



# Risk-informed design of seismic isolation systems for nuclear facilities

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# 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

# Earthquake simulators

- Two high-performance simulators
- 7m by 7m platforms
- Located in a trench
- 50T payload/simulator
- 0 to 50 Hz at 50T
- Equipment qualification
  - 6 components of input
  - Substation equipment; A/E/M/P systems; NPP; tanks
  - IEEE 693, AC 156, GR 63 Core, NQA-1



# Geo laminar box

- 1D input
- 6m tall; 5m by 2.7m in plan; 80m<sup>3</sup> of soil
- Instrumentation
  - Shape arrays
  - Acceleration, displacement
- Soil-foundation interaction
- Soil-structure interaction
- Validation of numerical codes
  - Site response
  - SSI



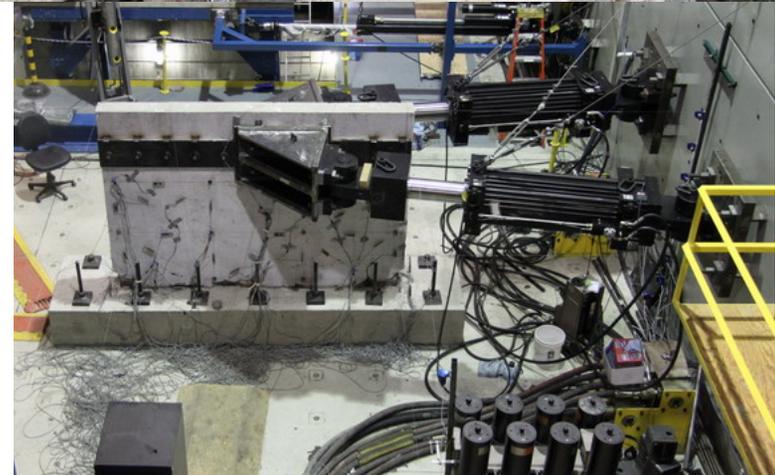
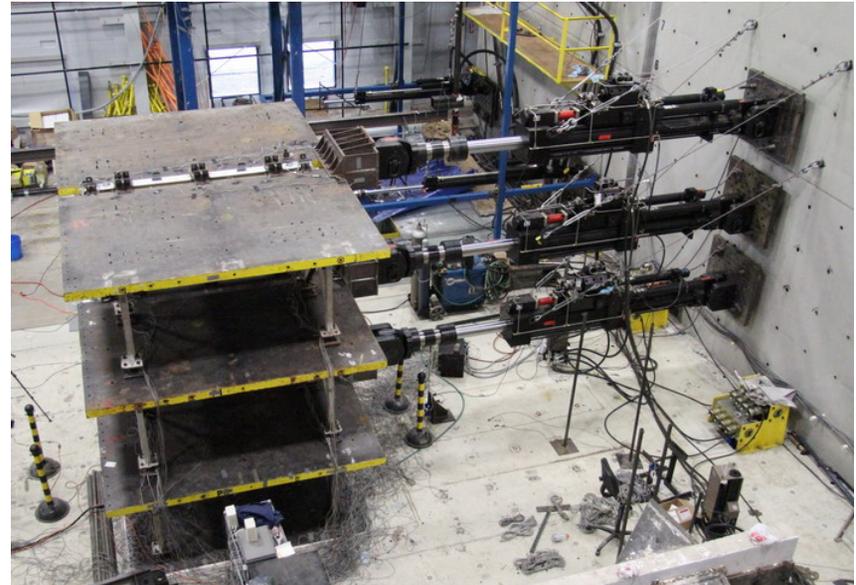
# Nonstructural simulator

- Two-level systems
- Large displacement ( $\pm 1\text{m}$ ), high velocity ( $2.5\text{m/s}$ ), frequency ( $5\text{ Hz}$ )
- Impose acceleration and drift histories simultaneously
- Systems of acceleration and displacement-sensitive components
- Derive fragility functions
- Tested to date
  - Non-load bearing walls
  - Piping systems
  - Hybrid nonstructural systems

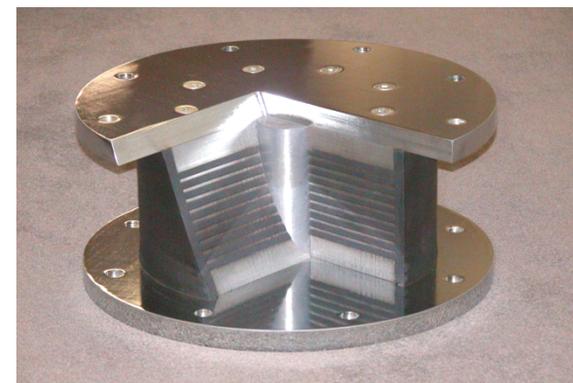
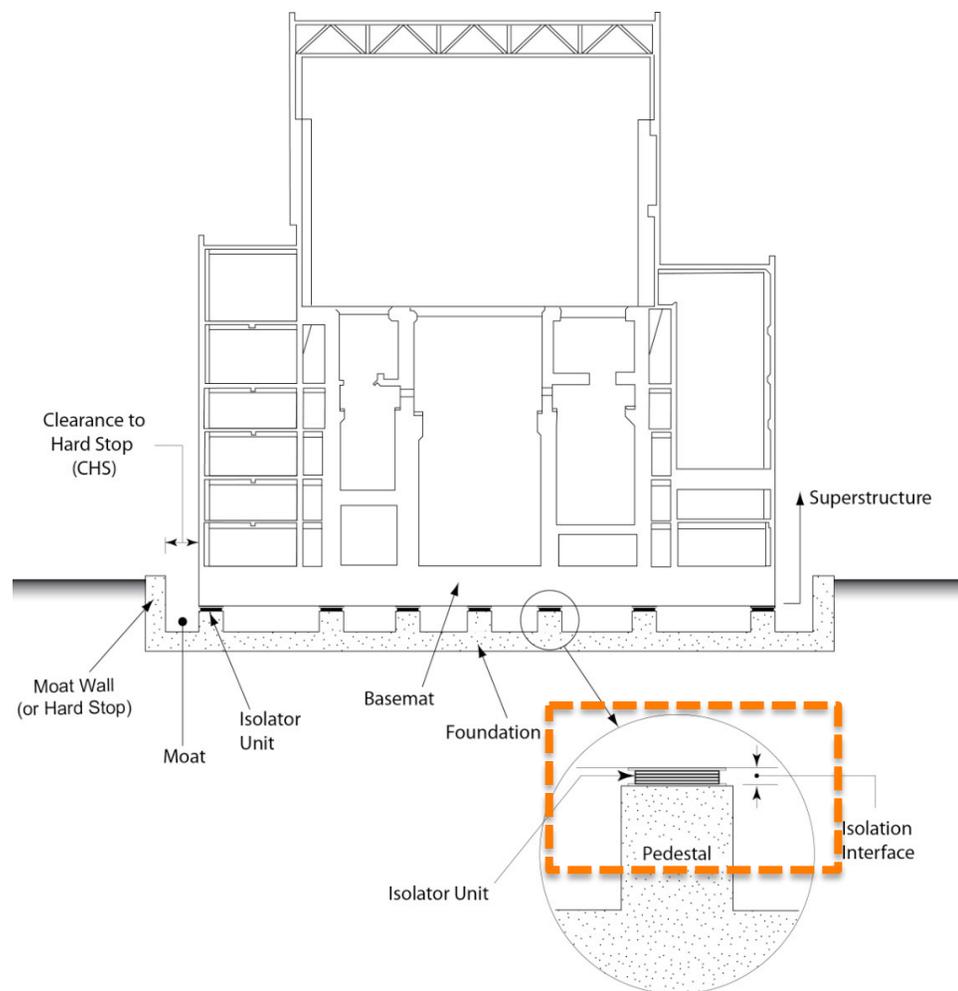


# Actuators

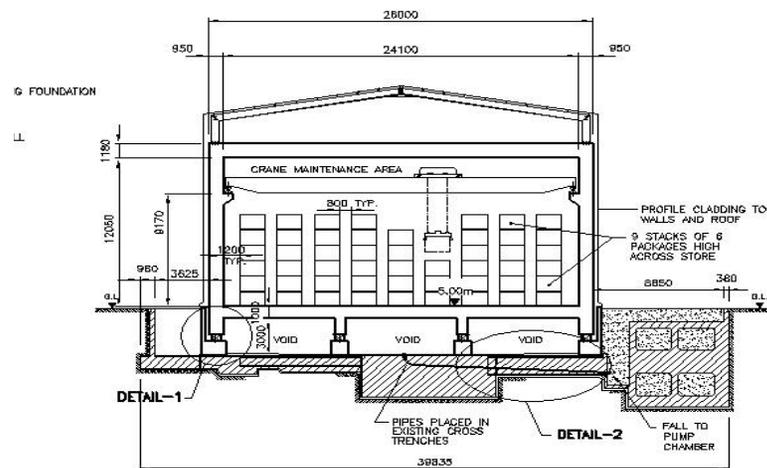
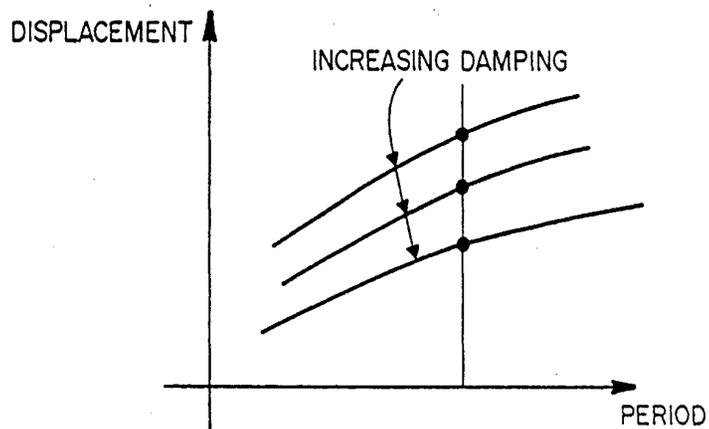
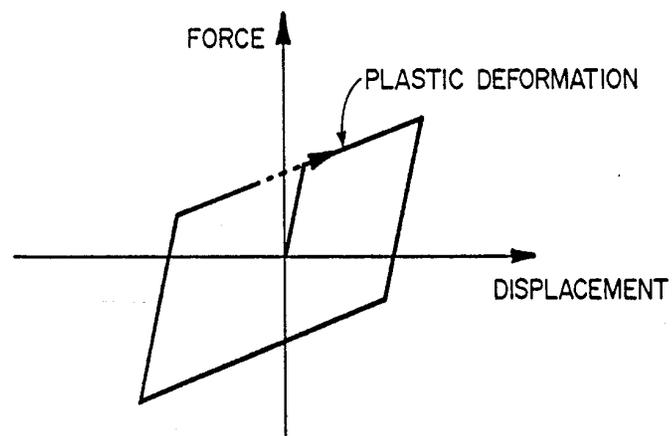
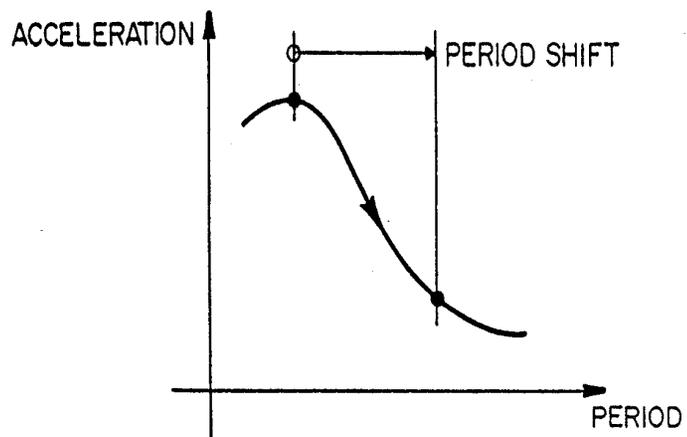
- Three dynamic
  - 100T, 1.5m/sec,  $\pm 0.5$ m
- Two static
  - 200T,  $\pm 0.5$ m
- Strong wall, floor
- Tests to date
  - Steel, SC and concrete walls
  - Steel braced frames
  - Hybrid simulations

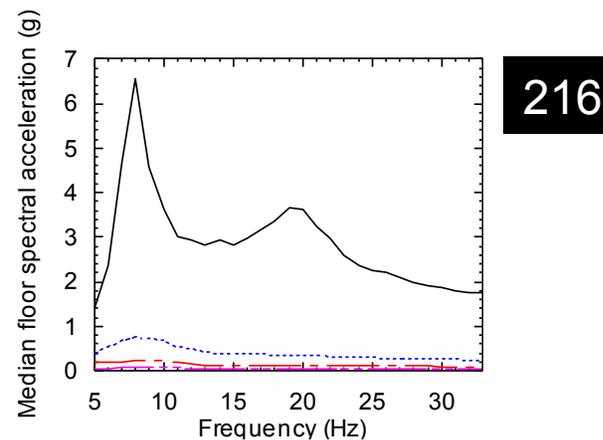
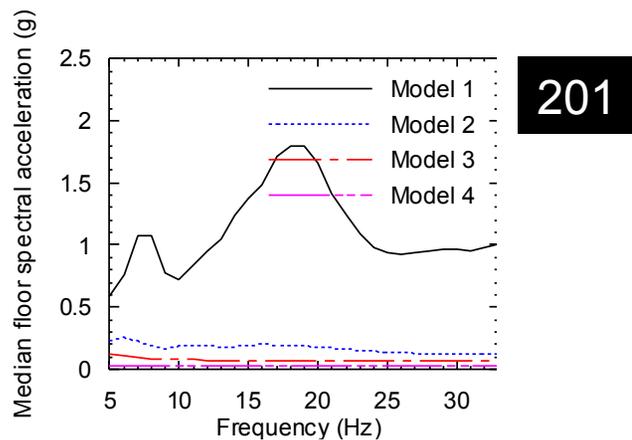
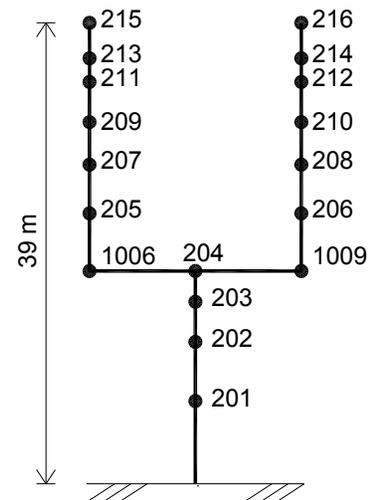
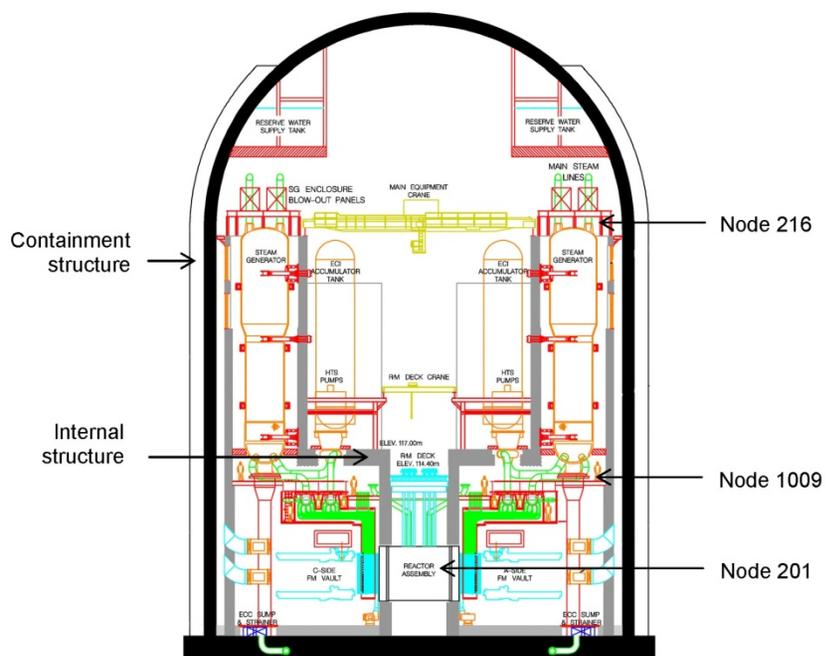


# Regulatory guidance for isolation



# Seismic isolation





# 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

| Hazard  | Use  | Isolation system  |  |  | Superstructure  | Other SSCs  | Umbilical lines   | Hard Stop or Moat  |
|---|--|---|--|--|---|---|---|--|
|   |  | Isolation system displacement   | Performance  | Acceptance criteria  | Performance   | Performance   |   |  |
| <b>DBE</b><br>Response spectrum per Chapter 2 | Production testing of isolators.<br>Design loads for isolated superstructure.<br>In-structure response spectra (ISRS). | Mean and 80 <sup>th</sup> percentile isolation system displacements.    | No damage to the isolation system for DBE shaking.   | Production testing of each isolator for the 80 <sup>th</sup> percentile isolation system displacement and corresponding axial force.<br>Isolators damaged by testing cannot be used for construction.    | Conform to consensus materials standards for 80 <sup>th</sup> percentile demands.<br>Greater than 99% probability that component capacities will not be exceeded.<br>Greater than 99% probability that the superstructure will not contact the moat. <sup>1</sup>         | Conform to ASME standards for 80 <sup>th</sup> percentile demands; adjust ISRS per Section 6.2.3.<br>Greater than 99% probability that component capacities will not be exceeded. | -   | -  |
| <b>BDBE</b><br>150% of DBE                    | Prototype testing of isolators.<br>Selecting moat width (or Clearance to Stop).  | 90 <sup>th</sup> percentile isolation system displacement. <sup>2</sup> | Greater than 90% probability of the isolation system surviving BDBE shaking without loss of gravity-load capacity. | Prototype testing of a sufficient <sup>3</sup> number of isolators for the CS displacement and the corresponding axial force.<br>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 90 <sup>th</sup> percentile displacement.<br>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 90 <sup>th</sup> percentile displacement.<br>Damage to the moat is acceptable in the event of contact. |

1. Can be achieved by satisfying the requirement for BDBE shaking.
2. 90<sup>th</sup> 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.

**Table 8-1. Performance and design expectations for seismically isolated nuclear power plants<sup>1</sup>**

| Ground motion levels  | Isolation system  |   | Superstructure design and performance  | Umbilical line design and performance  | Moat or hard stop design and performance  |
|---|---|---|--|--|---|
|   | Isolation unit and system design and performance criteria   | Approach to demonstrating acceptable performance of isolator unit   |  |  |   |
| <p><b>GMRS+<sup>2</sup></b><br/>The envelope of the RG1.208 GMRS and the minimum foundation input motion<sup>3</sup> for each spectral frequency</p>  | <p>No long-term change in mechanical properties.<br/>100% confidence of the isolation system surviving without damage when subjected to the mean displacement of the isolator system under the GMRS+ loading.</p> | <p>Production testing must be performed on each isolator for the mean system displacement under the GMRS+ loading level and corresponding axial force.</p>  | <p>The superstructure design and performance must conform to NUREG-0800 under GMRS+ loading.</p>                             | <p>Umbilical line design and performance must conform to NUREG-0800 under GMRS+ loading.</p>   | <p>The moat is sized such that there is less than 1% probability of the superstructure contacting the moat or hard stop under GMRS+ loading.</p>  |
| <p><b>EDB<sup>4</sup> GMRS</b><br/>The envelope of the ground motion amplitude with a mean annual frequency of exceedance of <math>1 \times 10^{-5}</math> and 167% of the GMRS+ spectral amplitude</p> | <p>90% confidence of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under EDB loading.</p>   | <p>Prototype testing must be performed on a sufficient number of isolators at the CHS<sup>5</sup> 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.</p> | <p>There should be less than a 10% probability of the superstructure contacting the moat or hard stop under EDB loading.</p> | <p>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.<sup>6</sup></p> | <p>CHS displacement must be equal to or greater than the 90th percentile isolation system displacement under EDB loading.<br/><br/>Moat or hard stop designed to survive impact forces associated with 95th percentile EDB isolation system displacement.<sup>7</sup> Limited damage to the moat or hard stop is acceptable but the moat or hard stop must perform its intended function.</p> |

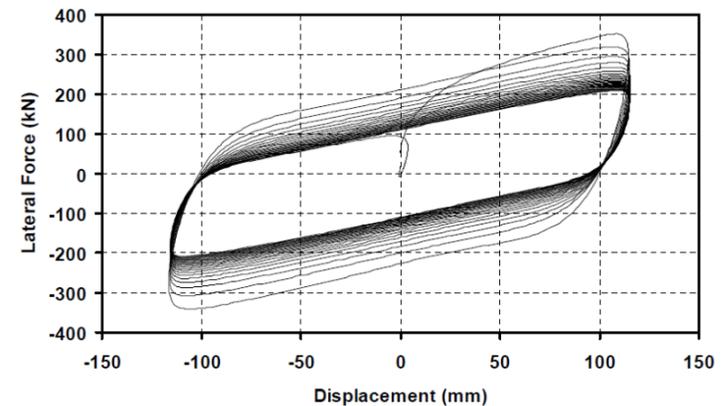
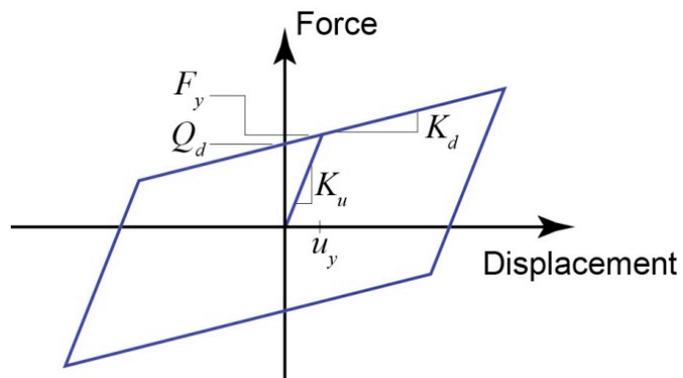
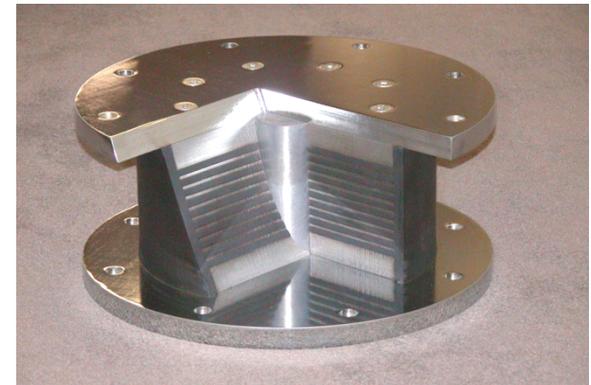
1. Analysis and design of safety-related components and systems should conform to NUREG-0800, as in a conventional nuclear structure.
2. 10CFR50 Appendix S requires the use of an appropriate free-field spectrum with a peak ground acceleration of no less than 0.10g at the foundation level. RG1.60 spectral 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

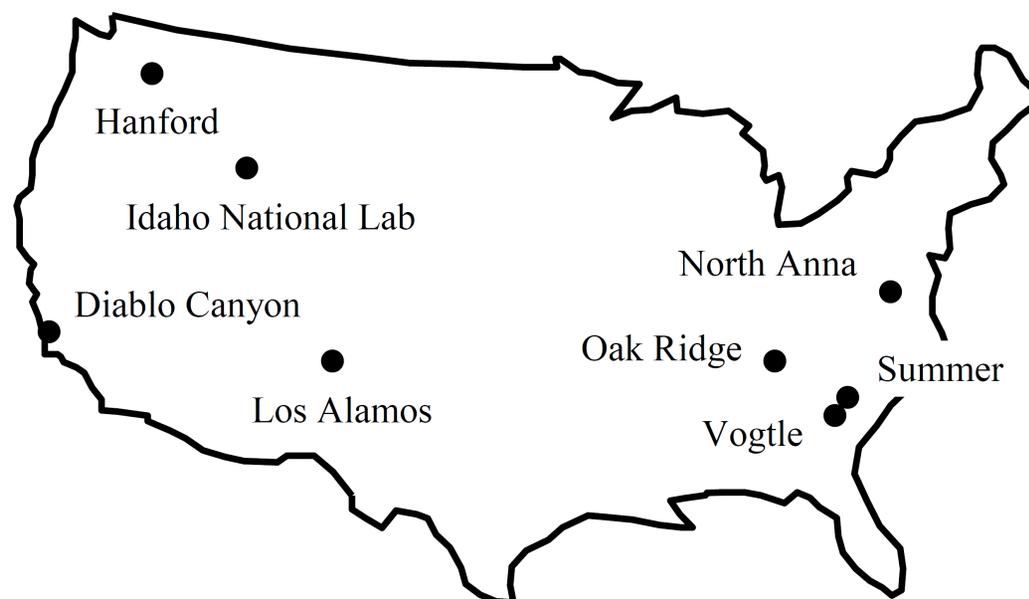
- Procedures and rules for
  - Low damping natural rubber
  - Lead-rubber
  - Friction Pendulum type
- Stable, predictable hysteresis



# 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](http://opensees.berkeley.edu/wiki/index.php/ElastomericX)
  - Lead rubber bearing  
[opensees.berkeley.edu/wiki/index.php/LeadRubberX](http://opensees.berkeley.edu/wiki/index.php/LeadRubberX)
  - High damping rubber bearing  
[opensees.berkeley.edu/wiki/index.php/HDR](http://opensees.berkeley.edu/wiki/index.php/HDR)

# 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 <sup>1</sup> | 0.12       | 0.22   | 0.20   | 0.21      | 0.25    | 0.14  | 0.36       | 0.83          |
|            | UHRS2 <sup>2</sup> | 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          |

<sup>1</sup>UHRS with an MAFE of  $10^{-4}$

<sup>2</sup>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)**

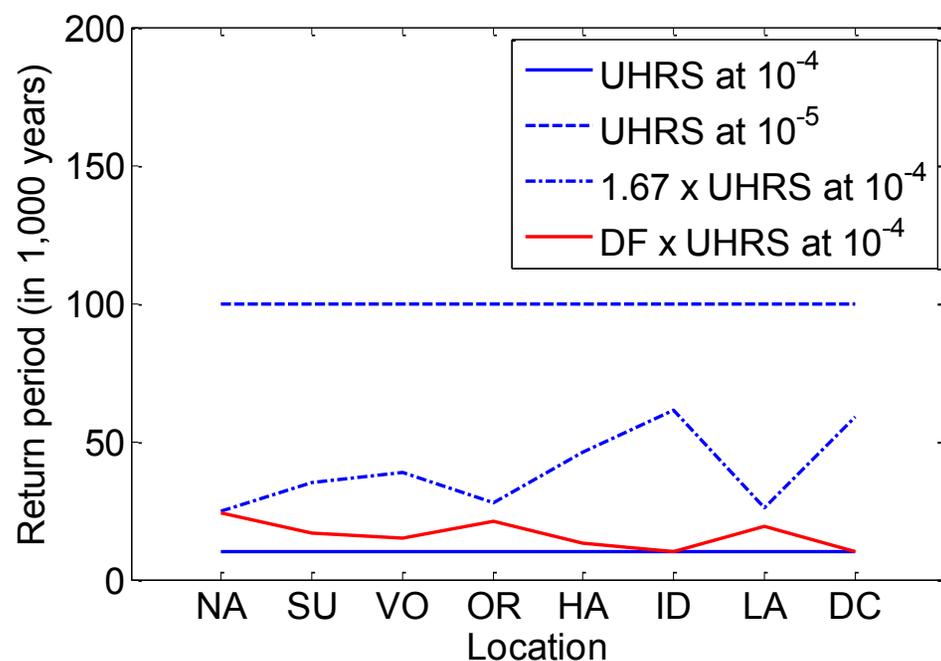
| Period (s) | Hazard definition  | Site       |        |        |           |         |       |            |               |
|------------|--------------------|------------|--------|--------|-----------|---------|-------|------------|---------------|
|            |                    | North Anna | Summer | Vogtle | Oak Ridge | Hanford | Idaho | Los Alamos | Diablo Canyon |
| 1          | UHRS1 <sup>1</sup> | 10         | 10     | 10     | 10        | 10      | 10    | 10         | 10            |
|            | UHRS2 <sup>2</sup> | 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            |

<sup>1</sup>UHRS with an MAFE of  $10^{-4}$

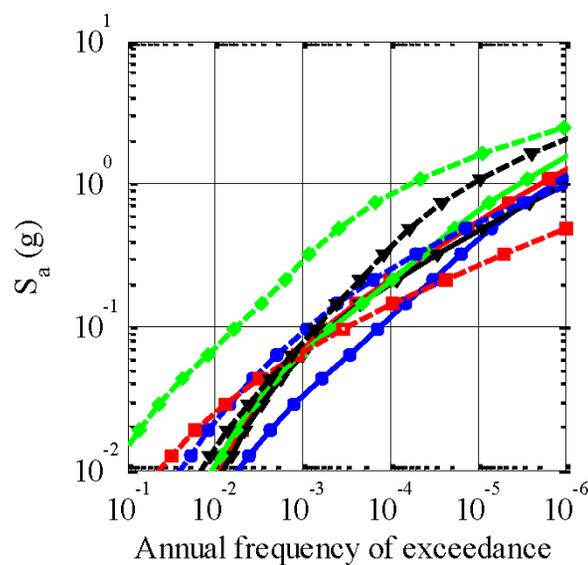
<sup>2</sup>UHRS with an MAFE of  $10^{-5}$

# Sites of nuclear facilities in the US

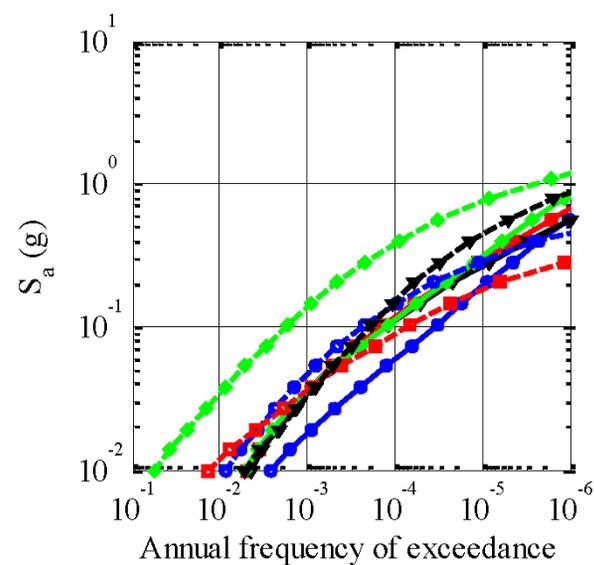
- Return periods for  $S_a$  at 1 s



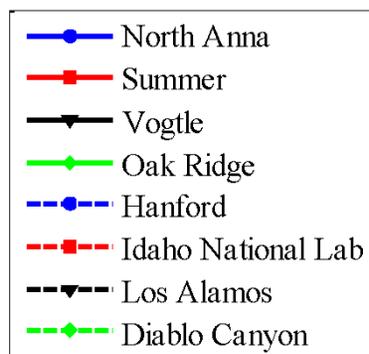
# Seismic hazard curves



(c) Period = 1 s

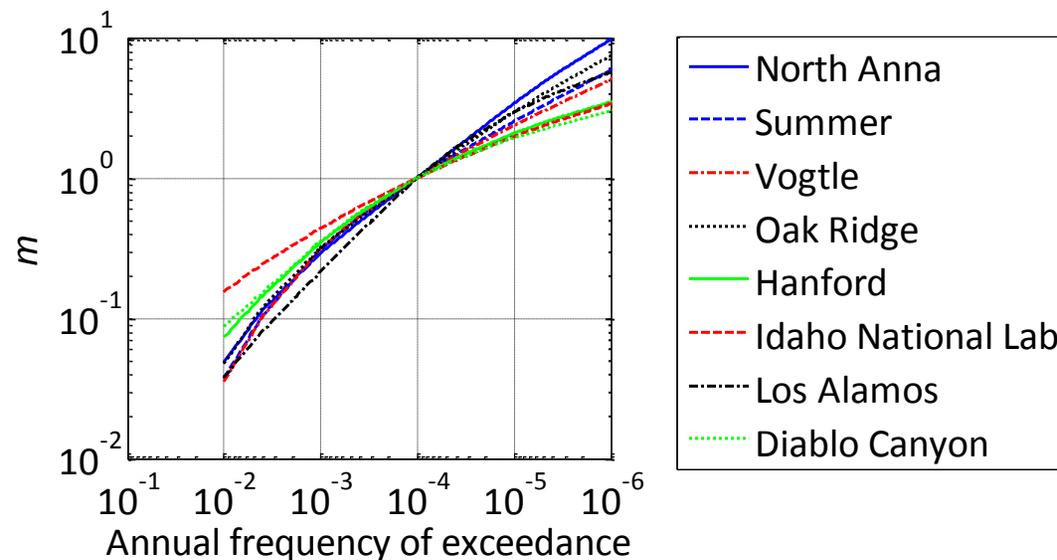


(d) Period = 2 s



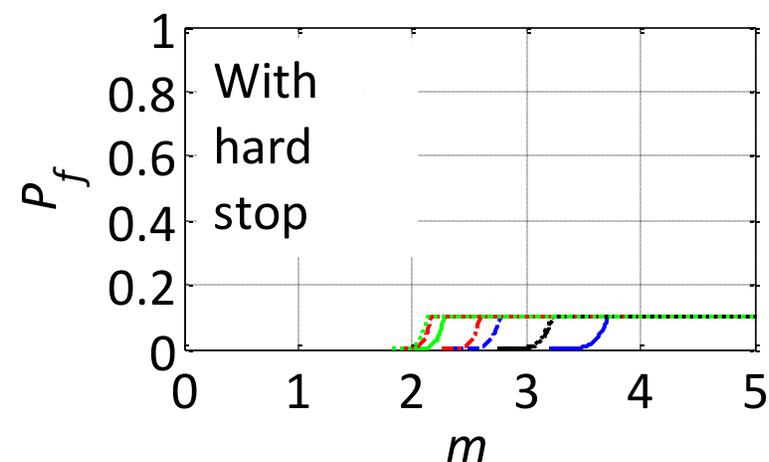
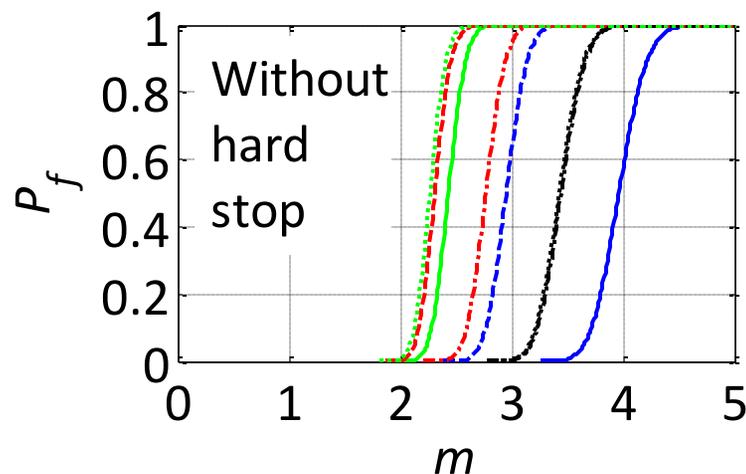
# Seismic hazard curves

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

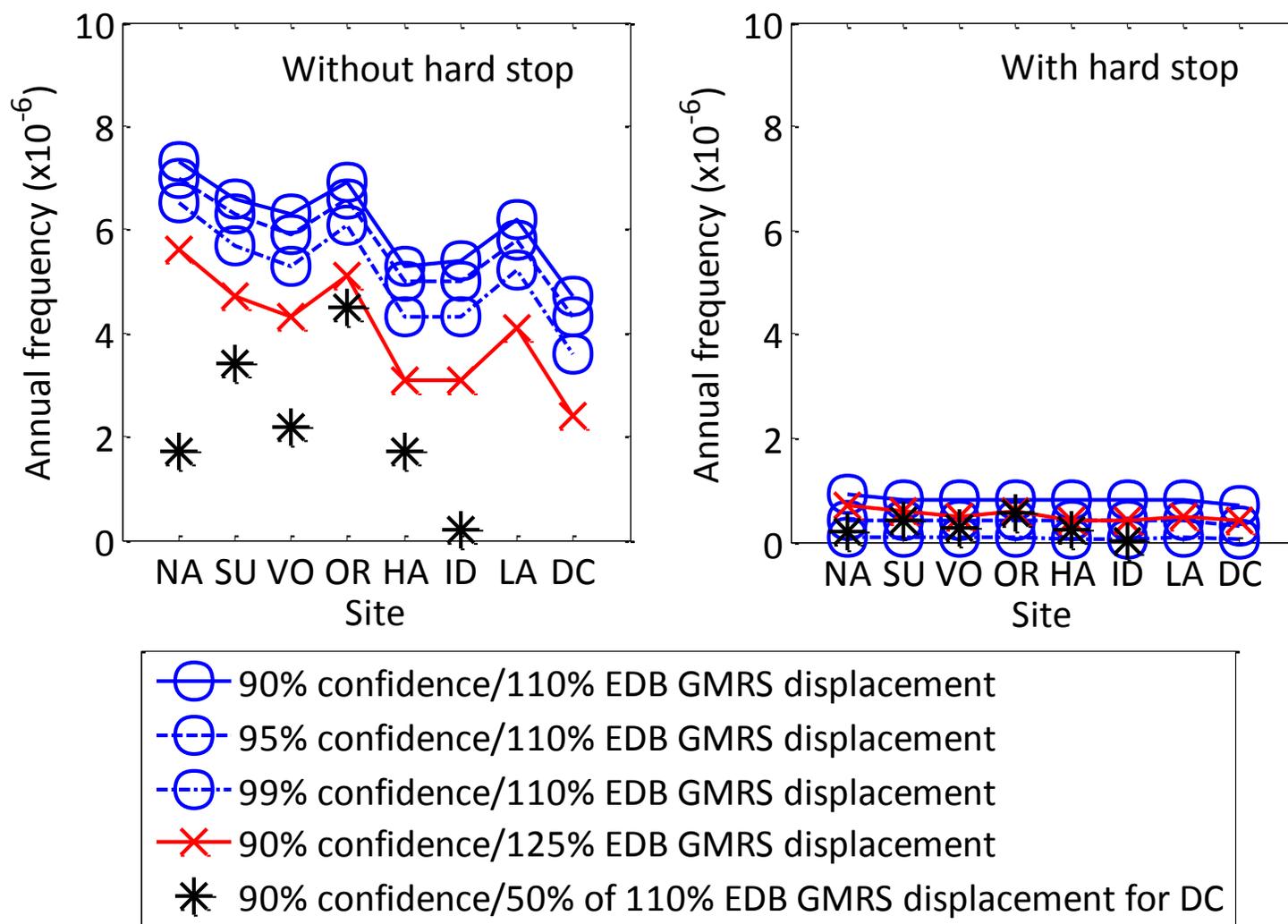


# Median fragility curves: NRC space

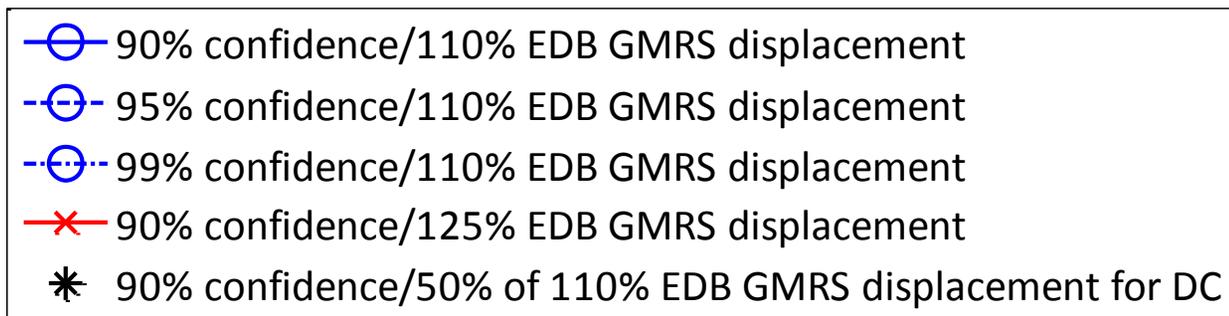
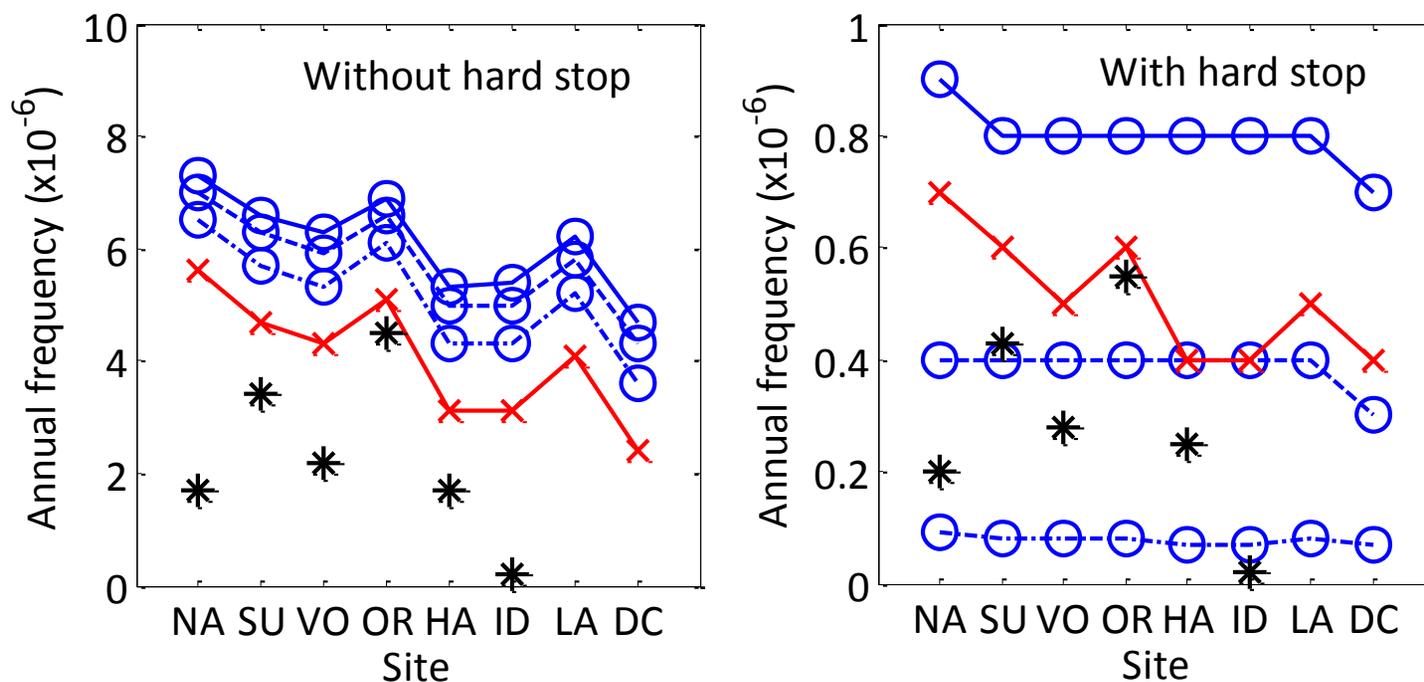
- Isolation system and individual isolators
  - Assumed fully correlated
  - Lognormal distribution parameters
  - Variability small for high quality isolators
  - Median 110% EDB GMRS displacement  $\geq 90^{\text{th}}$  percentile EDB GMRS displacement



# Risk calculations: NRC space

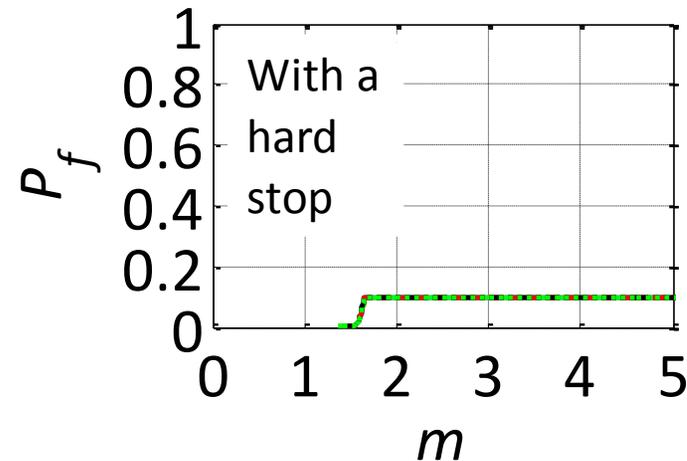
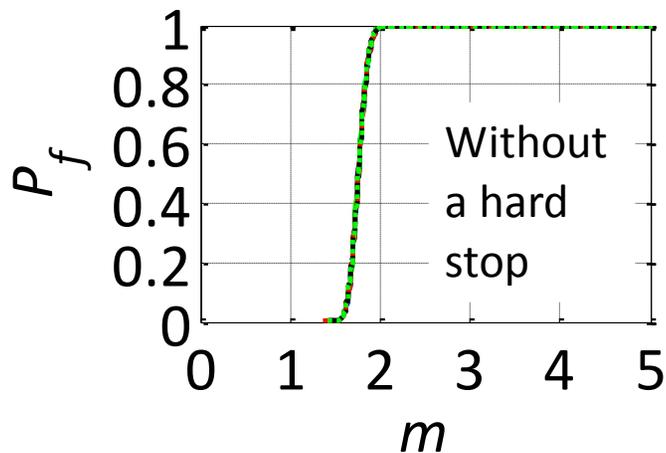


# Risk calculations: NRC space

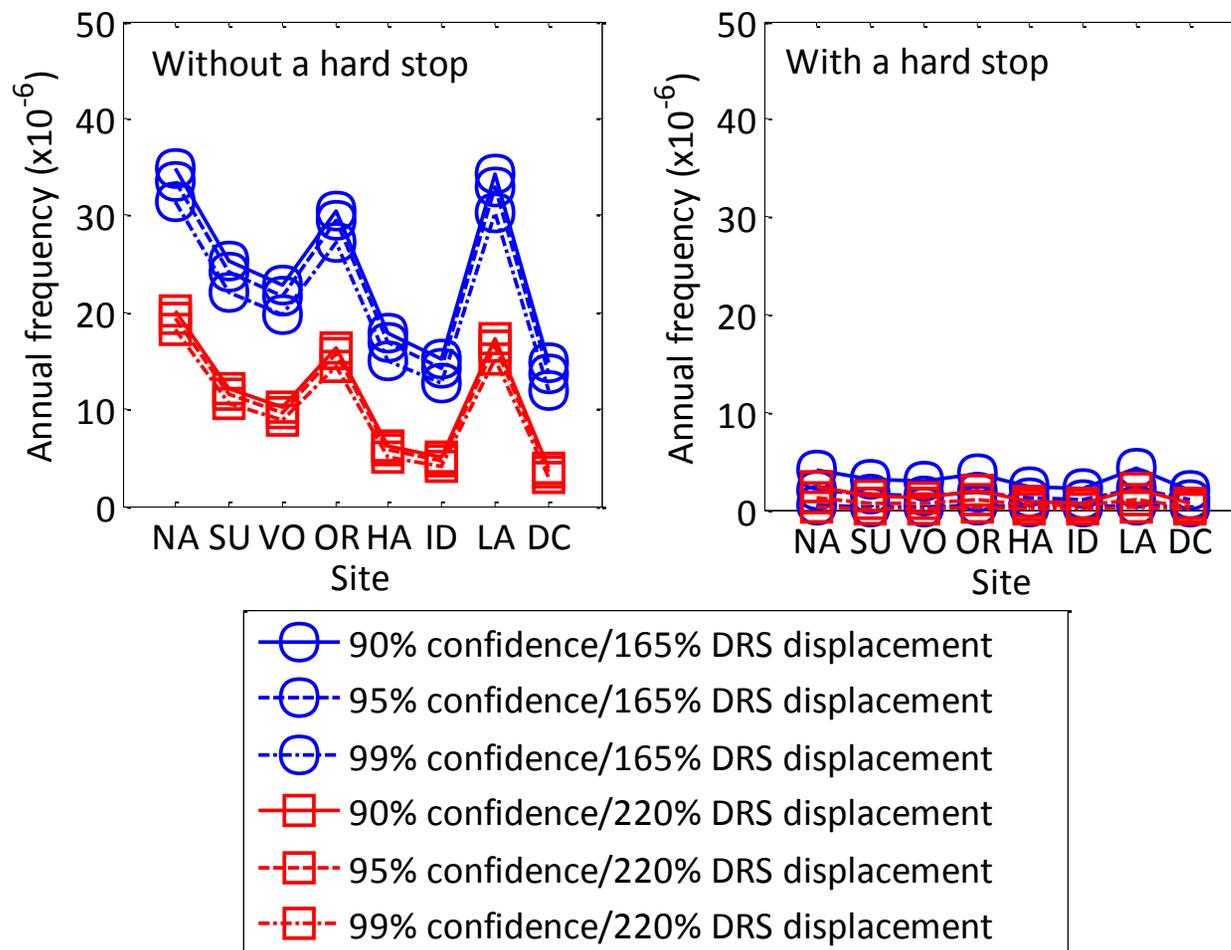


# Median fragility curves: DoE space

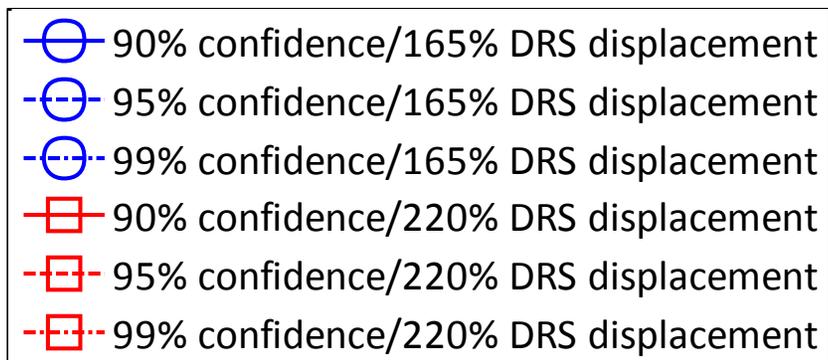
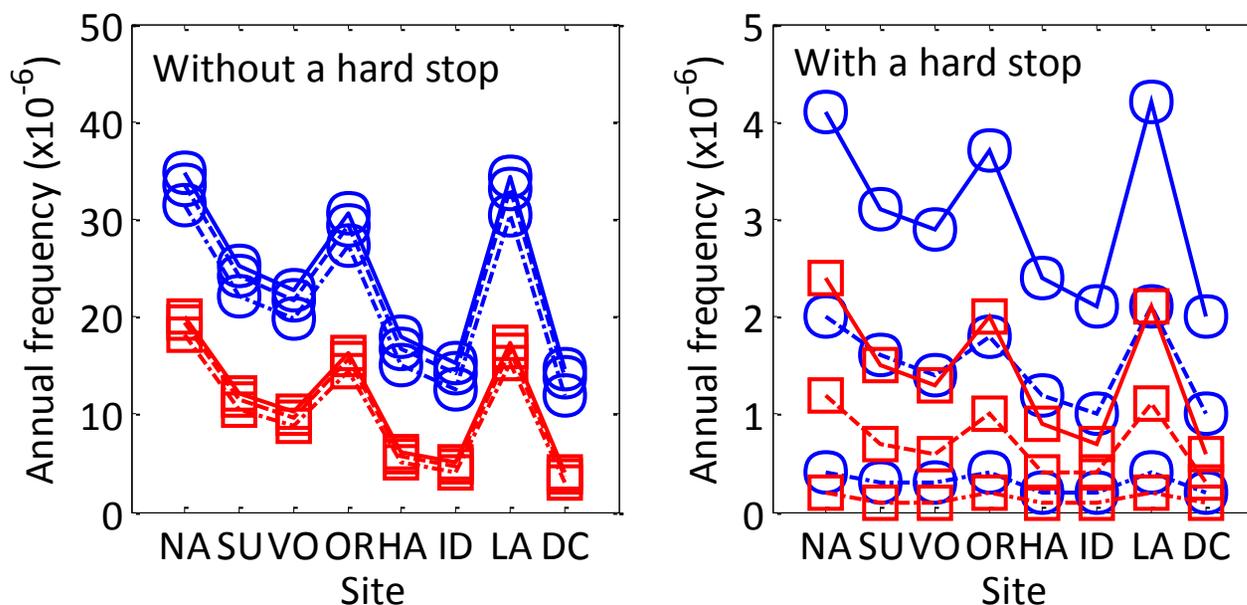
- Isolation system
  - Assumed fully correlated
  - Lognormal distribution parameters
  - Variability small for high quality isolators
  - Median 165% (220%) DRS displacement = 90<sup>th</sup> percentile 150% (200%) DRS displacement



# 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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# Acknowledgments

- Manish Kumar<sup>2</sup>
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