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Guidelines for the seismic isolation of advanced reactors: topical report

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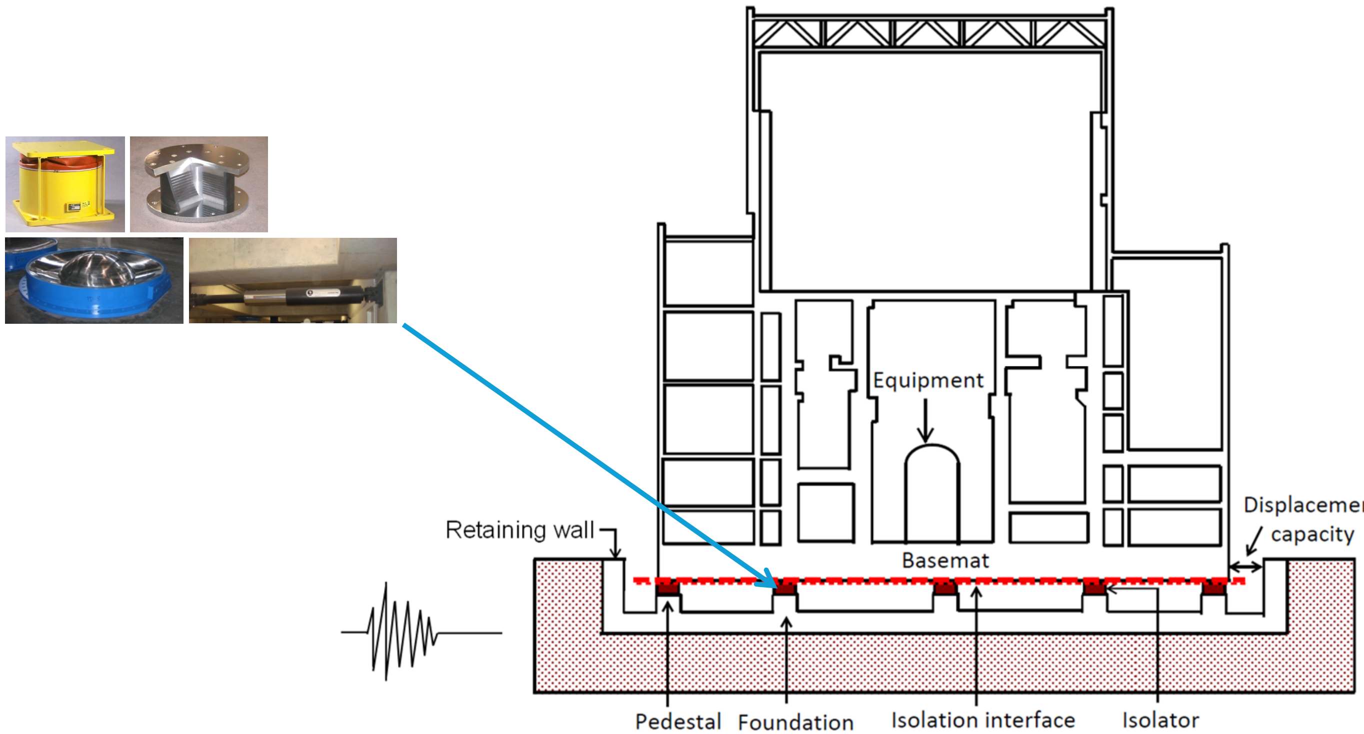
Project background

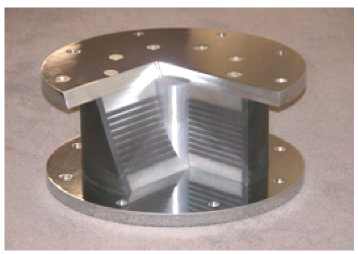
- Effort selected for cost-shared funding in 2020 by DOE through Funding Opportunity DE-FOA-0001817, "US Industry Opportunities for Advanced Nuclear Technology Development"
- Builds upon decades of non-nuclear seismic isolation experience and efforts to develop standards for use in nuclear industry
- Modeled an archetype advanced reactor building, equipment, and site on which to demonstrate a pathway for performance-based design of a seismic isolation system
- Requesting NRC endorsement of the pathway via a Topical Report
- Developed plans for commercial grade dedication and dynamic testing as well as example specifications for isolator procurement
- Regular engagement with NRC and industry to validate direction and incorporate feedback to promote/maximize usefulness of pathway

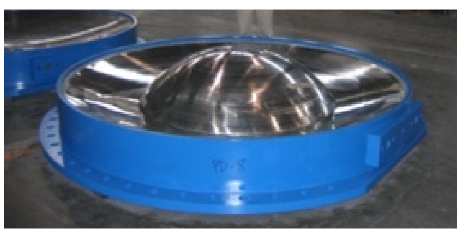
Some terminology

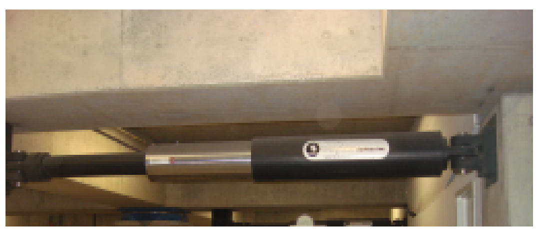


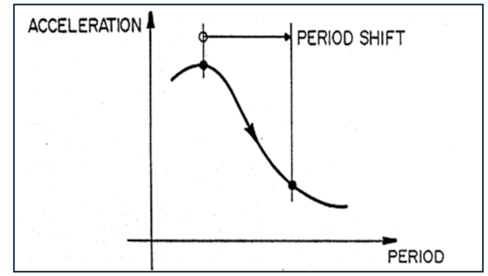
Seismic isolation

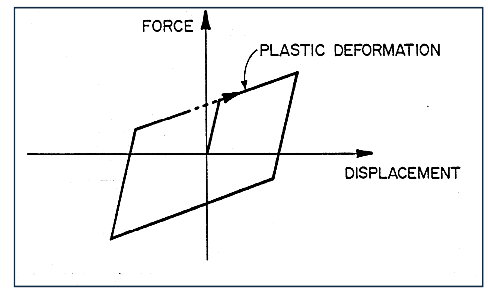
- 2D horizontal or 3D
  - Nearly all 10,000+ applications 2D horizontal

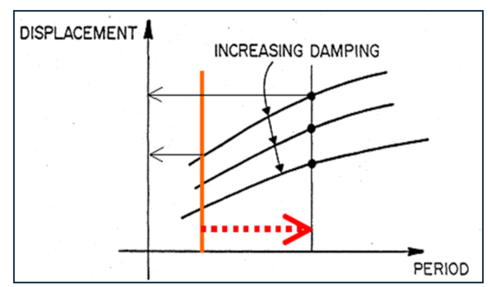






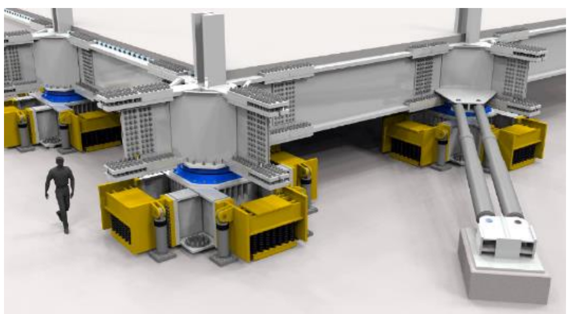




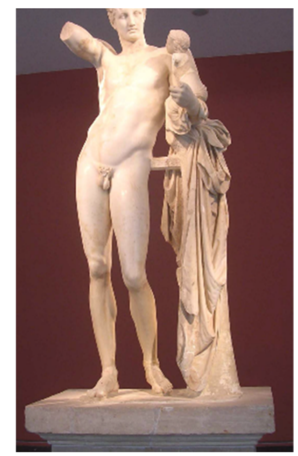


Seismic isolation

- Isolated LLWRs: Cruas and Koeberg
  - Synthetic rubber bearings
  - 2D horizontal isolation



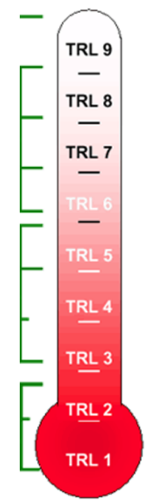
Arup, 2020



Technical basis, USNRC- and DOE-funded

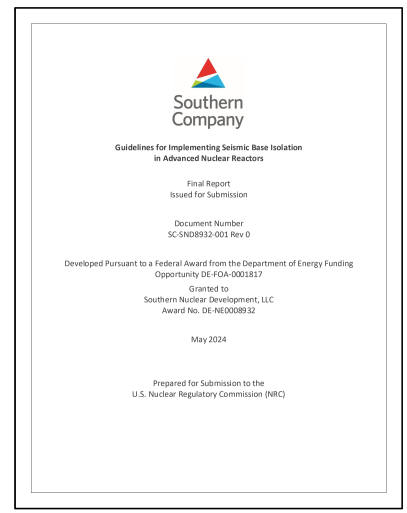
- USNRC (2008-2017): Seismic isolation of large light water reactors
- DOE (2014-2016): Seismic isolation of components in advanced nuclear reactors
- DOE (2016-2018): Evaluation of the potential effect of seismic risk at DOE facilities
- DOE (2017-2019): Seismic isolation of advanced reactors with considerations of fluid structure interaction
- DOE (2018-2020): Seismic isolation of major advanced reactor systems for economic improvement and safety assurance
- EPRI (2018-2019): Cost basis for utilizing seismic isolation for nuclear power plant design
- ARPA-E (2018-2021): Reducing the overnight capital cost of advanced reactors using equipment-based seismic protective systems
- DOE via Southern Company (2021-2024): Topical report on seismic isolation of advanced reactors
- DOE ARDP via MIT (2021-2024): Horizontally configured high-temperature gas reactor
- DOE NEUP (2022-2025): Gamma irradiation effects on the mechanical properties of seismic protective devices

Technology readiness: seismic isolation



Seismic isolation topical report

- Develops a reactor-agnostic pathway for applicants to develop, document and qualify a seismic isolation system for an advanced reactor by including
  - Seismic isolation systems: technology, use, guidelines
  - Earthquake shaking definitions, performance expectations
  - Archetype reactor building, equipment, siting
  - Risk-based design of a seismic isolation system
  - Qualification, prototype, and production testing
  - Specifications for supply of isolators and dampers
  - Commercial grade dedication
  - Generating a displacement demand curve
  - Achieving a risk target, including derivation of fragility functions
  - Selecting a target performance goal: how to start?
  - Isolation-system options: judging different systems



Southern Company

Guidelines for Implementing Seismic Base Isolation in Advanced Nuclear Reactors

Final Report
Issued for Submission

Document Number
SC-SND8932-001 Rev 0

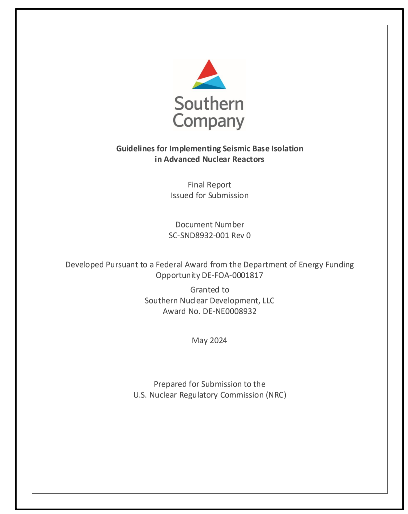
Developed Pursuant to a Federal Award from the Department of Energy Funding Opportunity DE-FOA-0001817
Granted to
Southern Nuclear Development, LLC
Award No. DE-NE0008932

May 2024

Prepared for Submission to the
U.S. Nuclear Regulatory Commission (NRC)

Seismic isolation topical report

- Front matter
  - Cradle to grave guidance
  - Passive isolation systems only
    - No semi-active or active systems, why?
  - Which one: risk-based, risk-informed, or performance based?
  - Applicability
    - Microreactors, advanced reactors/SMRs, large light water reactors
  - Seismic isolation checklist
  - Role of isolation in defense-in-depth
    - Additional echelon of defense via reduced seismic demands
    - Superior quality, passive, predictable performance (how?)
    - Does not change the need to confirm adequate DiD



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Seismic isolation checklist

- Establish a target performance goal (TPG) for the seismic isolation system
- Generate seismic hazard curves, uniform hazard response spectra, and ground-motion time series
- Establish an isolation-system-specific seismic displacement demand curve
- Determine the median displacement capacity of the isolation system required to achieve the TPG
- Establish DB earthquake shaking for the isolation system
- Compute displacements, velocities, and forces for prototype and production testing
- Compute earthquake-induced demands on the superstructure and substructure
- Prepare specifications for supply of isolators and dampers
- Prepare specifications for prototype and production testing of isolators and dampers
- Prepare a plan for commercial grade dedication of isolators and dampers
- Prepare requirements for maintenance, operation, and testing of isolators and dampers

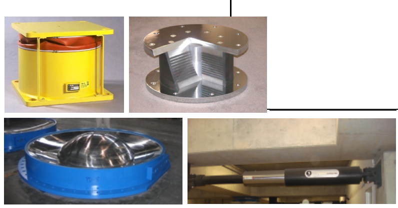
❖ SSCs above the isolation interface treated per industry practice

Requested NRC review and possible endorsement via a SER

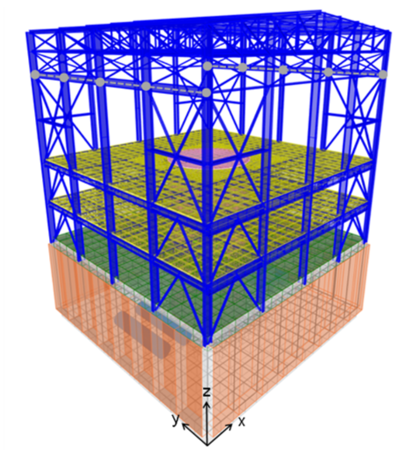
- Role of seismic isolation solutions in ensuring adequate defense-in-depth
- Earthquake shaking definitions for isolation-system design
- Performance expectations for the seismic isolation system
- General requirements for isolation-system design
- Requirements for seismic inputs to support performance calculations
- Methods of dynamic analysis, and numerical models for isolators and dampers
- Requirements for design of connections for isolators and dampers; isolation-system substructure; structures, systems, and components above the seismic isolation interface; systems and components crossing the seismic isolation interface; and clearance around the isolated building
- Performance-based design of a seismic isolation system
- Minimum standards for qualification, prototype, and production testing of isolators and dampers
- Specifications for supply of isolators and dampers
- Plan for commercial grade dedication of isolators and dampers
- Process to establish a log standard deviation for the fragility function of a seismic isolation system

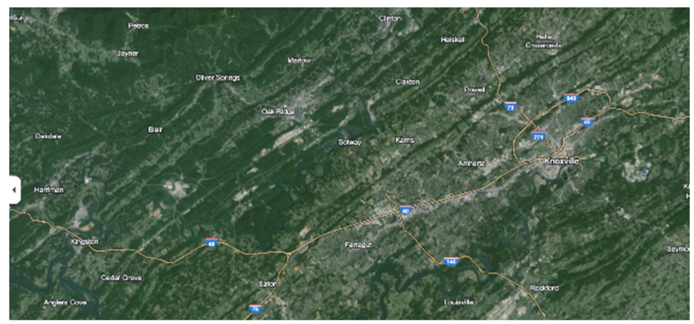
Performance expectations for isolators and dampers

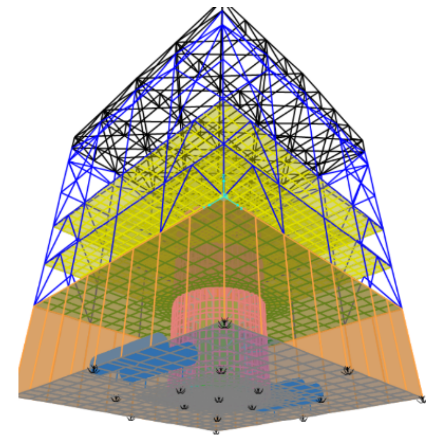
	DB shaking	@TPG
Use	Production testing of isolators and dampers	Prototype testing of isolators and dampers
Isolator and damper displacement	Mean maximum	D_{50} from fragility analysis
Damper velocity	Mean maximum	Mean maximum from TPG shaking
Acceptance criteria	Production testing of each isolator for mean maximum horizontal displacement and corresponding axial force	Prototype testing of three isolators of each type and size for D_{50} displacement and TPG axial force
	Production testing of each damper for mean maximum displacement and corresponding maximum velocity	Prototype testing of three dampers of each type and size for D_{50} displacement and TPG velocity
	No damage to isolators	Isolator damage is acceptable but load-carrying capacity for gravity loading is maintained
	No damage to dampers	No damage to dampers

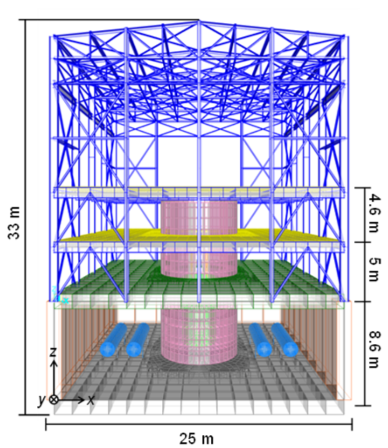


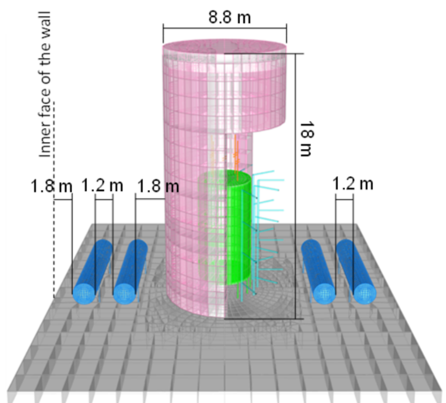
Archetype reactor building, equipment, siting, SDC4

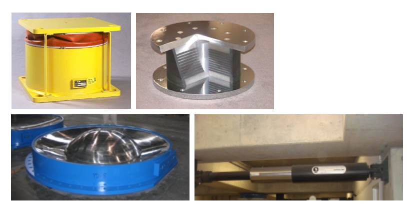


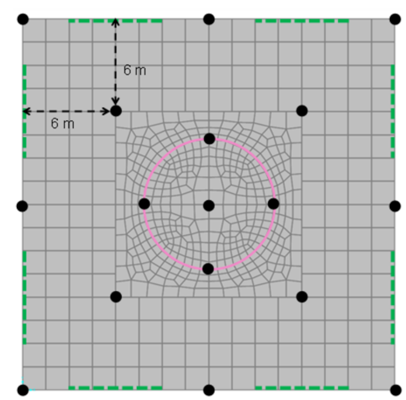




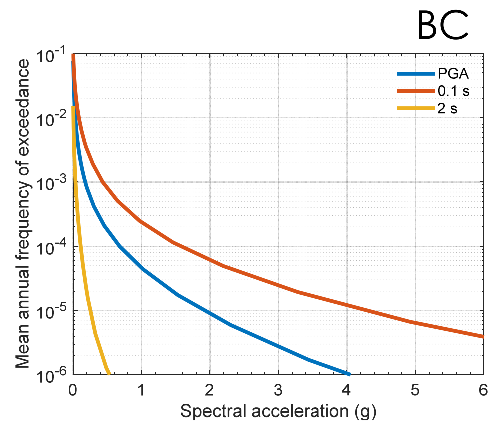


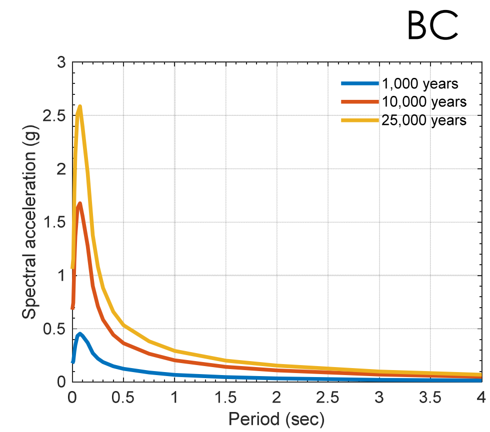


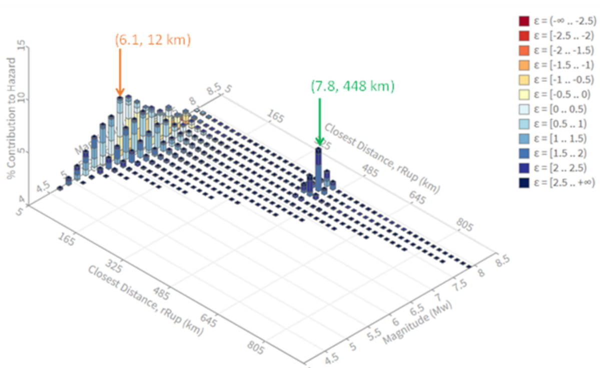


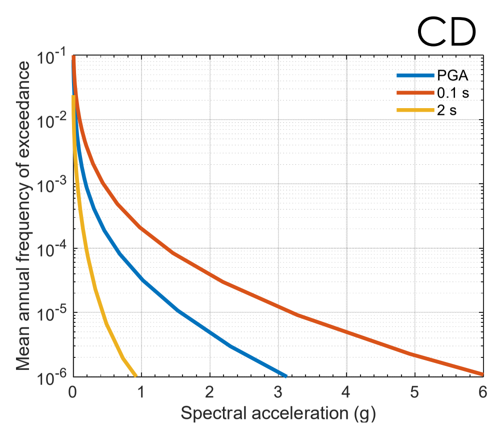


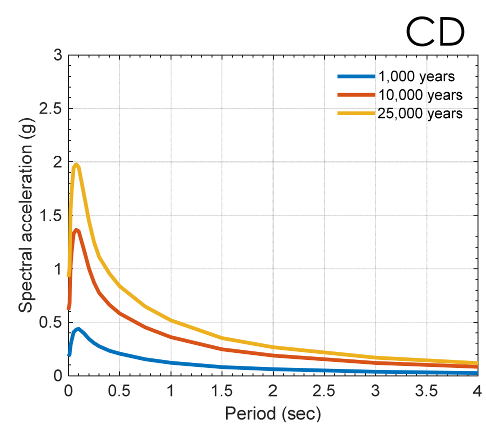
Performance-based design of a seismic isolation system











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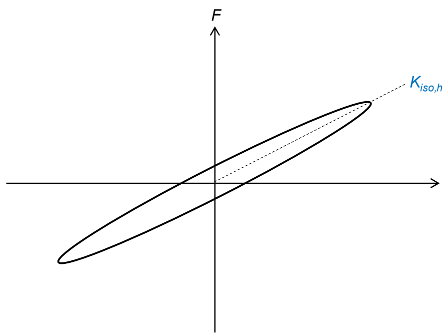
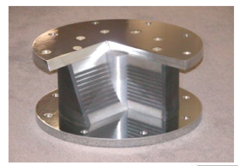
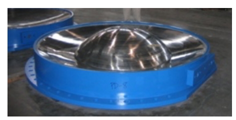
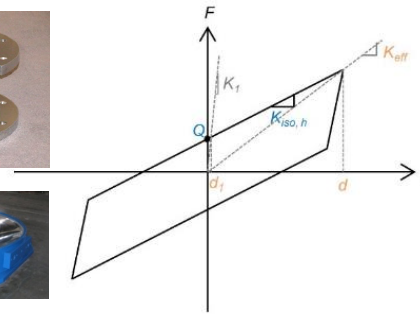
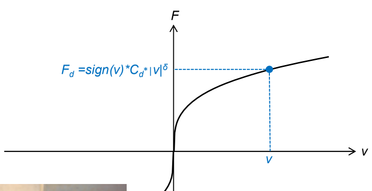
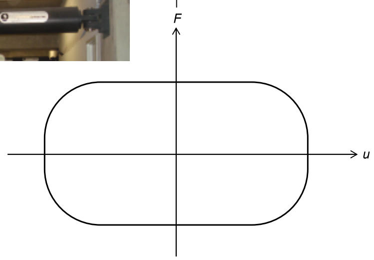


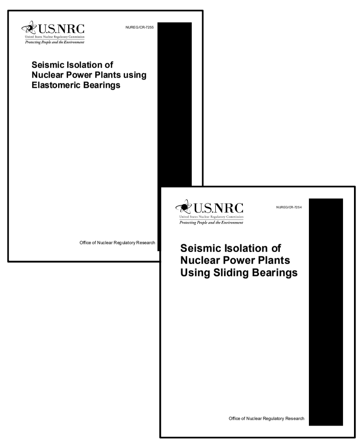


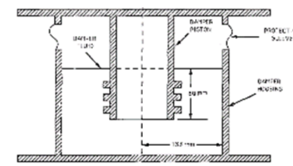


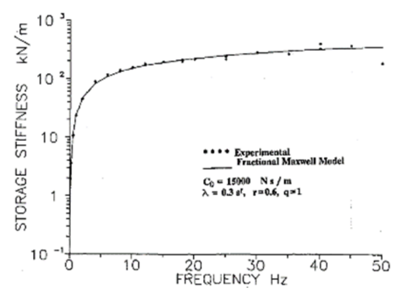


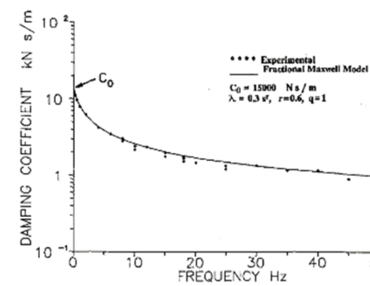






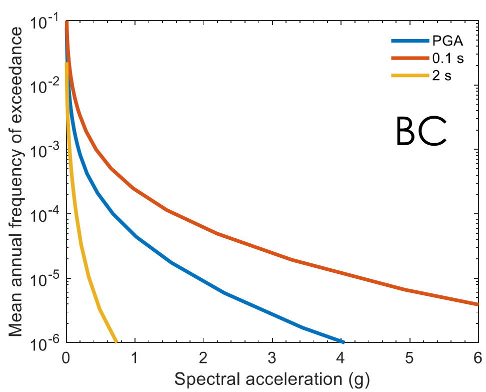


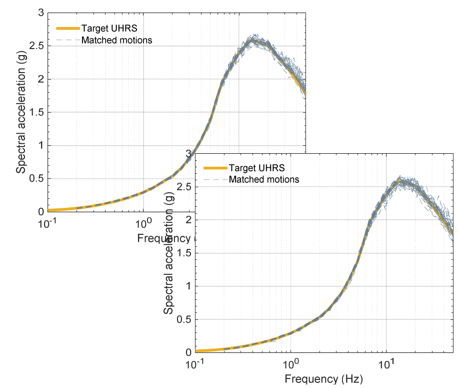


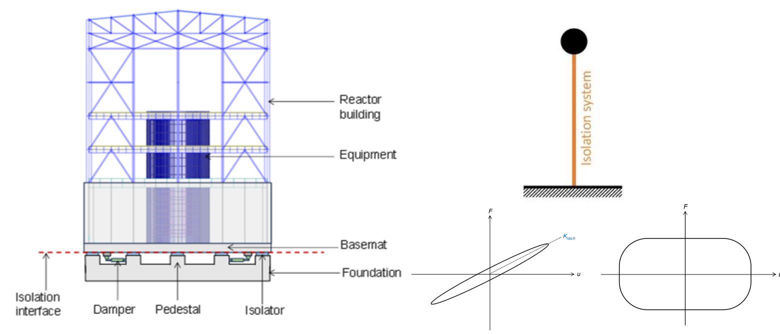


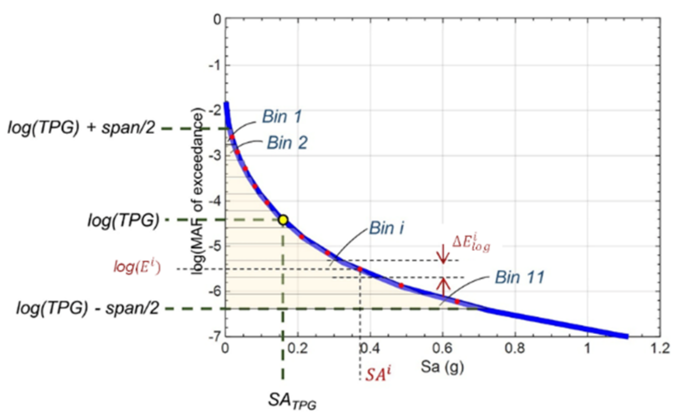
Makris and Constantinou, 1992
Parsi et al., 2024

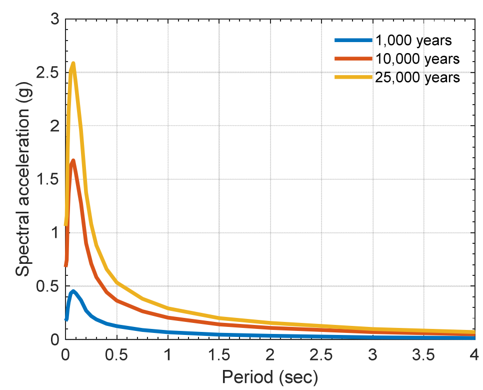
Generating a displacement demand curve

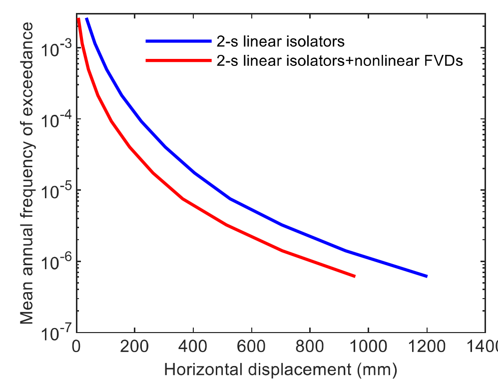






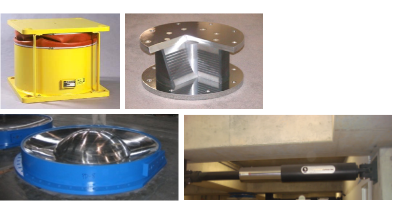






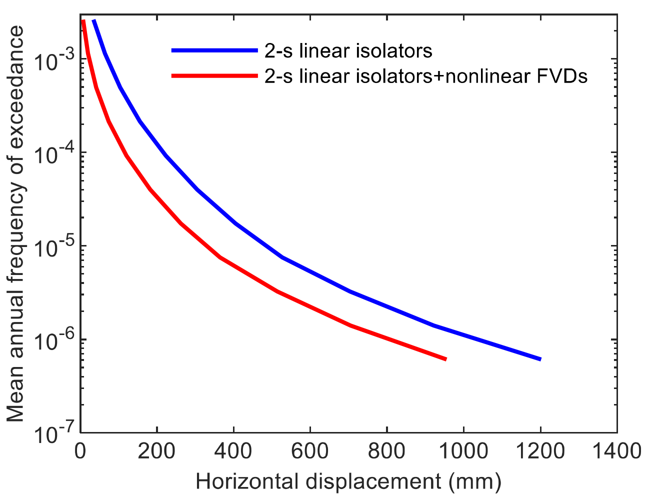
Deriving an isolation system fragility function

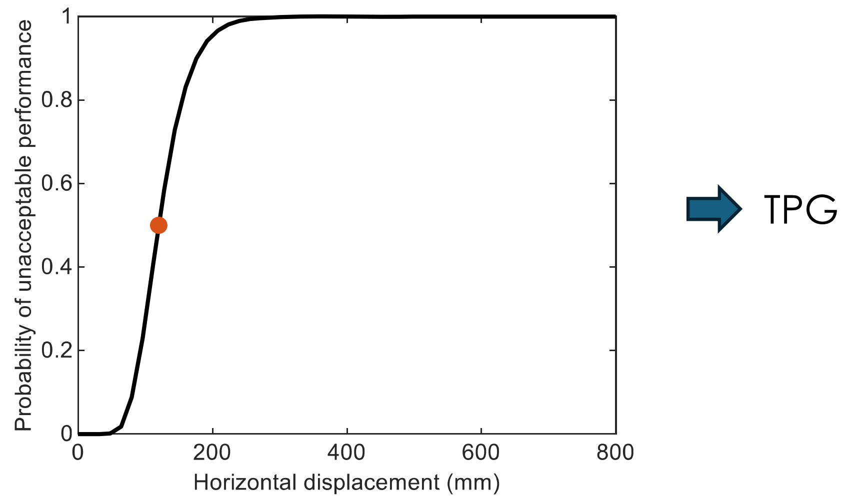
- Isolation-system fragility function
  - Defined by a median capacity (D50) and a log standard deviation, beta
    - Median capacity underestimated by testing, why?
  - Beta addresses uncertainties in displacement demand and capacity
    - Parameters per EPRI (2018)
      - Ground motion, modeling, damping, mode contribution, input time series, foundation-structure interaction, strength, inelastic energy absorption
      - Monte Carlo analysis of Huang et al. (2009) for linear and bilinear isolation systems for beta for ground motion and modeling
      - Beta for model fidelity uncertainty per EPRI (2018) = 0.05
    - Composite beta = 0.13 for linear systems, = 0.22 for nonlinear systems



Performance-based design of a seismic isolation system

- Isolation-system fragility function
  - Pre-determined log standard deviation per Appendix D (0.15 to 0.25)
  - Increment D50 to achieve user-specified target performance goal (TPG)

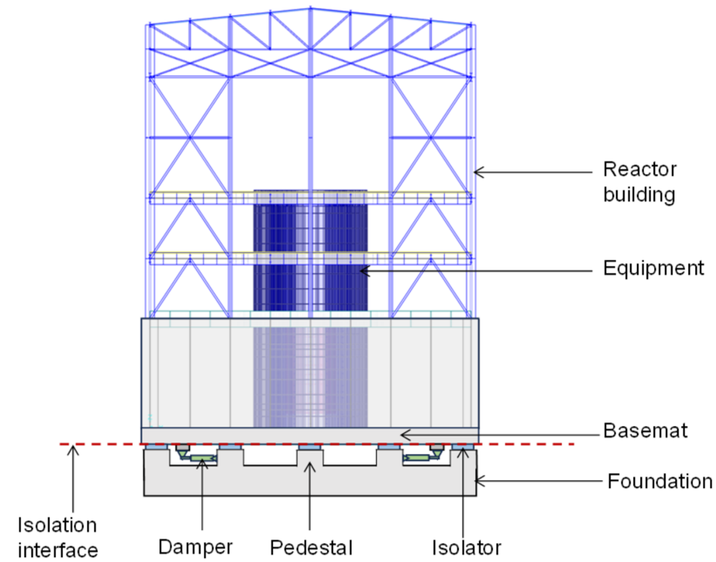


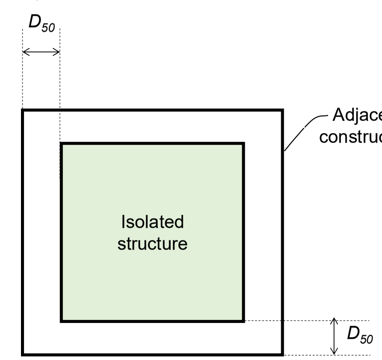


Performance-based design of a seismic isolation system

- Use of displacement F50
  - Prototype testing of isolators and dampers
  - Clearance to adjacent construction
  - Forces at F50 along each horizontal axis + TPG shaking demands
    - Design and detailing of substructure (pedestals, foundation)
    - Design of connections to substructure and superstructure

❖ Analysis and design of SSCs





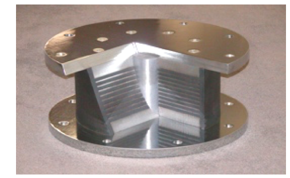
Qualification, prototype, and production testing

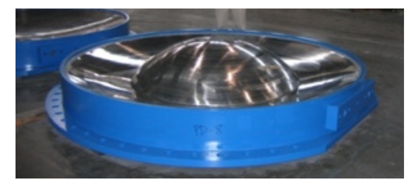
- Requirements based on 35 years of US industry practice
  - ASCE 7, ASCE 41, AASHTO, applications to mission-critical structures
  - Nuclear applications no less onerous requirements than non-nuclear
- Qualification testing
  - Project independent, to be executed before being considered for a nuclear energy application
  - Dynamic testing of devices and shake-table testing of systems of devices
  - Verified and validated numerical models
  - Demonstrate that change in mechanical properties less than (+20%, -20%) over design life
    - Obliges prior experience and testing of technology, accelerated aging tests not permitted
  - Prior deployment in non-nuclear, mission-critical applications in the US, moderate to high seismic hazard
- Prototype testing
  - Project specific, requirements for all isolators and dampers addressed in the topical, full size
  - Test three of each type and size of isolator and damper (rationalize number of types)
  - Demonstrate that isolators and dampers can sustain demands consistent with the TPG
  - Dynamic per loading environment
- Production testing
  - Project specific, requirements for all isolators and dampers addressed in the topical
  - Test 100% of isolators and dampers prior to shipment to construction site
  - Demonstrate that isolators and dampers can sustain demands consistent with DBE shaking
  - Dynamic or slow speed, depending on device; dampers tested dynamically

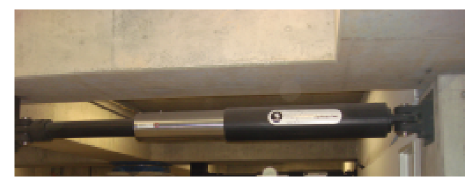
	DB shaking	@TPG
Use	Production testing of isolators and dampers	Prototype testing of isolators and dampers
Isolator and damper displacement	Mean maximum	D_{50} from fragility analysis
Damper velocity	Mean maximum	Mean maximum from TPG shaking
Acceptance criteria	Production testing of each isolator for mean maximum horizontal displacement and corresponding axial force	Prototype testing of three isolators of each type and size for D_{50} displacement and TPG axial force
	Production testing of each damper for mean maximum displacement and corresponding maximum velocity	Prototype testing of three dampers of each type and size for D_{50} displacement and TPG velocity
	No damage to isolators	Isolator damage is acceptable but load-carrying capacity for gravity loading is maintained
	No damage to dampers	No damage to dampers

Specifications

- Provides a pathway for both applicants and regulator
- Based on 35 years of US industry practice
  - Low-damping natural rubber bearings
  - Lead-rubber bearings, natural rubber as the base elastomer
  - Spherical sliding bearings (or Friction Pendulum™)
    - Single concave and triple concave
  - 1D fluid viscous dampers
- Generated by best-in-class consultants
  - Deep experience in seismic isolators and dampers
    - Analysis, design, testing, procurement, inspection
- Reviewed by the US suppliers of isolators and dampers

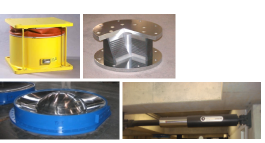






Commercial grade dedication

- Why? The alternative to NQA-1
- CGD undertaken to "…provide reasonable assurance that a commercial grade item to be used as a basic component will perform its intended safety function and, in this respect, is deemed equivalent to an item designed and manufactured under a 10 CFR Part 50, Appendix B…"
- Assurance is achieved by "… identifying the critical characteristics of the item and verifying their acceptability by inspections, tests, or analyses by the purchaser or third-party dedicating entity."
- Draws on EPRI (2014) "Plant engineering: guideline for the acceptance of commercial-grade items In nuclear safety-related applications"
- Chapter 8 plan for CGD
  - Step 6: select acceptance criteria methods and document acceptance criteria
  - Step 7: conduct acceptance activities
    - 100% testing of all production isolators and dampers for DBE demands
      - No other safety-related items in a nuclear power plant are tested so rigorously



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