	Moat or hard stop design and performance
GMRS+[2] The envelope of the RG1.208 GMRS and the minimum foundation input motion[3] for each spectral frequency	No long-term change in mechanical properties. 100% confidence of the isolation system surviving without damage when subjected to the mean displacement of the isolator system under the GMRS+ loading.	Production testing must be performed on each isolator for the mean system displacement under the GMRS+ loading level and corresponding axial force.	The superstructure design and performance must conform to NUREG-0800 under GMRS+ loading.	Umbilical line design and performance must conform to NUREG-0800 under GMRS+ loading.	The moat is sized such that there is less than 1% probability of the superstructure contacting the moat or hard stop under GMRS+ loading.
EDB[4] **GMRS** The envelope of the ground motion amplitude with a mean annual frequency of exceedance of 1×10^{-5} and 167% of the GMRS+ spectral amplitude	90% confidence of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under EDB loading.	Prototype testing must be performed on a sufficient number of isolators at the CHS[5] displacement and the corresponding axial force to demonstrate acceptable performance with 90% confidence. Limited isolator unit damage is acceptable but load-carrying capacity must be maintained.	There should be less than a 10% probability of the superstructure contacting the moat or hard stop under EDB loading.	Greater than 90% confidence that each type of safety-related umbilical line, together with its connections, remains functional for the CHS displacement. Performance can be demonstrated by testing, analysis or a combination of both.[6]	CHS displacement must be equal to or greater than the 90th percentile isolation system displacement under EDB loading. Moat or hard stop designed to survive impact forces associated with 95th percentile EDB isolation system displacement.[7] Limited damage to the moat or hard stop is acceptable but the moat or hard stop must perform its intended function.

1. Analysis and design of safety-related components and systems should conform to NUREG-0800, as in a conventional nuclear structure.

2. 10CFR50 Appendix S requires the use of an appropriate free-field spectrum with a peak ground acceleration of no less than 0.10g at the foundation level. RG1.60 spectral shape anchored at 0.10g is often used for this purpose.

3. The analysis can be performed using a single composite spectrum or separately for the GMRS and the minimum spectrum.

4. The analysis can be performed using a single composite spectrum or separately for the 10^{-5} MAFE response spectrum and 167% GMRS.

5. CHS=Clearance to the Hard Stop

6. Seismic Category 2 SSCs whose failure could impact the functionality of umbilical lines should also remain functional for the CHS displacement.

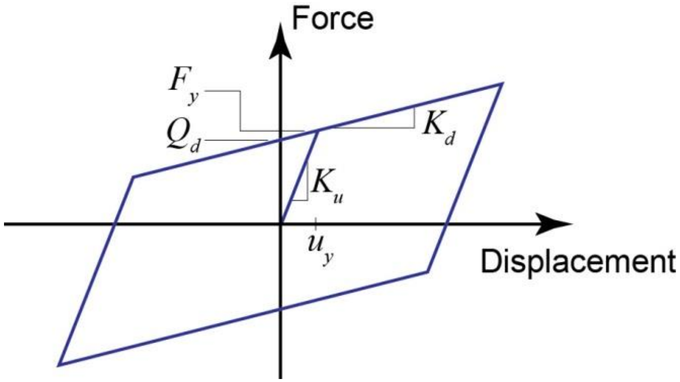
7. Impact velocity calculated at the displacement equal to the CHS assuming cyclic response of the isolation system for motions associated with the 95th percentile (or greater) EDB displacement.

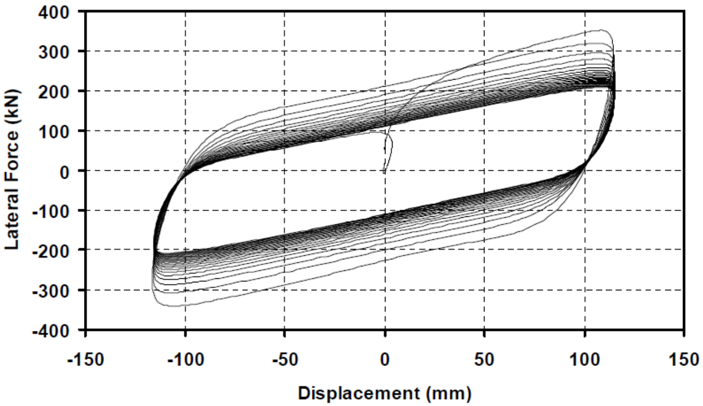
Isolators and isolation systems

- Addressed for US practice
  - Low damping natural rubber
  - Lead-rubber
  - Spherical sliding (FP) bearing
- Acknowledged in the NUREG/ASCE 4/ASCE 43
  - High-damping rubber
  - Synthetic rubber (neoprene)
  - EradiQuake
  - 3D isolation systems

Isolators and isolation systems

- Procedures and rules for
  - Low damping natural rubber
  - Lead-rubber
  - Friction Pendulum type
- Stable, predictable hysteresis





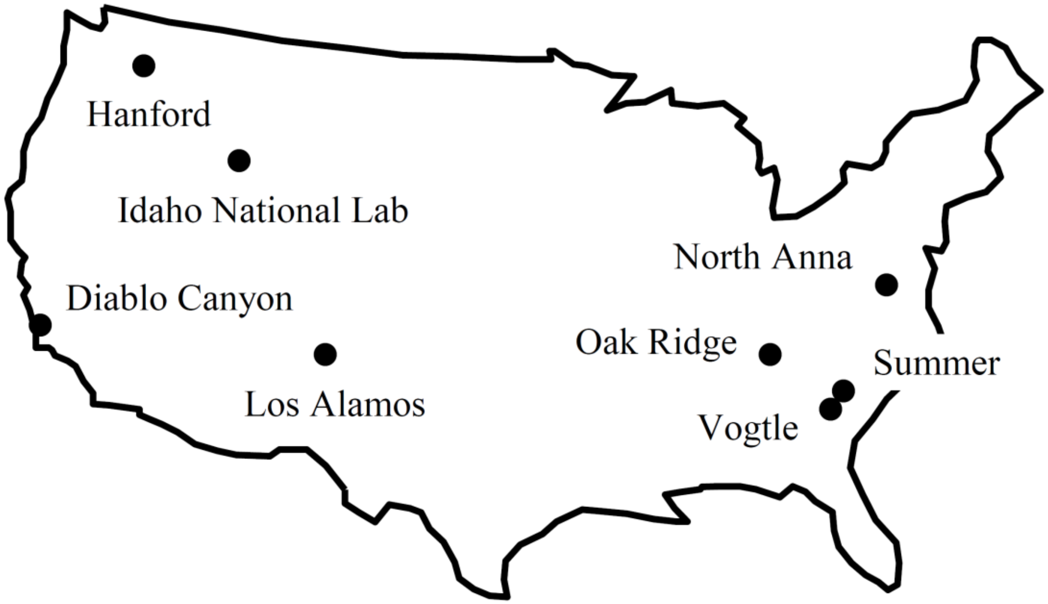
Isolators and isolation systems

- Developments funded by USNRC
  - Focus on behavior under extreme loadings
- Verified and validated models per ASME
  - OpenSees, ABAQUS and LS-DYNA
  - Friction Pendulum bearing
  - Low damping rubber bearing
    opensees.berkeley.edu/wiki/index.php/ElastomericX
  - Lead rubber bearing
    opensees.berkeley.edu/wiki/index.php/LeadRubberX
  - High damping rubber bearing
    opensees.berkeley.edu/wiki/index.php/HDR

Isolators and isolation systems

- Qualification of *other* types of isolators
  - Dynamic testing of prototype isolators for BDBE demands
  - Development of V+V numerical models of the isolator capable of predicting response under extreme loadings
    - Isolator MUST be "analyzable" for extreme loadings
  - Basic chemistry, lab tests and field applications to show that mechanical properties do not change by more than 20% over design life
  - System level testing using 3D inputs
  - V+V of numerical tools to predict response of the isolation system

Risk calculations



Sites of nuclear facilities in the US

Table 6-9: Spectral ordinates (in g) at 1 s and 2 s for seismic hazards defined for conventional and seismically isolated nuclear power plants at eight sites of nuclear facilities (also see Figure 6-13)

Period (s)	Hazard definition	Site							
		North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
1	UHRS1[1]	0.12	0.22	0.20	0.21	0.25	0.14	0.36	0.83
	UHRS2[2]	0.41	0.54	0.47	0.64	0.53	0.27	1.06	1.59
	1.67×UHRS1	0.19	0.36	0.34	0.35	0.42	0.23	0.60	1.39
	DF×UHRS1	0.19	0.27	0.24	0.31	0.27	0.14	0.51	0.84
2	UHRS1	0.06	0.12	0.11	0.11	0.14	0.09	0.15	0.38
	UHRS2	0.19	0.29	0.26	0.31	0.29	0.18	0.44	0.75
	1.67×UHRS1	0.10	0.19	0.18	0.19	0.24	0.15	0.25	0.64
	DF×UHRS1	0.09	0.15	0.13	0.15	0.15	0.09	0.21	0.39

[1]UHRS with an MAFE of 10^{-4}
[2]UHRS with an MAFE of 10^{-5}

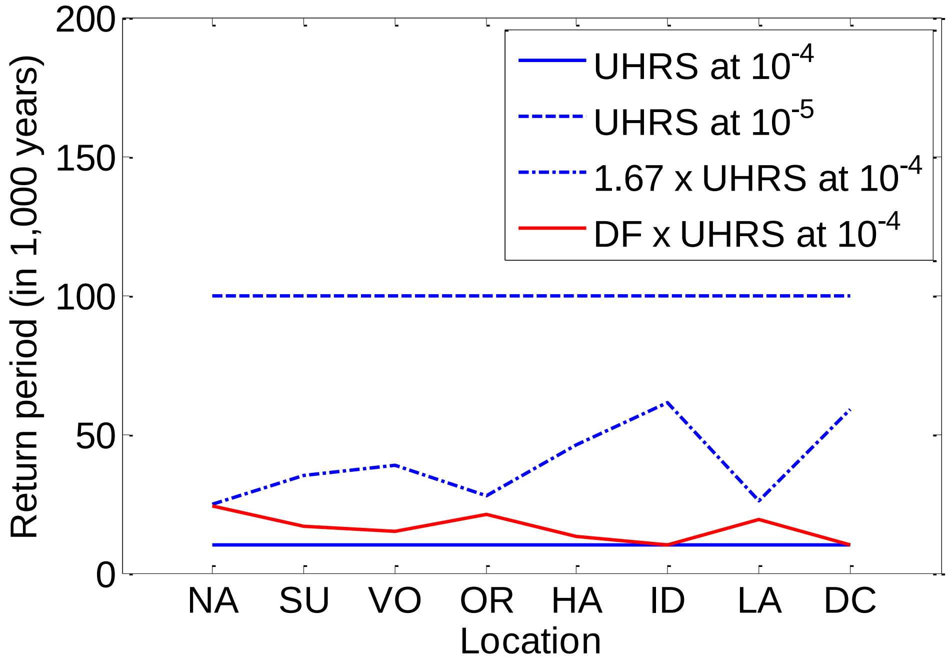
Table 6-10: Return periods corresponding to the spectral accelerations at 1 s and 2 s reported in Table 6-9 (in 1,000 years)

Period (s)	Hazard definition	Site							
		North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
1	UHRS1[1]	10	10	10	10	10	10	10	10
	UHRS2[2]	100	100	100	100	100	100	100	100
	1.67×UHRS1	25	35	39	28	46	61	26	59
	DF×UHRS1	24	17	15	21	13	10	19	10
2	UHRS1	10	10	10	10	10	10	10	10
	UHRS2	100	100	100	100	100	100	100	100
	1.67×UHRS1	28	34	36	31	48	48	26	54
	DF×UHRS1	24	17	16	20	12	12	19	11

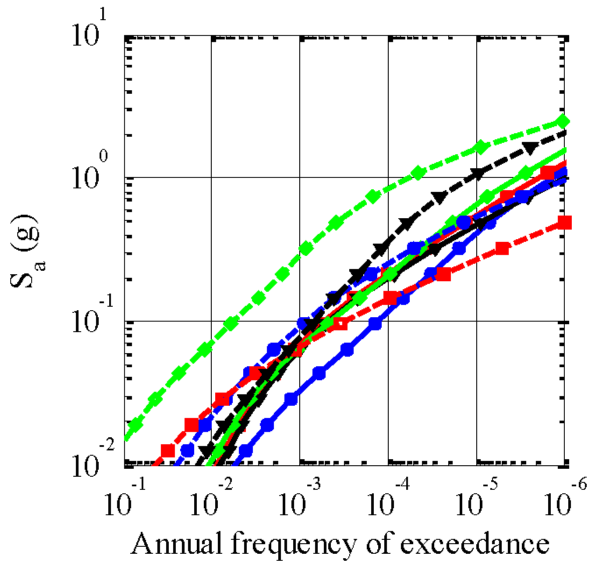
[1]UHRS with an MAFE of 10^{-4}
[2]UHRS with an MAFE of 10^{-5}

Sites of nuclear facilities in the US

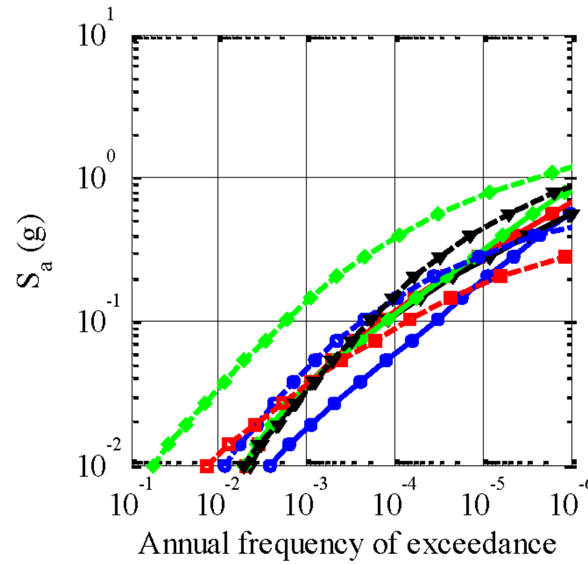
- Return periods for S_a at 1 s



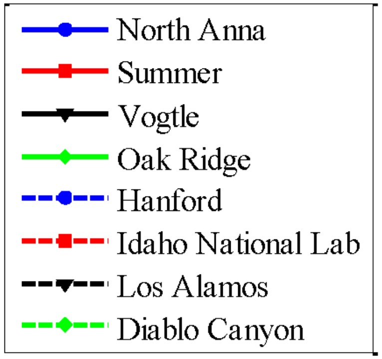
Seismic hazard curves



(c) Period = 1 s

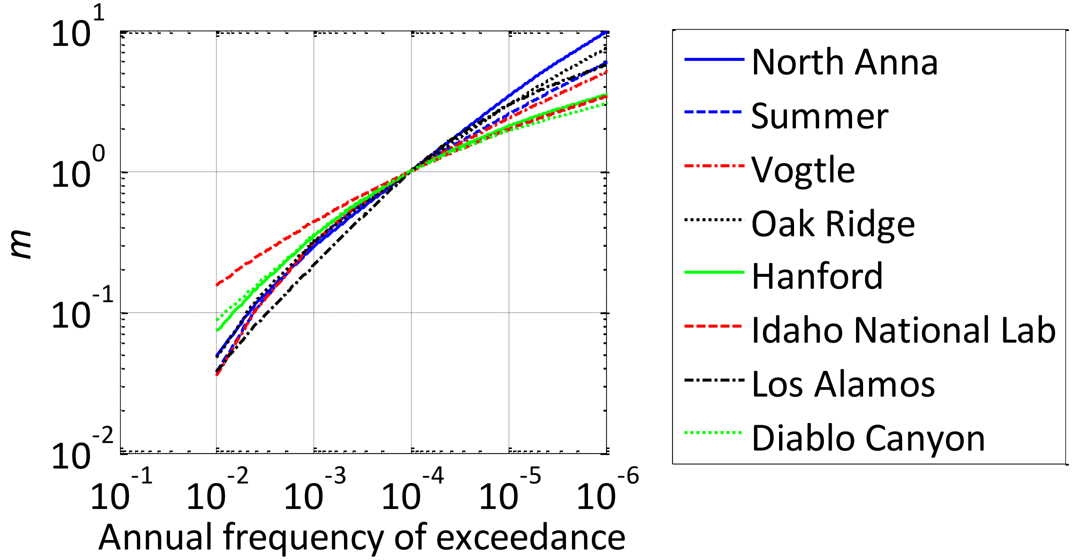


(d) Period = 2 s



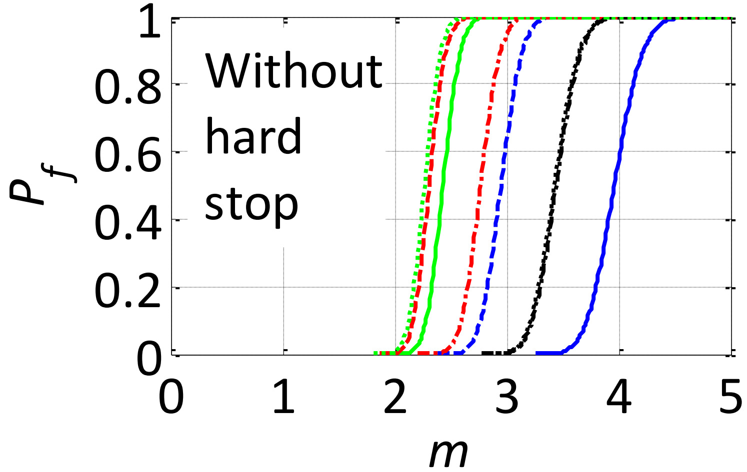
Seismic hazard curves

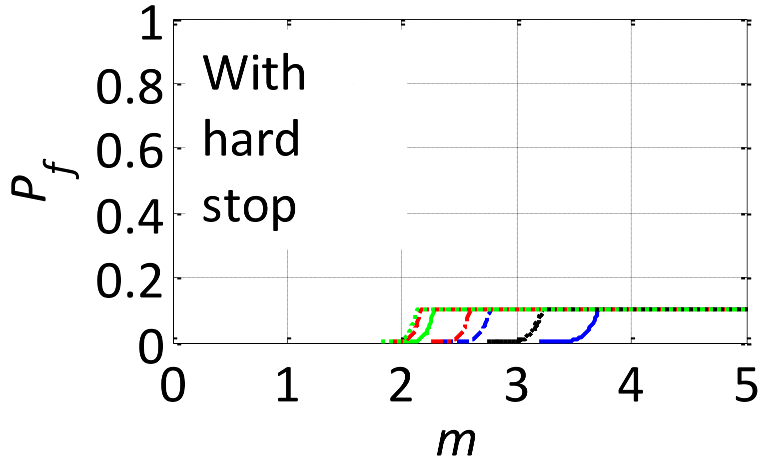
- Defined as multiples, *m*, of GMRS+
  - Computed in terms of average of multiples of spectral ordinates at 1 s and 2 s
  - *DF* = 1



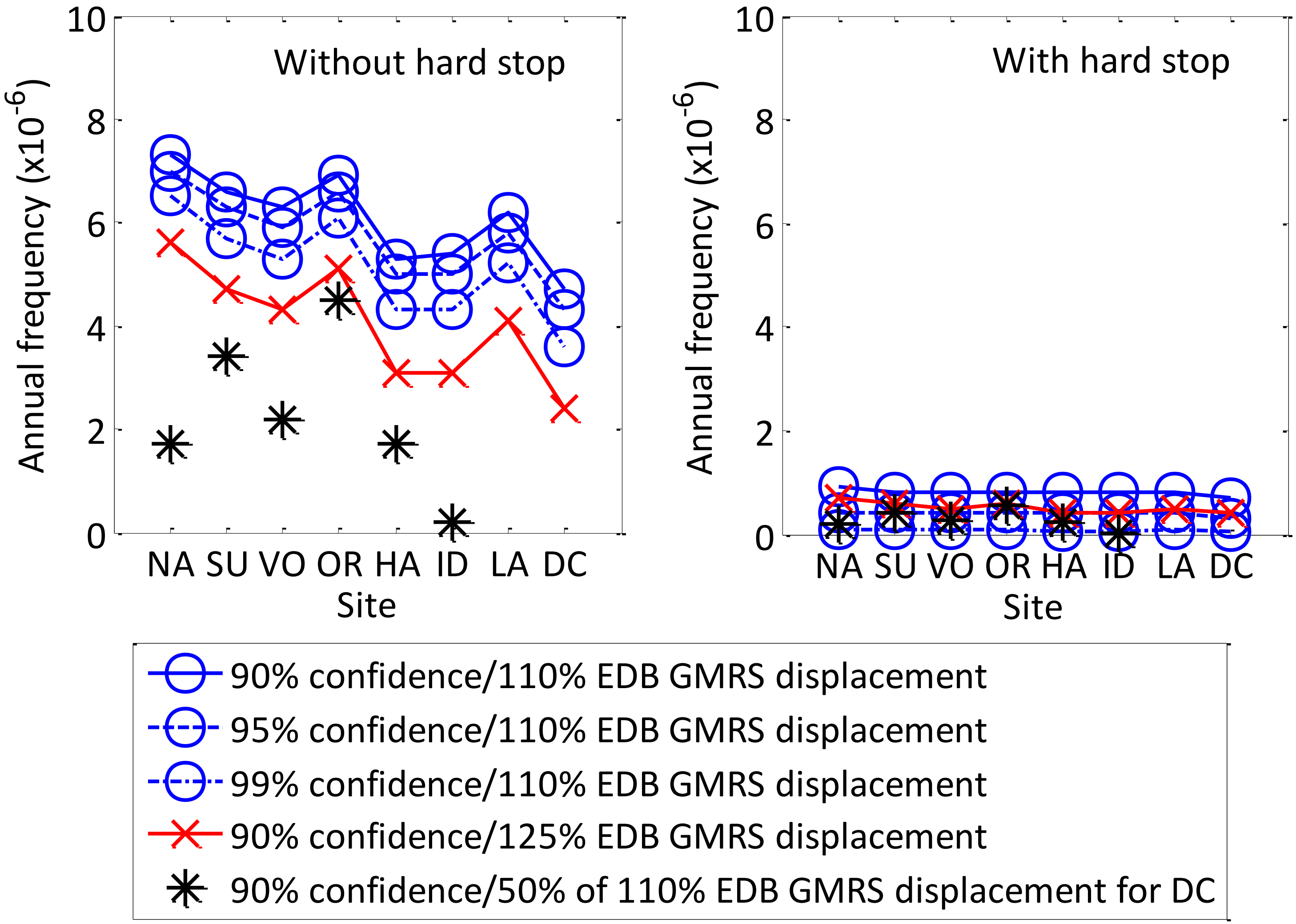
Median fragility curves: NRC space

- Isolation system and individual isolators
  - Assumed fully correlated
  - Lognormal distribution parameters
  - Variability small for high quality isolators
  - Median 110% EDB GMRS displacement ≥ 90th percentile EDB GMRS displacement

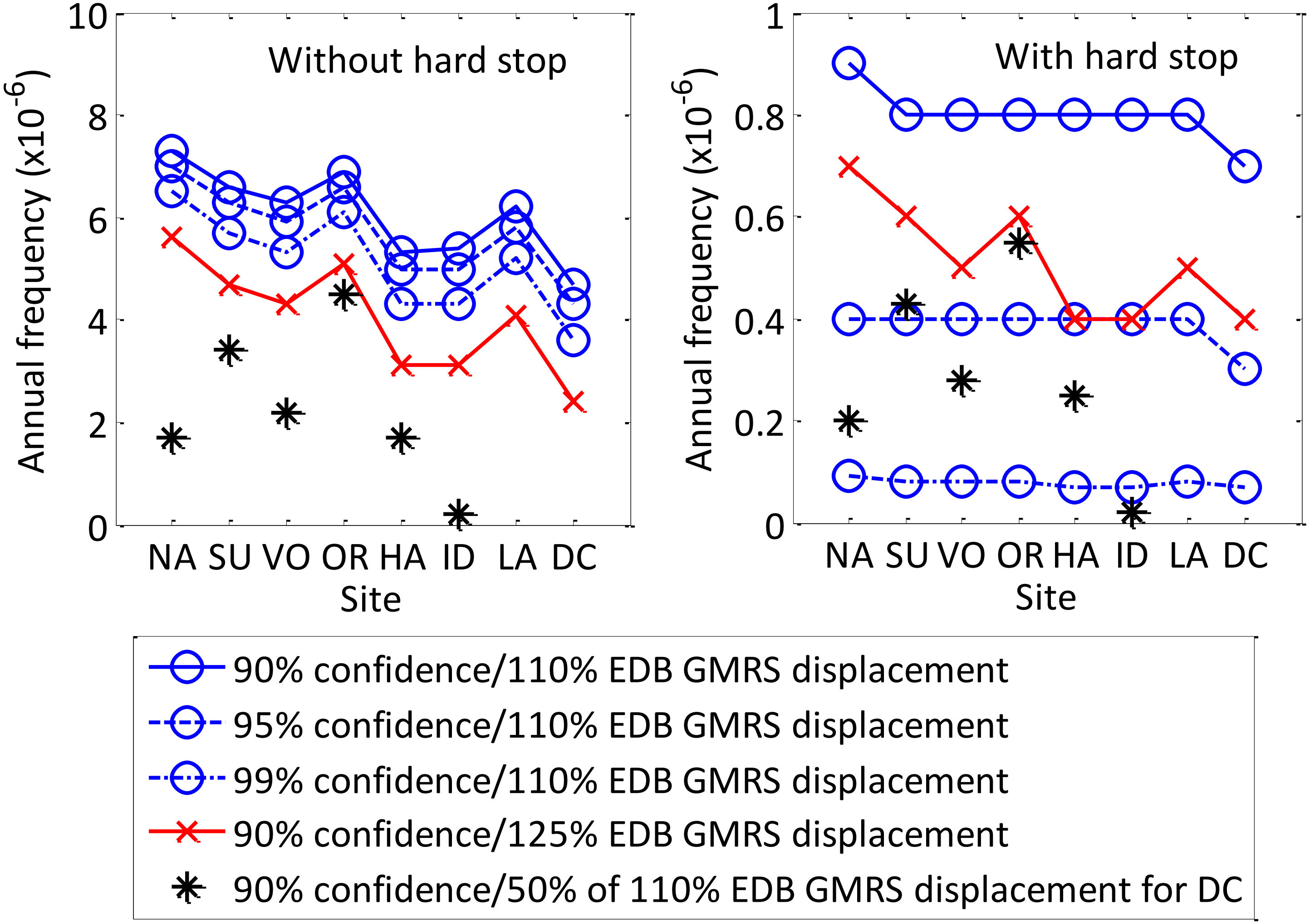




Risk calculations: NRC space

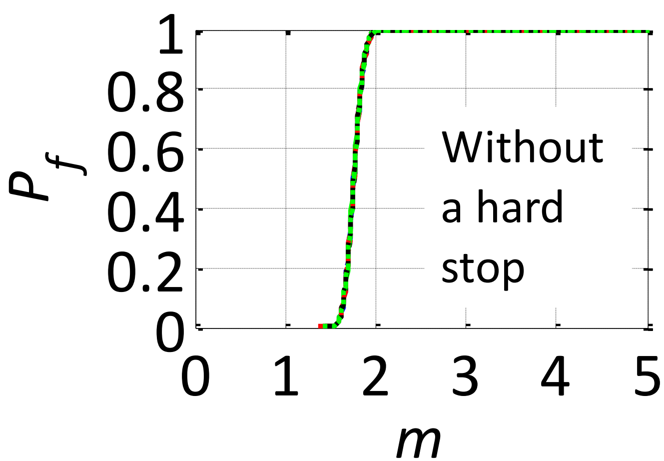


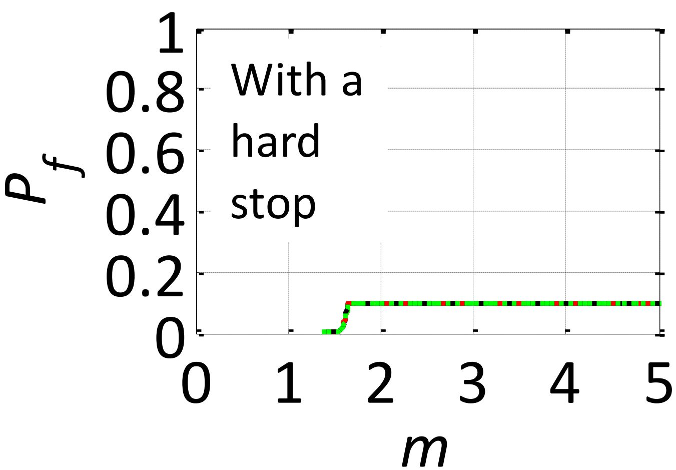
Risk calculations: NRC space



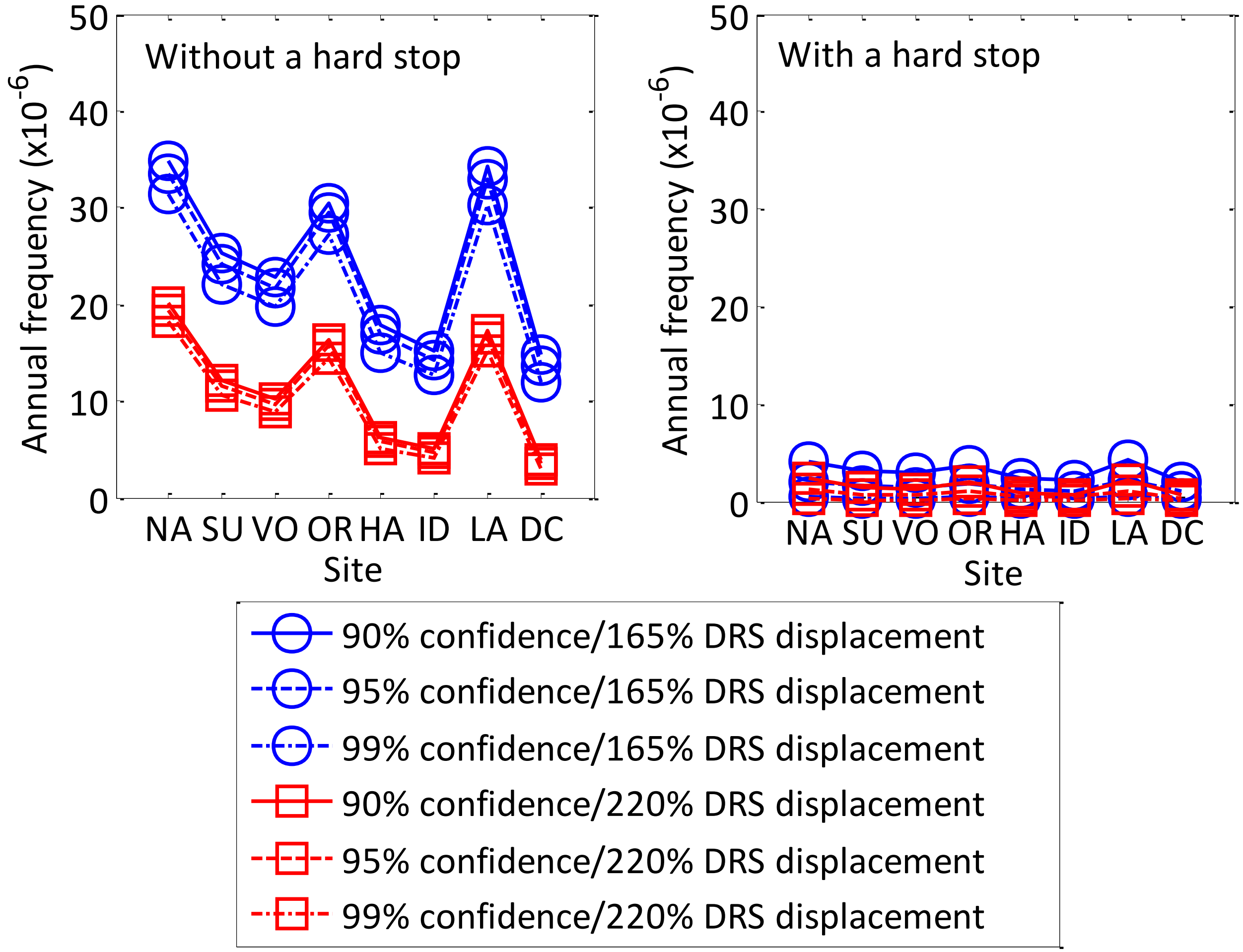
Median fragility curves: DoE space

- Isolation system
  - Assumed fully correlated
  - Lognormal distribution parameters
  - Variability small for high quality isolators
  - Median 165% (220%) DRS displacement = 90th percentile 150% (200%) DRS displacement

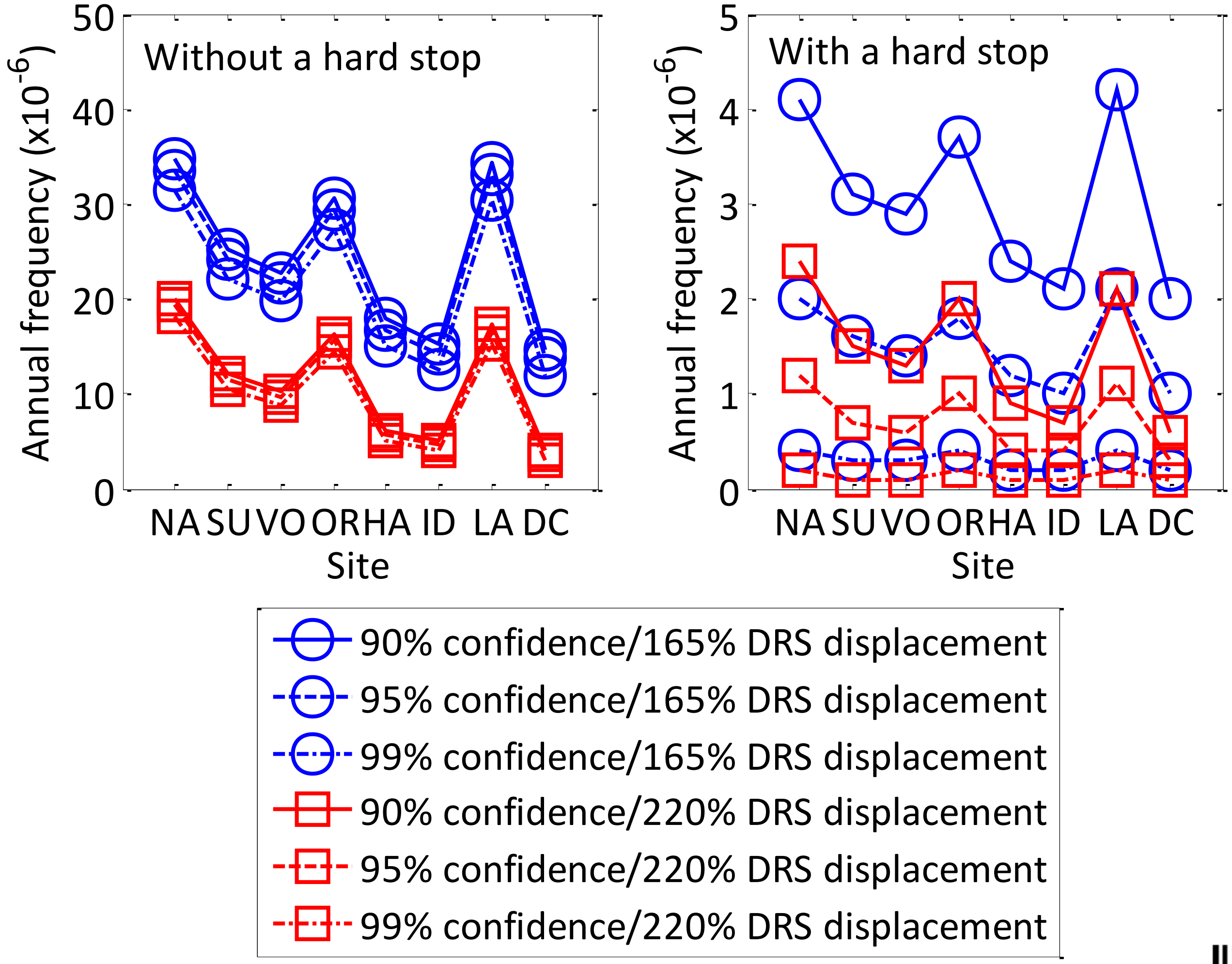




Risk calculations: DoE space



Risk calculations: DoE space



On-going nuclear-related studies

- PRA methodologies to address isolation
  - Huang et al. 2009, Lungmen NPP
- Nonlinear SSI analysis
  - Numerical and physical simulations
  - Hybrid simulations
- RC and SC shear walls
  - Design procedures and fragility functions
- Missile impact on RC and SC walls
- Isolation of components and subsystems
  - Integration with SSI

On-going nuclear-related studies

- Component isolation
  - 3D isolation possible
  - Component geometry and fragility
    - Different from LLWR
    - Isolator design for non-seismic fragility
  - Alternate isolator(s)
    - Family of component isolators
    - Extend Chapter 10(12) of ASCE 4(43)
    - Expand seismic isolation NUREG
  - Fully coupled time domain analysis
    - Seismic input filtered by structure

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