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United States Nuclear Regulatory Commission
Protecting People and the Environment

Presentations for February 7, 2019 Public Meeting
Regulatory Improvements for Advanced Reactors

In order of discussion, the meeting included the following topics and presentations

1) NRC Slides

2) Preparation for Advanced Reactors Environmental Reviews
Jack Cushing, NRC

3) Regulatory Interfaces with Advanced Reactor Civil/Structural Topics Jason Redd, Southern Company

4) Civil/Structural Engineering Research Updates
J Pires, NRC/RES, J. Xu, NRC/NRO

5) New Plant Cost Reduction and Regulatory Interface
M. Nichols, NEI

6) Design Optimization for Safety and Cost Using MATODON
C. Bolisetti, INL

7) Application of Seismic Protective Systems to Advanced Nuclear Reactors
A. Whittaker, University at Buffalo

8) Development of Generic Seismic Hazard Curves to Support Design Process
M Stutzke, NRC/NRO

United States Nuclear Regulatory Commission

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Public Meeting on Possible Regulatory Process Improvements for Advanced Reactor Designs

February 7, 2019

Telephone Bridge
(888) 793-9929
Passcode: 1039025

Public Meeting

- Telephone Bridge

  (888) 793-9929

  Passcode: 1039025
- Opportunities for public comments and questions at designated times
- *Focus Topic: Civil/Structural Issues*

Outline

- Introductions
- Streamlining Environmental Reviews (NRC, NEI)
- Civil / Structural
  - Regulatory Interfaces (J. Redd, Southern)
  - NRC Research Updates (J. Pires, NRC)

    -Lunch-
  - Civil/Structural Materials (M. Nichols, NEI)
  - Seismic Isolation (A. Whittaker, UB & C. Bolisetti, INL)
  - Generic Seismic Hazard Curves (M. Stutzke, NRC)
  - NRC Lessons Learned, Open Discussion
- Status Update, Future Meetings

Environmental Reviews

- Preparation for Advanced Reactors Environmental Reviews

  Jack Cushing, NRC

  Kati Austgen, NEI

Break

Meeting/Webinar will begin shortly

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Seismic Isolation

- Regulatory Interfaces with Advanced Reactor Civil/Structural Topics

  Jason Redd, Southern Company
- Civil/Structural Engineering Research Updates

  J Pires, NRC/RES

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Lunch

Meeting/Webinar will begin at 1:00pm

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Advanced Reactor Program

Civil / Structural Issues

- New Plant Cost Reduction and Regulatory Interface

  M. Nichols, NEI

- Application of Seismic Protective Systems to Advanced Nuclear Reactors
- Design Optimization for Safety and Cost Using MATODON

  A. Whittaker, UB & C. Bolisetti, INL

- Development of Generic Seismic Hazard Curves to Support Design Process

  M Stutzke, NRC/NRO

Civil / Structural Issues
Lessons Learned & Open Discussion

Dynamic Landscape

- Defense Authorization
  - Micro-Reactor Report (DOE)

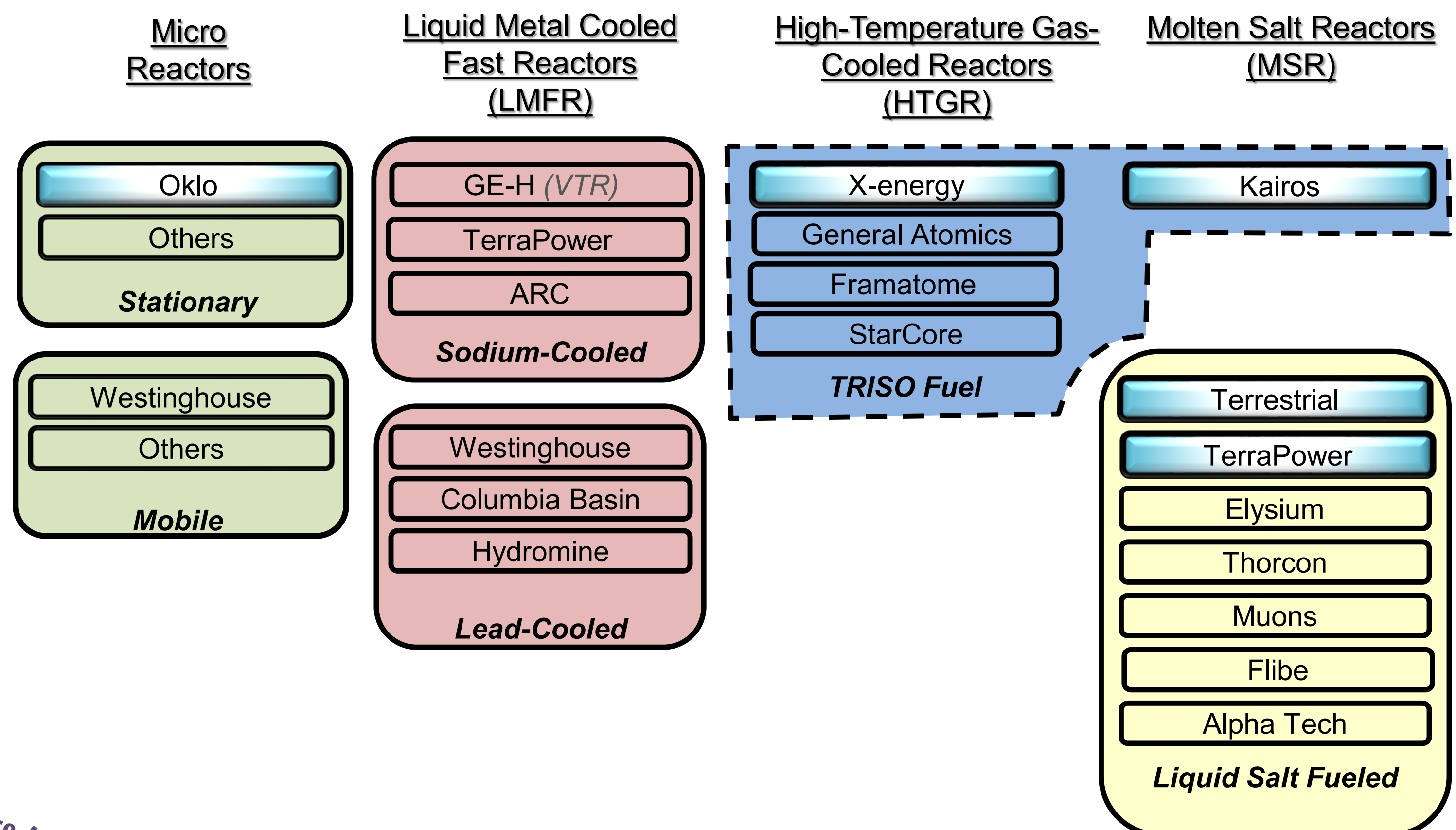
- Nuclear Energy Innovation Capabilities Act
  - Versatile Test Reactor
  - Modeling and Simulation
  - Enabling Nuclear Energy Innovation
  - Licensing Cost-Share Grant Program

- Nuclear Energy Innovation and Modernization Act
  - Staged Licensing
  - Risk Informed Licensing
  - Technology Inclusive Regulatory Framework

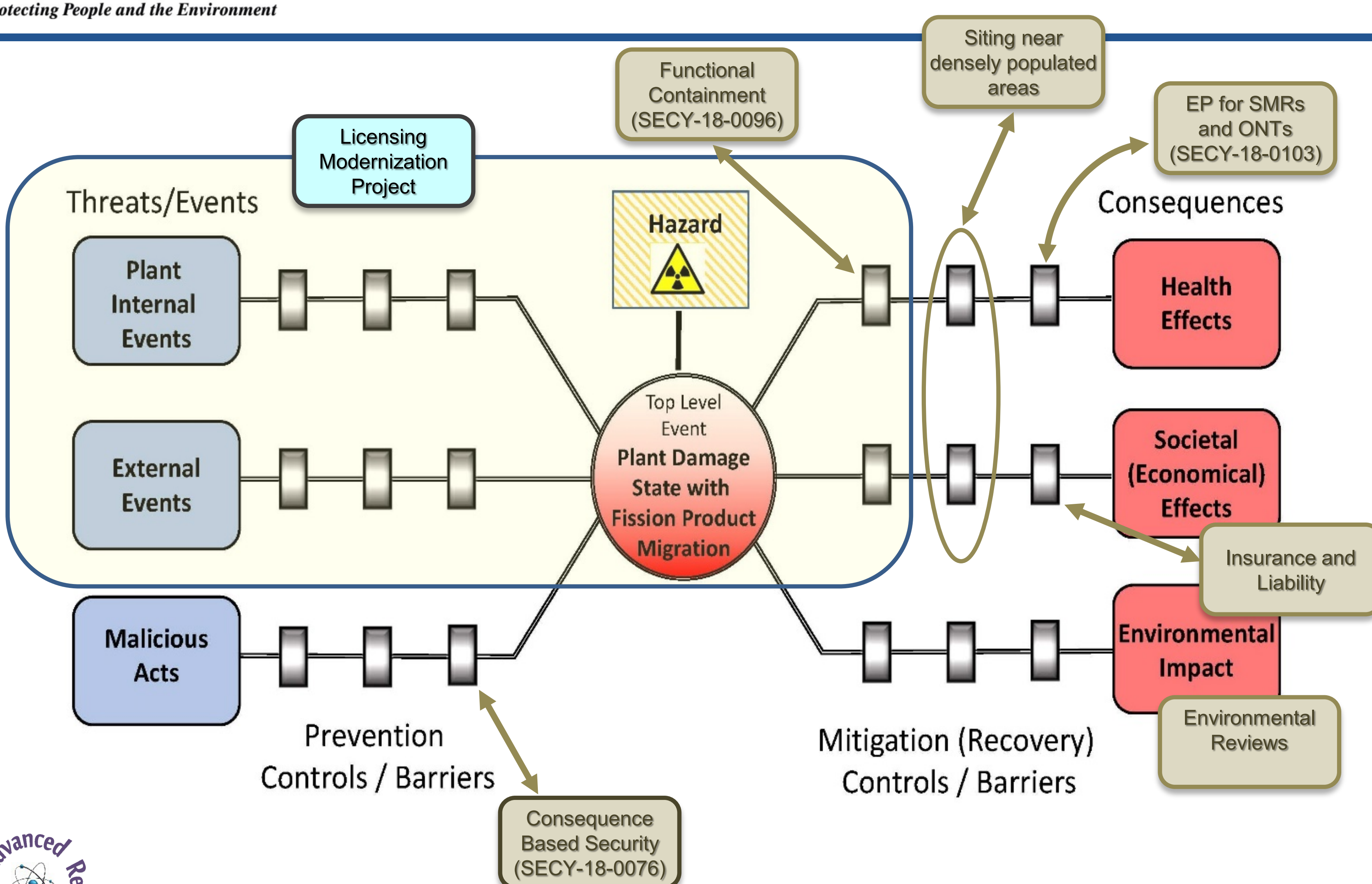
- DOD Strategic Capabilities Office RFI

Dynamic Landscape

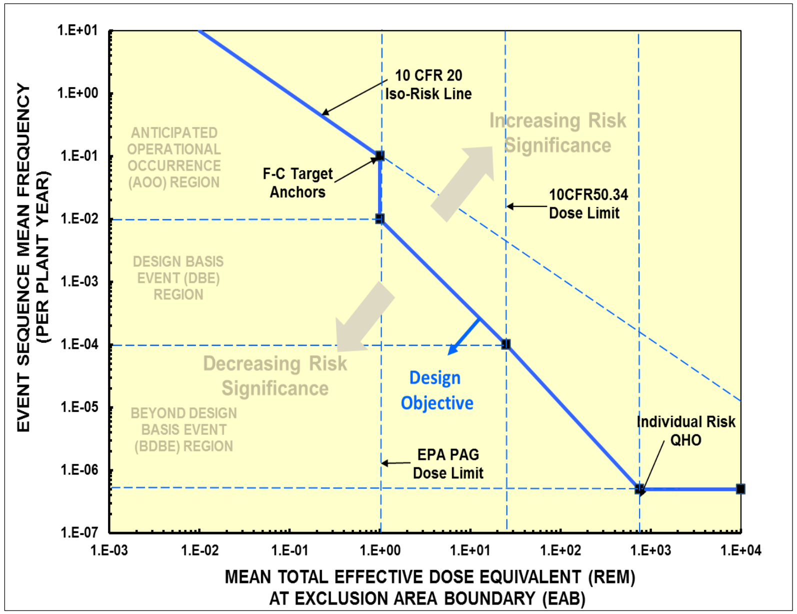
Advanced Reactor Landscape (SECY-19-0009)



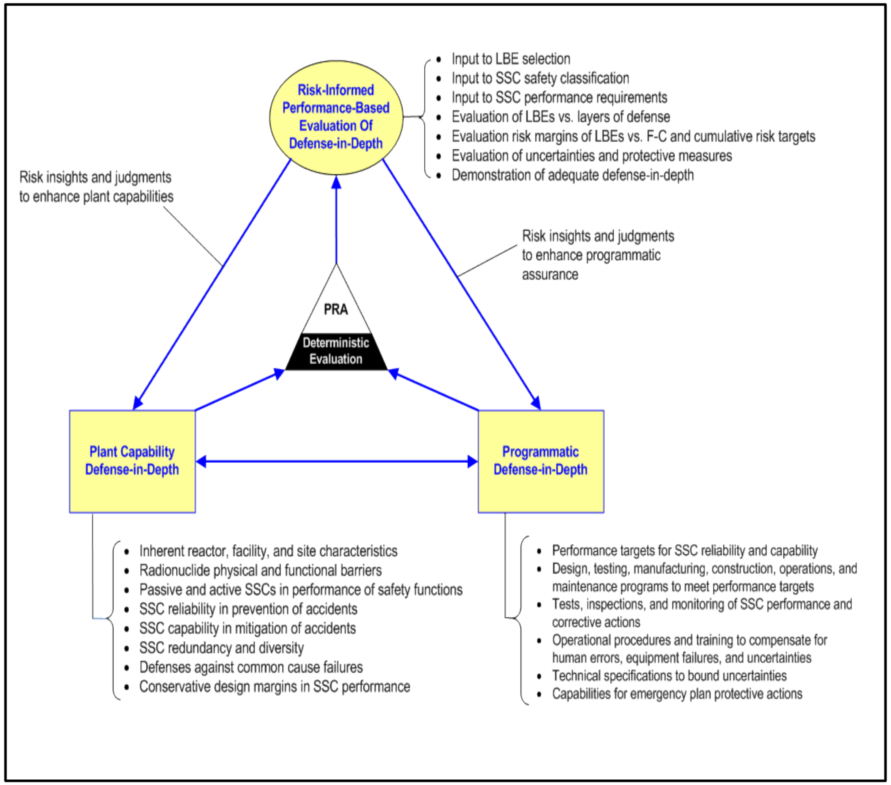
Integrated Design/Review



Licensing Basis Development



Underway: NEI 18-04, DG-1353, & Related SECY Paper



Being Initiated: Content of Applications, Mechanistic Source Term, Other ?

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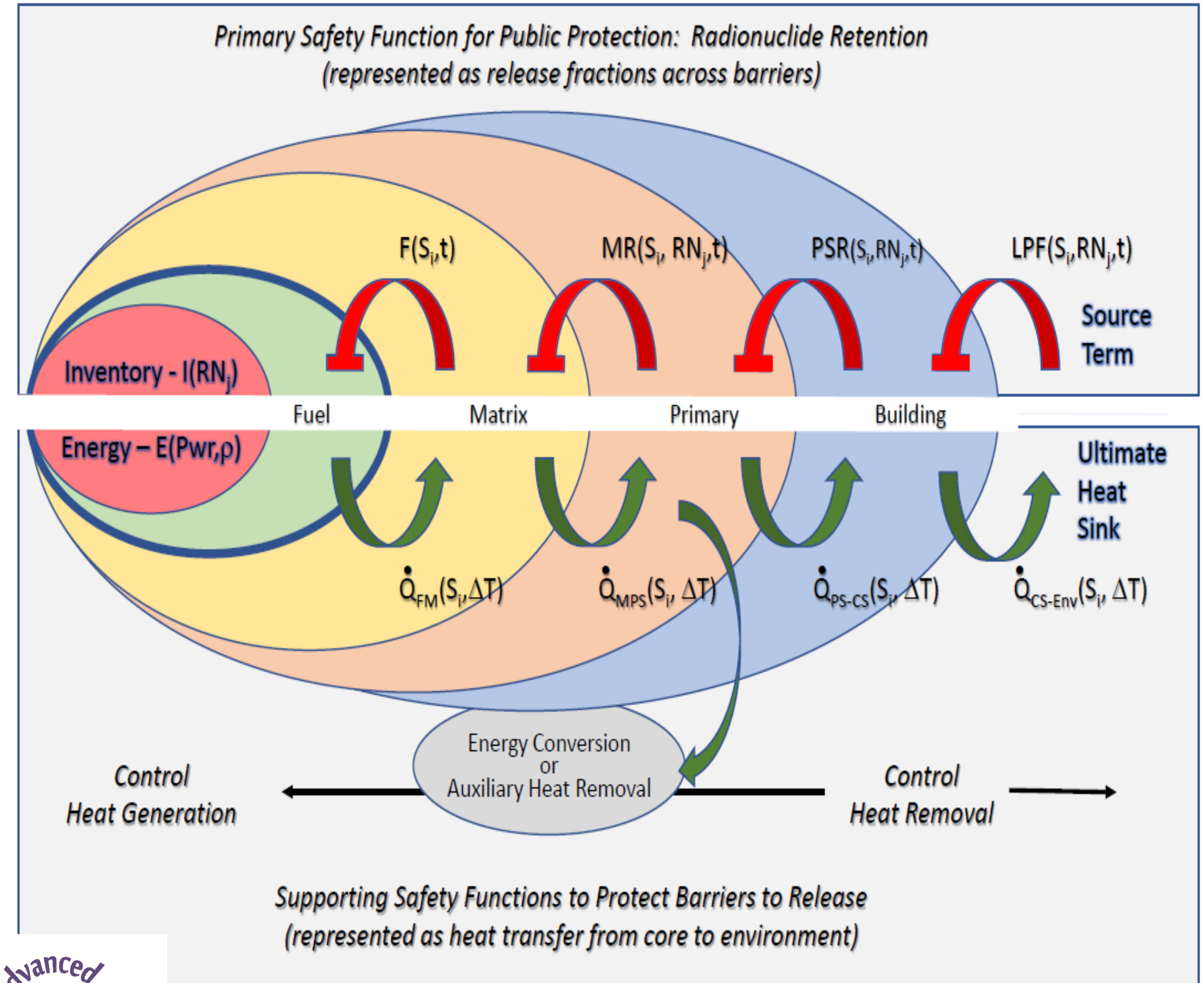
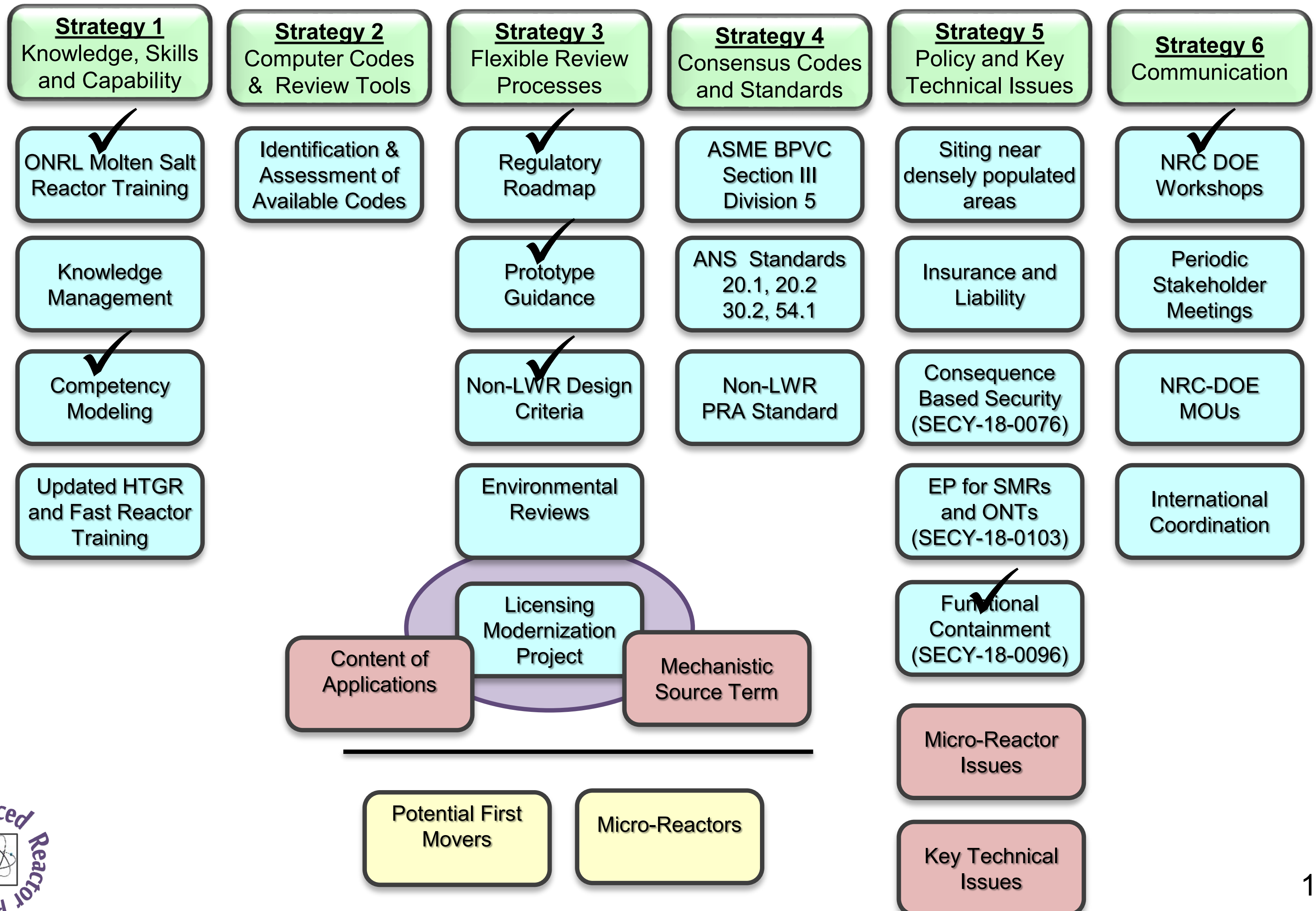
Fundamental Safety Functions and Mechanistic Source Term



$I(RN_j)$	Inventory
RN_j	Radionuclide Groups (j)
E	Heat Energy
Pwr	Power Level
ρ	Reactivity
F	Fuel Release Fraction
MR	Matrix Release Fraction
PSR	Primary System Release Fraction
LPF	Building Leak Path Factor
S_i	Event Sequences (i)
t	Time
$\dot{Q}$	Heat Transfer
FM	Fuel to Matrix
MPS	Matrix to Primary System
PS-CS	Primary System to Cooling System
CS-Env	Cooling System to Environment
ΔT	Temperature difference

Advanced Reactor Program

Strategies & Contributing Activities



Policy Table

Ongoing Activities		
1	Prototype Guidance Staged Licensing	Roadmap *(plan to update)*
2a	Source Term	Prepare MST Guidance
	Dose Calcs	
	Siting	Prepare Siting Guidance
2b	SSC Design Issues	NEI 18-04, DG-1353
3	Offsite EP	SECY-18-103
4	Insurance/Liability	Future (2021) Report to Congress *(no change acceptable)*
5	PRA in licensing	NEI 18-04, DG-1353
6	Defense in Depth	NEI 18-04, DG-1353
7	Physical Security *(limited scope)*	SECY-18-0076 *(limited to sabotage)*

Policy Table

Ongoing Activities		
8	LBEs	NEI 18-04, DG-1353
9a	Fuel Qualification	technology specific
9b	Materials Qualification	technology specific
10a	MC&A Cat II facilities	ML18267A184
10b	Security Cat II facilities	ML18267A184
10c	Collaboration • criticality benchmark • HALEU shipping	
11	Functional Containment Performance Criteria	SECY-18-0096 & SRM
	Advanced Manufacturing	

Policy Table

Open – Not Working		
1	Annual Fees	
2	Manufacturing License	
3	Process Heat	
4	Waste Issues	
5	Operator Staffing* Remote/Autonomous	

Policy Table

No Plans (Resolved or Need Feedback)		
1	Multi-module License	
2	Operator Staffing*	
3	Operational Programs	
4	Module Installation	
5	Decommissioning Funding	
6	Aircraft Impact Assessments	

Future Meetings

2019 Tentative Schedule; Periodic Stakeholder Meetings	
March 28	Proposed: Mechanistic Source Term & Siting
May 9	
June 27	
August 15	
October 10	
December 11	

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Preparation for Advanced Reactors Environmental Reviews

Jack Cushing, Senior Project Manager, Division of Licensing, Siting, and Environmental Analysis, Environmental Technical Review Branch

Agenda

- What is the NRC doing to prepare for advanced reactor environmental reviews?
- What can industry and applicants do to help the NRC prepare?
- Advanced reactor differences that may affect environmental reviews
- Resource areas
- Purpose and Need for an EIS
- Pre-application
- Suggestions for improving NRC's environmental process

What is the NRC Doing to Prepare for Advanced Reactor Environmental Reviews?

- Engaging with potential applicants
- Identifying issues for non-light water reactors
- Planning to develop interim staff guidance for micro-reactors
- Implementing lessons learned from previous environmental reviews
- Guidance on integrating other environmental laws into NEPA process
- Impacts of FAST-41/Executive Order 13807 on environmental review processes

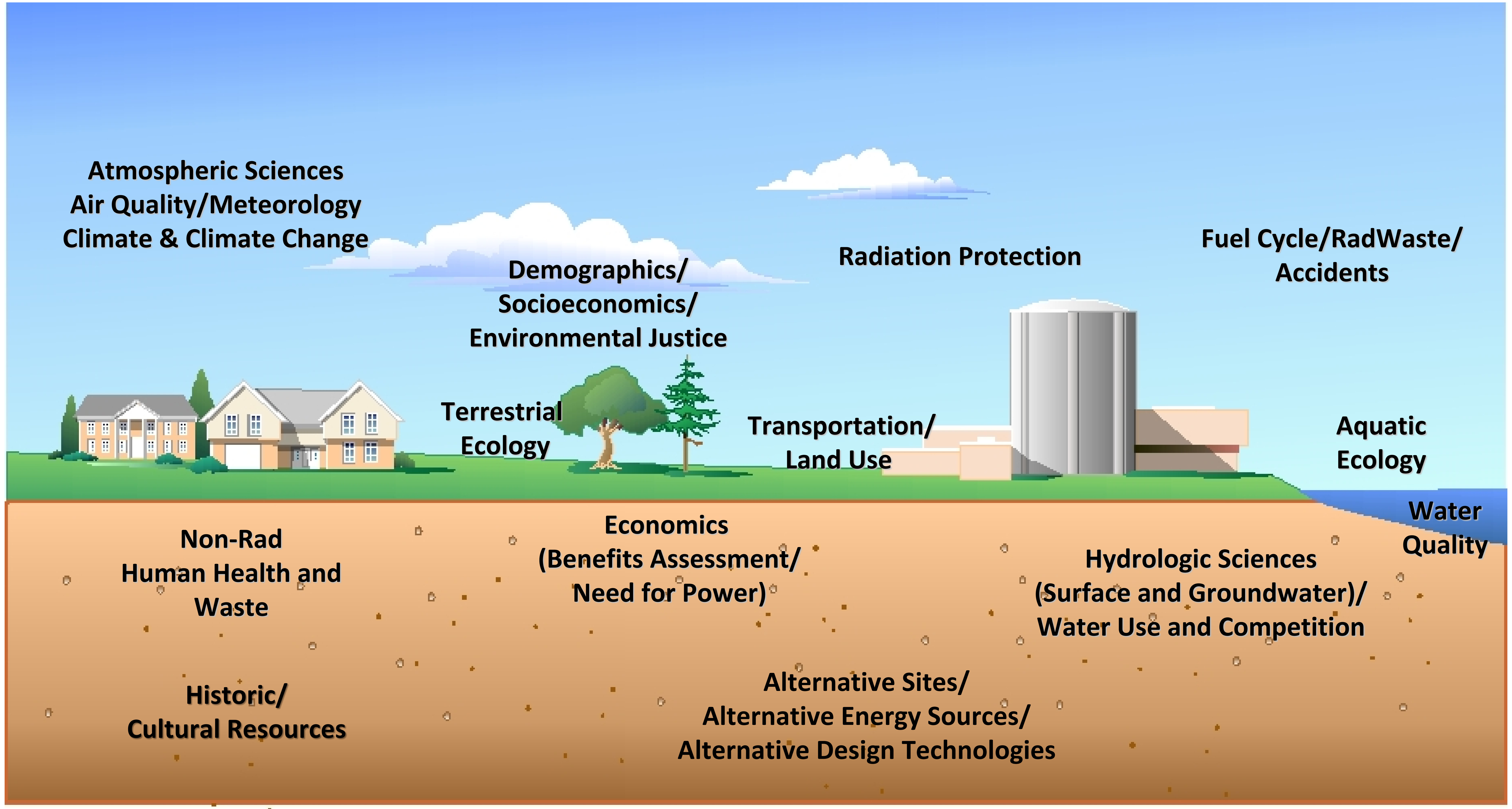
What Can the Industry and Applicants do to Help the NRC Prepare?

- Pre-application discussions with NRC and other Federal and State Agencies (as per FAST-41/Executive Order 13807)
- Continue to engage the NRC on advanced reactor issues
- Nuclear Energy Institute (NEI) guidance on pre-application NEI 10-7
- Provide suggestions to NRC on ways to improve the environmental review process

Different Types, Sizes, and Uses for Advanced Reactors Affect Environmental Review

- Different types of reactor designs and sizes will affect the radiological sections of the review (e.g., postulated accidents, fuel cycle impacts)
- Size - Guidance currently exists for large light water (LLWR) and small modular reactors
- Staff will be developing guidance for micro-reactors
- Micro-reactors use less resources
  - If a specific resource is not used, then there is no need to evaluate impact(s) to that resource
  - Evaluations should be appropriately scaled to the significance of the impacts

Resource Areas Evaluated in EIS

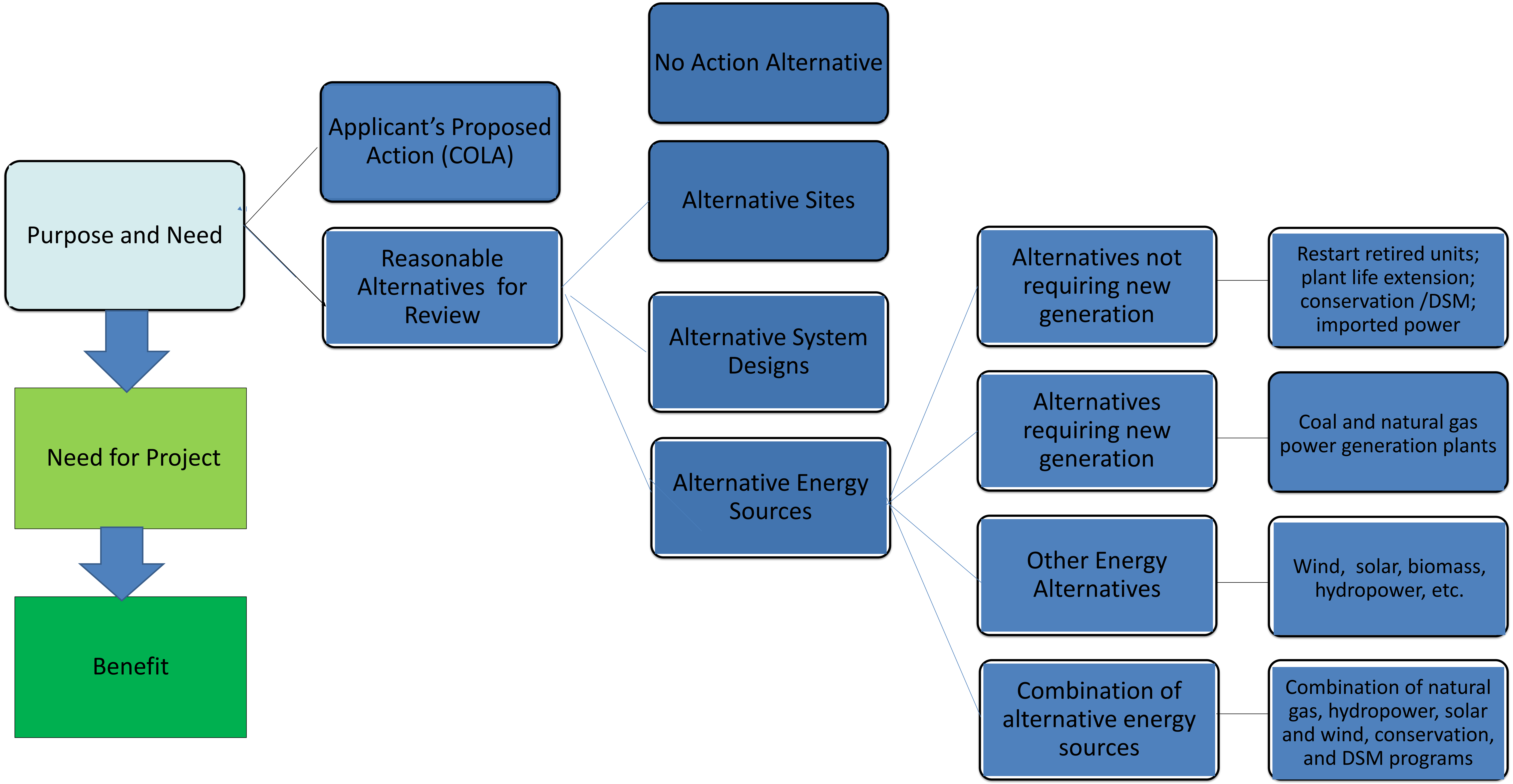


Evaluate Resources Based on Significance

- 10 CFR 51.45 (b)(1) “Impacts shall be discussed in proportion to their significance.”
- If resource shown on previous slide is not used then no need to evaluate that resource
- For example, if no wetlands impacted then no need to evaluate impacts to wetlands

Purpose and Need for Large Reactor:

Could be different for an advanced reactor with different alternatives



Pre-application is Important!

- Each project and site will be different – pre-application interactions with NRC can facilitate mutual understanding of these differences and potential impacts on EIS development
- EO 13807 requires coordination between the applicant and all federal agencies issuing permits
- Pre-application interactions will need to include these other agencies

Questions or Suggestions For Improving the NRC's Environmental Review Processes?

Jack Cushing, NRO/DLSE

Ph: (301) 415-1424

Email: Jack.Cushing@nrc.gov

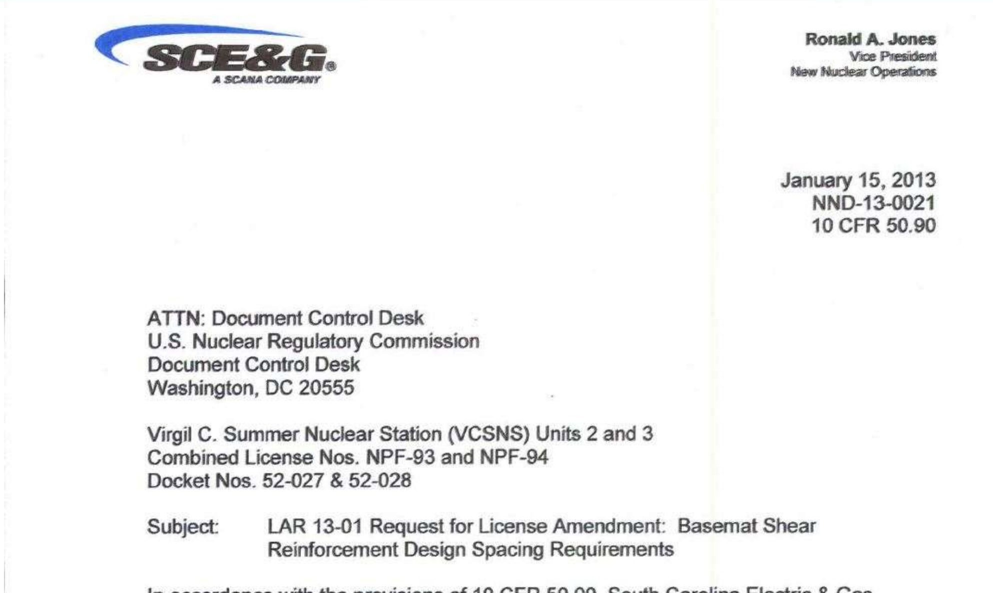
Regulatory Interfaces with Advanced Reactor Civil / Structural Topics

Jason Redd, PE
jpredd@southernco.com

February 7, 2019

Southern Company

Why is the AR Community Interested in Civil/Structural Regulatory Interfaces Today?



SCE&G
A SCANA COMPANY

Ronald A. Jones
Vice President
New Nuclear Operations

January 15, 2013
NND-13-0021
10 CFR 50.90

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555

Virgil C. Summer Nuclear Station (VCSNS) Units 2 and 3
Combined License Nos. NPF-93 and NPF-94
Docket Nos. 52-027 & 52-028

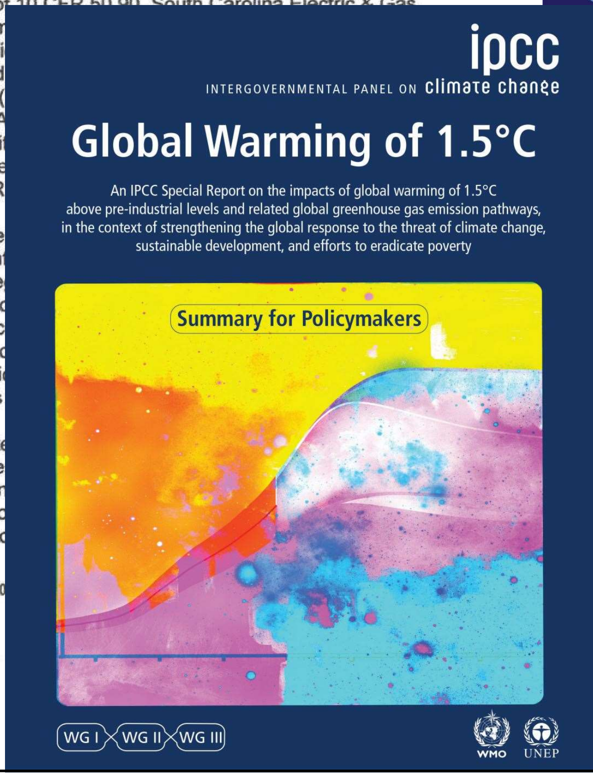
Subject: LAR 13-01 Request for License Amendment: Basemat Shear Reinforcement Design Spacing Requirements

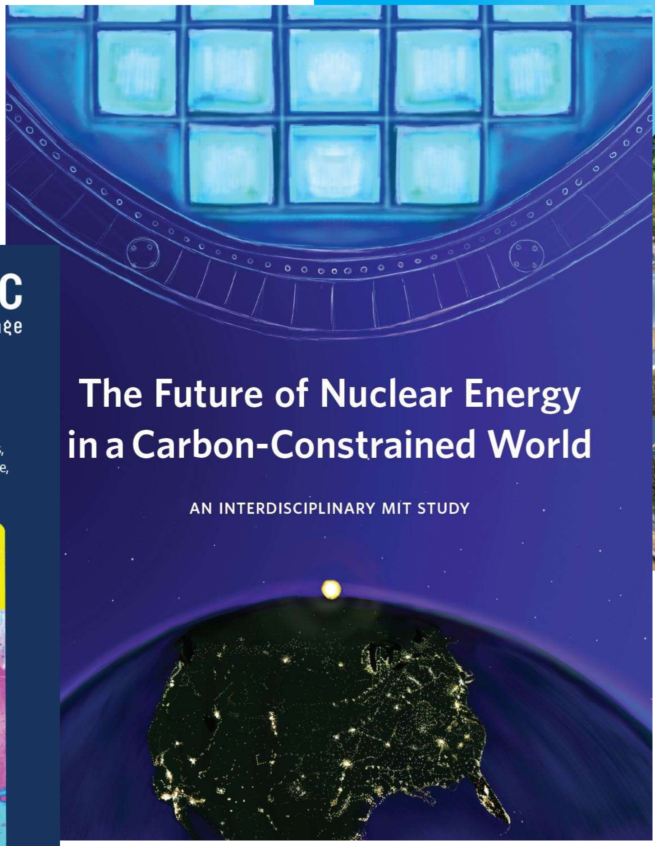
In accordance with the provisions of 10 CFR 50.90, South Carolina Electric & Gas
Company (SCE&G) requests an am
(VCSNS) Units 2 and 3 combined li
respectively). The proposed amend
specific Design Control Document (
Final Safety Analysis Report (UFSA
shear reinforcement bar spacing wi
departures from information provide
License Amendment Request (LAR

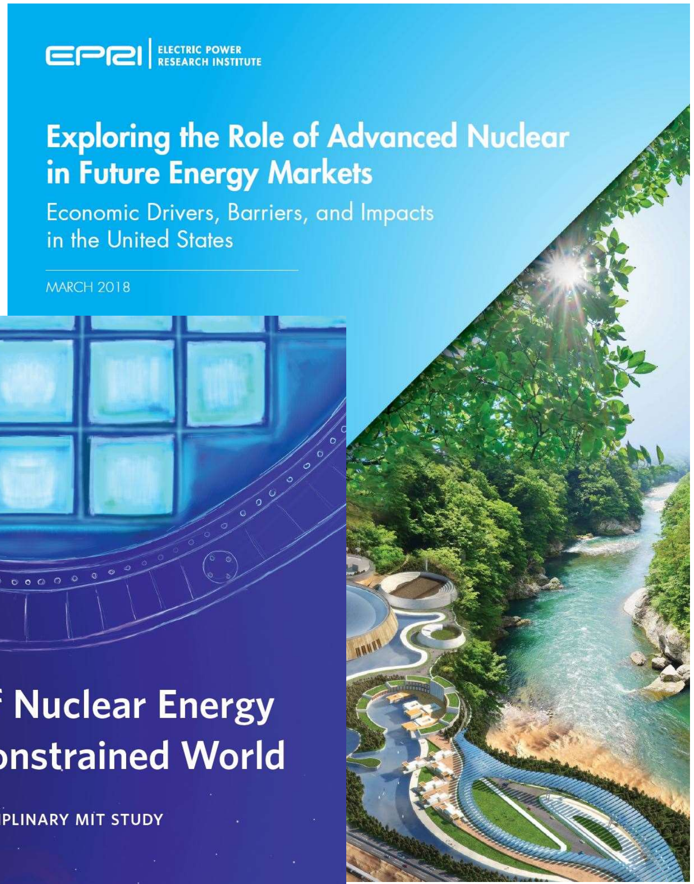
The requested departures are nece
maximum spacing of the shear rein
description, technical evaluation, re
Hazards Consideration determinatio
proposed changes in the LAR are c
markups of the text and figure depic
safety analysis report (UFSAR) whi
in Enclosure 2. This letter contains

This license amendment is requeste
of this license amendment would re
subsequent dependent construction
proposed amendment (through inco
the UFSAR) within 30 days of appro

SCE&G | New Nuclear Deployment • P. O







Why is the AR Community Interested in Civil/Structural Regulatory Interfaces Today?

- Safety
  - This topical area includes natural hazard sources (i.e., earthquakes) and robust defenses against natural and manmade hazards (i.e. tornado missile protection).

- Deployment
  - Construction of any industrial facility typically includes both reinforced concrete and structural steel. Completion of these structures is often time-consuming and expensive.
  - Advances in civil design and construction which maintain safety while reducing schedule and cost are available, but many have not yet been considered in NRC licensing applications.
  - Both the advanced reactor community and regulator have an interest in promptly identifying novel features and innovative approaches to design and construction which may be incorporated in a future license application so that these topics can be addressed in a deliberate, open manner with broad stakeholder engagement.

Commission Policy Statement

To provide for more timely and effective regulation of advanced reactors, the Commission encourages the earliest possible interaction of applicants, vendors, other government agencies, and the NRC to provide for early identification of regulatory requirements for advanced reactors and to provide all interested parties, including the public, with a timely, independent assessment of the safety and security characteristics of advanced reactor designs. Such licensing interaction and guidance early in the design process will contribute towards minimizing complexity and adding stability and predictability in the licensing and regulation of advanced reactors.

-Policy Statement on the Regulation of Advanced Reactors: Final Policy Statement, 73 Federal Register 60,612, and 60,616 (October 14, 2008)

Recent Assessments and Reports

- Numerous government agencies, national laboratories, trade groups, NGOs, and academic organizations have conducted research on 1) lessons learned from past nuclear power construction, 2) ideas for enabling future nuclear power deployment.*

- Civil / structural topics are consistently identified as cost and schedule drivers for overall NPP projects.

- Recommendations from these assessments and reports which are purely commercial in nature, i.e., supply chain development and obtaining sufficient skilled trades workers, are <u>not</u> the subject of this presentation.

- Industry seeks to begin discussions with the NRC Staff on select recommendations from these assessments and reports which have a clear regulatory interface.

*A sample of relevant assessments and reports is included as an Appendix to this presentation.

Licensing Modernization

- The current body of NRC regulations in 10 CFR 50 and 10 CFR 52 are predominantly based upon and addressed towards LWRs.
- The general consensus is that the NRC has the tools available to license non-LWRs under the present rules.
- Modernization of the present regulations and guidance to become more technologically-inclusive, risk-informed, and performance-based is an explicit expectation of the NRC Commission, NRC senior management, and Congress.

- ASK:
  - NRC Staff continue excellent work towards approval and issuance of DG-1353 *Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Inform the Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors.*
    - » As referenced by DG-1353, implementation of NEI 18-04 *Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development* for determination of Licensing Basis Events; classification of structures, systems, and components; and determination of adequacy of Defense-in-Depth is a major step towards modernizing the application of the current regulatory framework.

Design Details in Licensing Documents

- During recent applications, the level of civil design detail required has proven periodically contentious between the NRC Staff and applicant.
- Depiction of some structural features, dimensions, and measurements has been incorporated in licensing documents which require prior NRC approval for departures at a preciseness uncommon for civil construction.

- ASK:
  - NRC executive management should clarify to the Staff and applicants the level of detail expected in applications and permits / licenses to ensure common expectations, understanding, and provide an opportunity for discussion should any party disagree with the clarification.
  - NRC Staff and applicant must ensure and document clear mutual understanding of terms such as “typical” and “representative” as used in licensing document text and Figures.

Changes During Construction

- During any construction project, from a home kitchen remodel to the construction of a nuclear power plant, changes are almost inevitable.
- Regulator needs: assurance proposed changes will not endanger public health or the environment.
- Developer needs: predictable, timely processes to make changes, aligned with potential impact on public health or the environment.

- ASK:
  - NRC establishment of predictable change processes, applicable to Part 50 and Part 52 regimes, to align requirements for NRC prior approval of changes with the potential impact of the change on public health or the environment.
    - » NEI white paper *Assessment of Licensing Impacts on Construction: Experience with Making Changes during Construction under Part 52* (October 2018) contains detailed recommendations.

NRC Staff Training

- Use of novel features and innovative approaches in future license applications create a potential gap in Staff knowledge.

- ASK:
  - How can industry work with the NRC Staff to ensure that the Staff has the opportunity for training, exposure, and experience with proposed novel features and innovative approaches to perform an informed, timely safety evaluation? What training does the NRC Staff need that Industry can advocate for with NRC management and Congressional allocations?

Seismic Isolation

- Seismic isolation of large civilian nuclear safety-related structures has not yet been pursued in the US; six large LWRs have been seismically isolated in France and South Africa.
- Globally installed in buildings, bridges, major equipment, and other structures for decades, seismic isolation has a robust analysis, design, and experience.
- Horizontal accelerations due to seismic input can be greatly reduced.
  – Reduced accelerations translate into reduced loads on SSC.

- ASK:
  – NRC near-term engagement with industry on development of seismic isolation analysis methodology and acceptance criteria.

Modular Construction & Factory Fabrication

- Modular civil construction has been licensed and conducted in the United States.
- Execution experience has been mixed in the US and worldwide.
- Level of detail in licensing documents and regulatory treatment of tolerances has proven challenging in practice.

- ASK:
  - NRC policy re-affirmation that the level of required detail in an application is that necessary to make a safety finding of "reasonable assurance of adequate protection of the public health and safety."
  - NRC and developer pre-application agreement on the role of tolerances, how and by which party(ies) tolerances are determined, and treatment of tolerances in licensing documents.
  - Industry solicits NRC Staff feedback on lessons learned from application review and Safety Evaluation Report writing experiences regarding modular construction.

Concrete and Steel

- Non-LWRs have off-normal events that differ significantly from LWRs.
- A subset of non-LWRs potentially have core exit temperatures considerably above typical LWR values during normal operation.
- Non-LWR liquid heat transfer fluids exhibit behaviors significantly different from water in the unlikely event of a leak. Molten salts and molten metal heat transfer fluids may contact normally ambient concrete and steel in such an event.

- ASK:
  – NRC Staff to share their current and planned activities in the area of concrete and structural steel exposed to high-temperature environments.

Concrete Reinforcement

- Rebar congestion is a common challenge in both commercial and nuclear safety-related construction.
- Rebar congestion has been associated with increased instances of poor consolidation, rock pockets, and voids.
- Rebar options have been developed and deployed to reduce congestion while maintaining compliance with code provisions.
  - Vogtle 3&4 received approval for use of headed reinforcement in accordance with ACI 318-11 Section 12.6 [ML13122A102]

- ASK:
  - Is the NRC considering endorsement of ACI 318-11 Section 12.6 for use generically in nuclear safety-related structures?

Advanced Concrete – SC Walls

- Steel-concrete (SC) composite walls licensed for AP1000.
- Level of detail in licensing documents and regulatory treatment of tolerances for SC wall modules has proven challenging in practice.
- No consensus code or standard available for SC structures until issuance of AISC N690-12 Supplement 1 in August 2015.
  - AISC N690-18 is the latest version of this Specification and incorporates the above.

- ASK:
  - What are NRC plans for endorsement of AISC N690-18 *Specification for Safety-Related Steel Structures for Nuclear Facilities* which includes steel-concrete composite walls.

Selected Reading

- Kammerer, Annie; Andrew Whittaker; Justin Coleman; *INL/EXT-15-36945 Regulatory Gaps and Challenges for Licensing Advanced Reactors Using Seismic Isolation*
- Champlin, Patrick A.; *Techo-Economic Evaluation of Cross-Cutting Technologies for Cost Reduction in Nuclear Power Plants*
- Lovering, Jessica R.; Arthur Yip; Ted Nordhaus; *Historical construction costs of global nuclear power reactors*
- Dawson, Karen; Piyush Sabharwall; *INL/EXT-17-43273 A Review of Light Water Reactor Costs and Cost Drivers*

Selected Reading

- MIT Energy Initiative; *Future of Nuclear Energy in a Carbon-Constrained World*
- The Royal Academy of Engineering; *Nuclear Construction Lessons Learned Guidance on best practice: concrete*
- Ganda, F.; *Report on the Update of Fuel Cycle Cost Algorithms*
- Nuclear Energy Institute; *Assessment of Licensing Impacts on Construction: Experience with Making Changes during Construction under Part 52*
- Finan, Ashley; *Enabling Nuclear Innovation, Strategies for Advanced Reactor Licensing*

Selected Reading

- Nordhaus, Ted; Jessica Lovering; Arthur Yip; Michael Shellenberger; *How to Make Nuclear Cheap*
- Energy Technologies Institute; *The ETI Nuclear Cost Drivers Project: Summary Report*

Non-Light Water Reactors Stakeholders Meeting

Civil/Structural Engineering Research Updates

Prepared by

Jose Pires (RES/DE) and Jim Xu (NRO/DEI on rotation to RES)

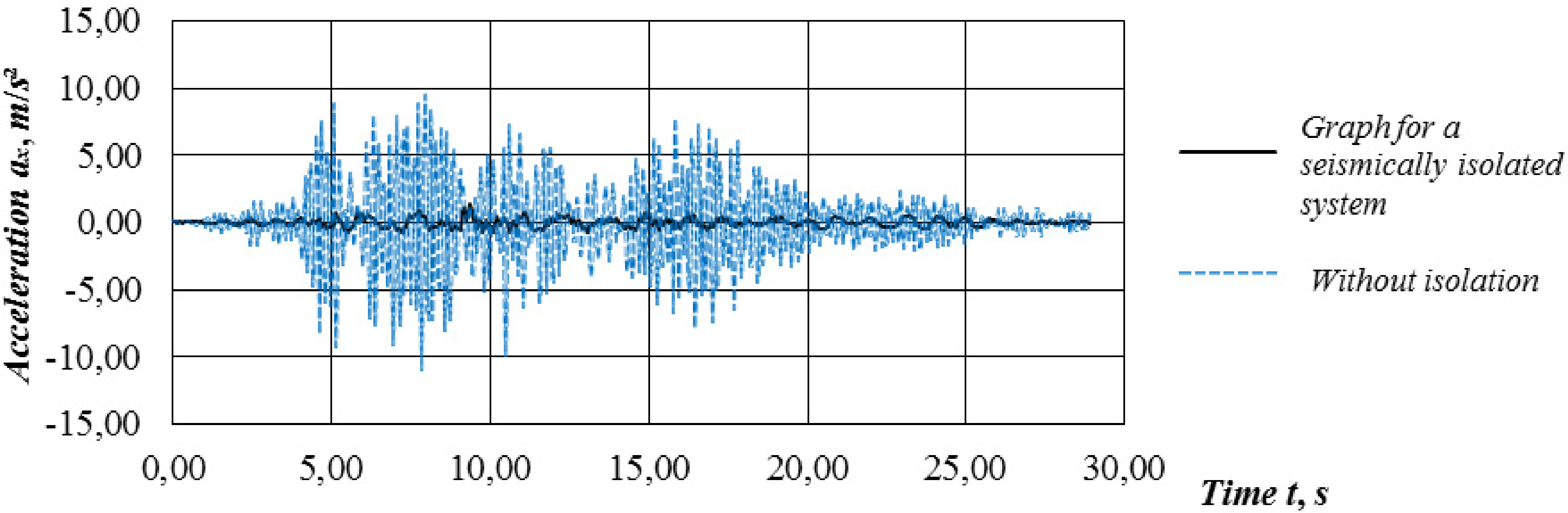
February 7, 2019

- Seismic Isolation
- Steel Plate Composite (SC) Construction
- Risk-Informed Performance-Based Approach to Seismic Safety

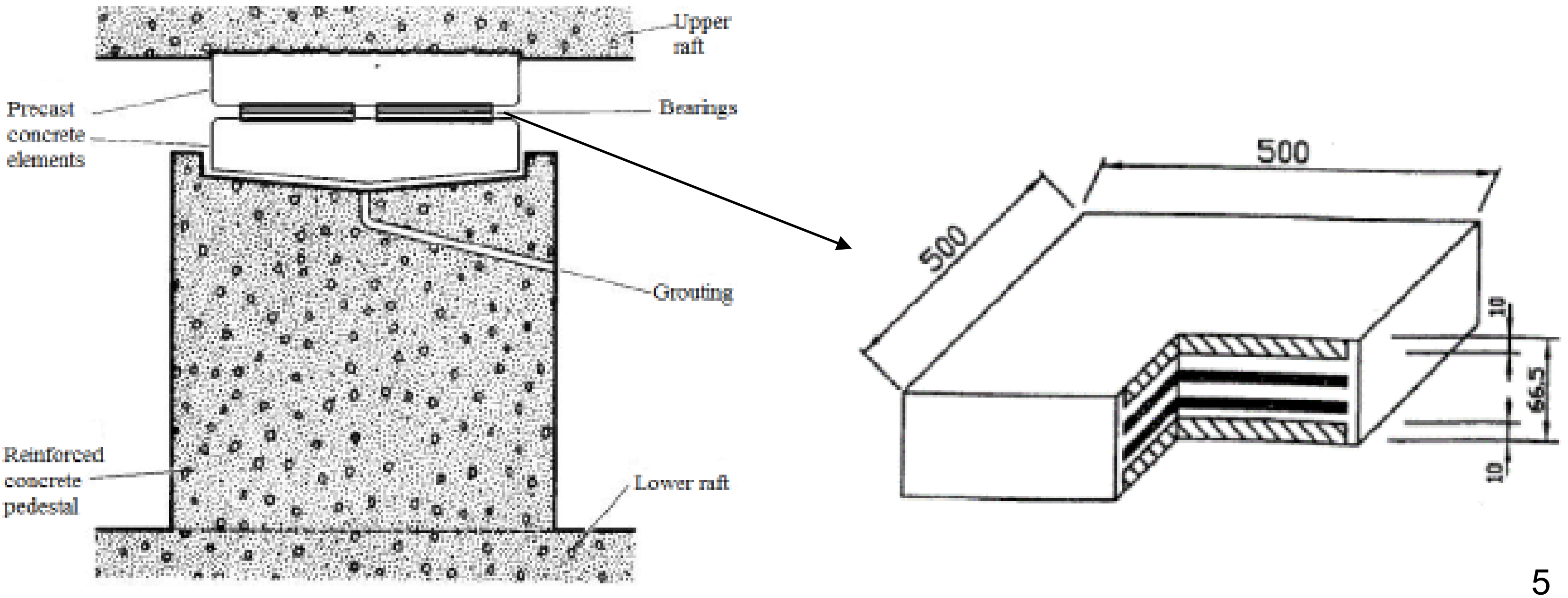
Prevent/Mitigate Seismic Damages

- Damage to structures can be reduced by earthquake resistant designs:
  - Strength based designs to ensure higher member capacities than seismic induced loads
  - Performance based designs to maximize absorbing earthquake energy without unacceptable structural damage.
- Reduce seismic motions in structures via mechanical devices (base isolators):
  - Rubber bearings (Low damping, high damping)
  - Lead rubber
  - Sliding bearing or friction pendulum

Effect of Base Isolators



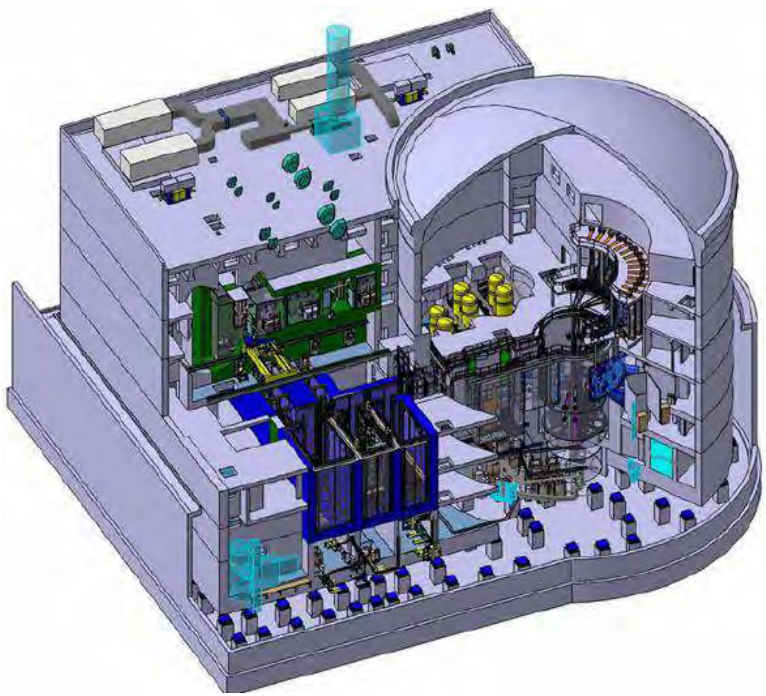
Seismic Isolation for Cruas NPP, France



Examples of Seismically Isolated Nuclear Facilities

- Cruas NPP, France (elastomeric)
- Koeberg NPP, South Africa (elastomeric with sliding plates)
- Argonne National Laboratory ALMR, U.S. (high damping rubber bearings)
- Jules Horowitz research reactor, France (elastomeric)
- ITER Tokamak reactor, France (elastomeric)
- Spent Fuel Pool in La Hague, France (elastomeric)
- Monju Fast Breeder Reactor, Japan (elastomeric)

Jules Horowitz Reactor, France



Reactor was isolated using synthetic rubber bearing seismic isolators

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Apple Park

Ring mounted on 700 steel base isolators that withstand large displacements (to remain functional after an earthquake)

Figures from Schuff Steel
https://www.schuff.com/project/apple-corporate-headquarters/

Regulatory Challenges

- Operating experience mostly in small, testing reactors and commercial facilities
- Single failure
- Performance criteria
  - Design Basis Earthquake
  - Beyond Design Basis Earthquake
- Design and analysis - nonlinear
- Reliability issues during operating life
- Inspection and maintenance procedures
- Seismic isolation of specific components
- Downstream effects

NRC-Sponsored Research

- NUREG/CR-7253 - Technical Considerations for Seismic Isolation of Nuclear Facilities (in press)

Provides technical perspectives of design, testing, and installation of seismic isolation systems in nuclear facilities including recommendations on performance-based criteria for design

- NUREG/CR-7254 – Seismic Isolation of Nuclear Power Plants Using sliding Bearings (in press)

Provides benchmarking of analytic techniques against testing data for friction bearings

- NUREG/CR-7255 – Seismic Isolation of Nuclear Power Plants Using Elastomeric Bearings (in press)

Provides benchmarking of analytic techniques against testing data for rubber bearings

- NUREG/CR -7196 – Large Scale Earthquake Simulation of a Hybrid Lead Rubber Isolation Designed with Consideration of Nuclear Seismicity

Experimental simulation and analysis of a hybrid lead-rubber isolation system for a large-scale 5-story steel moment frame (with the E-Defense shaking table in Japan)

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Examples of Ongoing Non-NRC Research

- EPRI
  - Cost basis for utilizing seismic isolation for nuclear power plant design, 4/18/18-12/31/2019
- DOE/TCF (Technology Commercialization Fund)
  - Seismic isolation of major advanced reactor systems for economic improvement and safety assurance, 3/01/2018-2/28/2020
- DOE/INL/BEA
  - Seismic isolation of advanced reactors with considerations of fluid structure interaction, 6/01/2017-11/30/2019
- DOE ARPA-E
  - Reducing the overnight capital cost of advanced reactors using equipment-based seismic protective systems, 10/1/2018-3/31/2021

Codes and Standards

- ASCE 4-16 and ASCE 43-18 for design, analysis, testing requirements for seismic isolators – Performance-based

		Isolation system			Superstructure	Other SSCs		
Hazard	Use	Isolation system displacement	Performance	Acceptance criteria	Performance	Performance	Umbilical lines	Hard Stop or Moat
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.

Going Forward

- Detailed look at ASCE 4 and ASCE 43
  - Apply performance based approach
  - Expected to be part of risk-informed and performance-based guidance for design
  - Leverage the standards
- Continue to interact with industry and stakeholders
  - Engage with DOE research
  - Participate in Non-Light Water Reactor Stakeholder meetings
  - Workshops with staff, outside experts and stakeholders
- Ensure NRC Infrastructure is ready for applications that utilize seismic isolation technologies

- Seismic Isolation
- Steel Plate Composite (SC) Construction
- Risk-Informed Performance-Based Approach to Seismic Safety

Steel Plate Composite (SC) Structures – AISC N690

- New reactors adopted modular SC structures as one of the major design features for some of their structures
- SC structures are used for the design of safety-related structures other than containment buildings
  - Containment internal structures for example

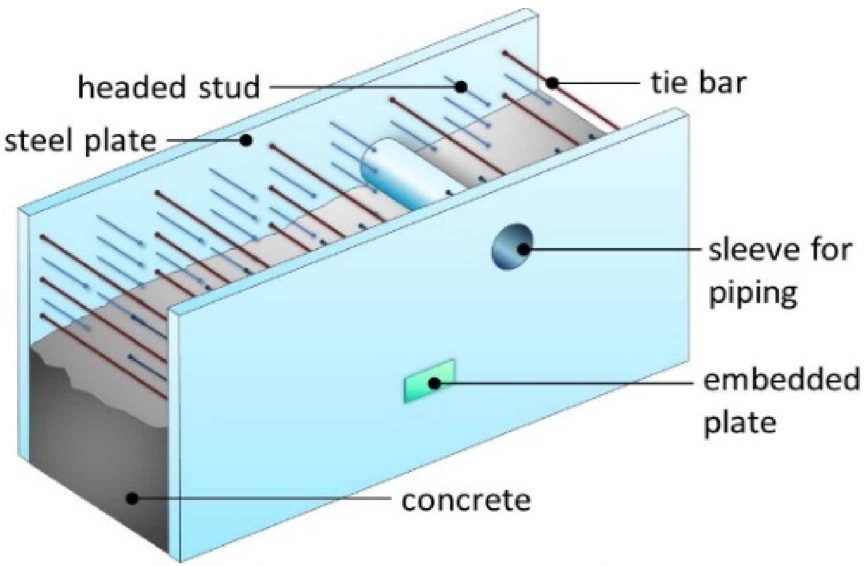
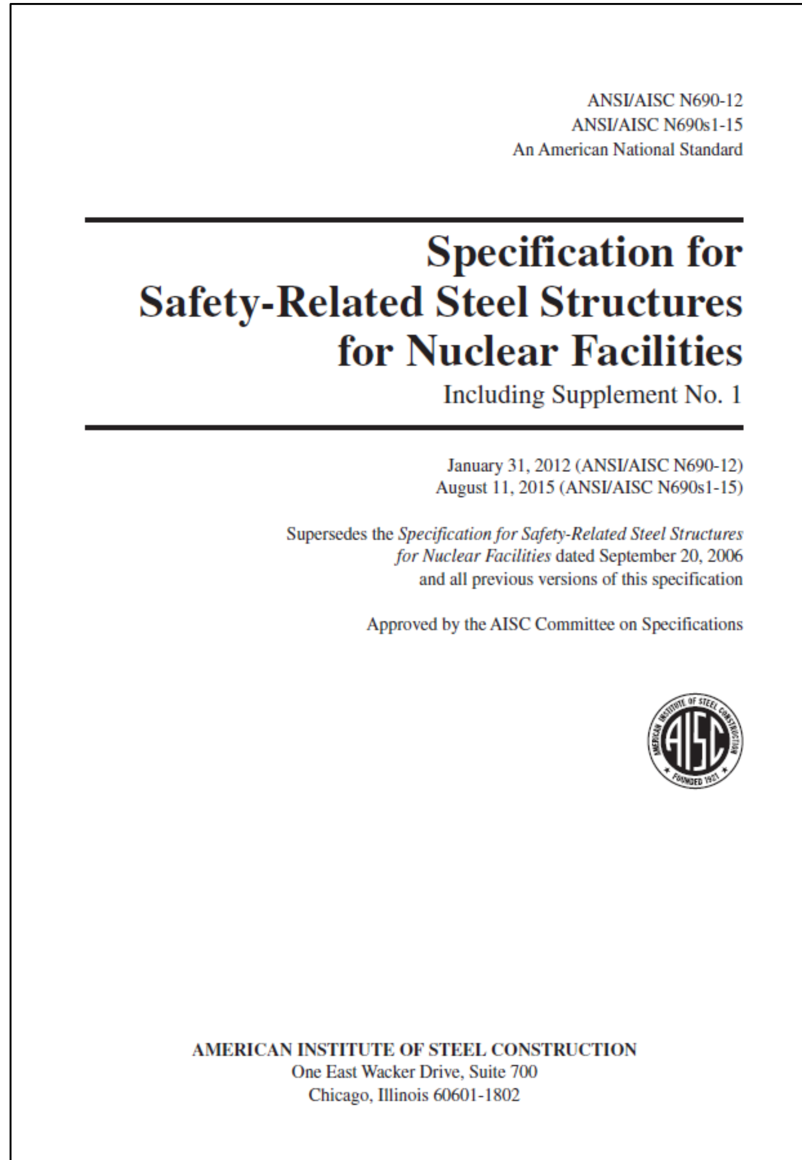


Illustration of SC Construction for Walls

Steel Plate Composite (SC) Structures – AISC N690

- The AISC started a multiyear effort to develop a standard for the design of SC structures
- In 2015, the AISC published the first U.S standard for the design of safety-related SC structures (Appendix N9 to N690)
- The NESCC and the NRC Standards Forum provided forums to discuss the progress of the standard and of the NRC review



ANSI/AISC N690-12
ANSI/AISC N690s1-15
An American National Standard

Specification for Safety-Related Steel Structures for Nuclear Facilities

Including Supplement No. 1

January 31, 2012 (ANSI/AISC N690-12)
August 11, 2015 (ANSI/AISC N690s1-15)

Supersedes the *Specification for Safety-Related Steel Structures for Nuclear Facilities* dated September 20, 2006 and all previous versions of this specification

Approved by the AISC Committee on Specifications

AMERICAN INSTITUTE OF STEEL CONSTRUCTION
One East Wacker Drive, Suite 700
Chicago, Illinois 60601-1802

Steel Plate Composite (SC) Structures – AISC N690

- Review of the N690s1-2015 requires review of:
  - AISC 360 (the N690 parent specification for the design of steel structures)
  - Evolution of the design of safety-related structures from the Allowable Stress Design (ASD) approach in the N690-1994 and its 2014 supplement to
  - The Allowable Strength Design (ASD) and Load and Resistance Factor Design approach (LRFD) in the current versions of N690
- The NRC review includes technical exchanges with AISC experts for clarifications and discussion of provisions in N690s1-2015 (for both steel and SC structures)

Steel and Steel Plate Composite (SC) Structures – AISC N690

- During the review process, the AISC updated N690 (for possible publication as N690-2018)
- Plan to complete a draft regulatory guide with the staff position on N690 as follows:
  - Complete the N690 review using the most recent update of N690
  - Conduct one additional technical exchange with AISC experts for further clarification of provisions
  - Prepare a draft regulatory guide (DG-1304) in the fourth quarter of FY19

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Protecting People and the Environment

- Seismic Isolation
- Steel Plate Composite (SC) Construction
- Risk-Informed Performance-Based Approach to Seismic Safety

U.S.NRC
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Protecting People and the Environment

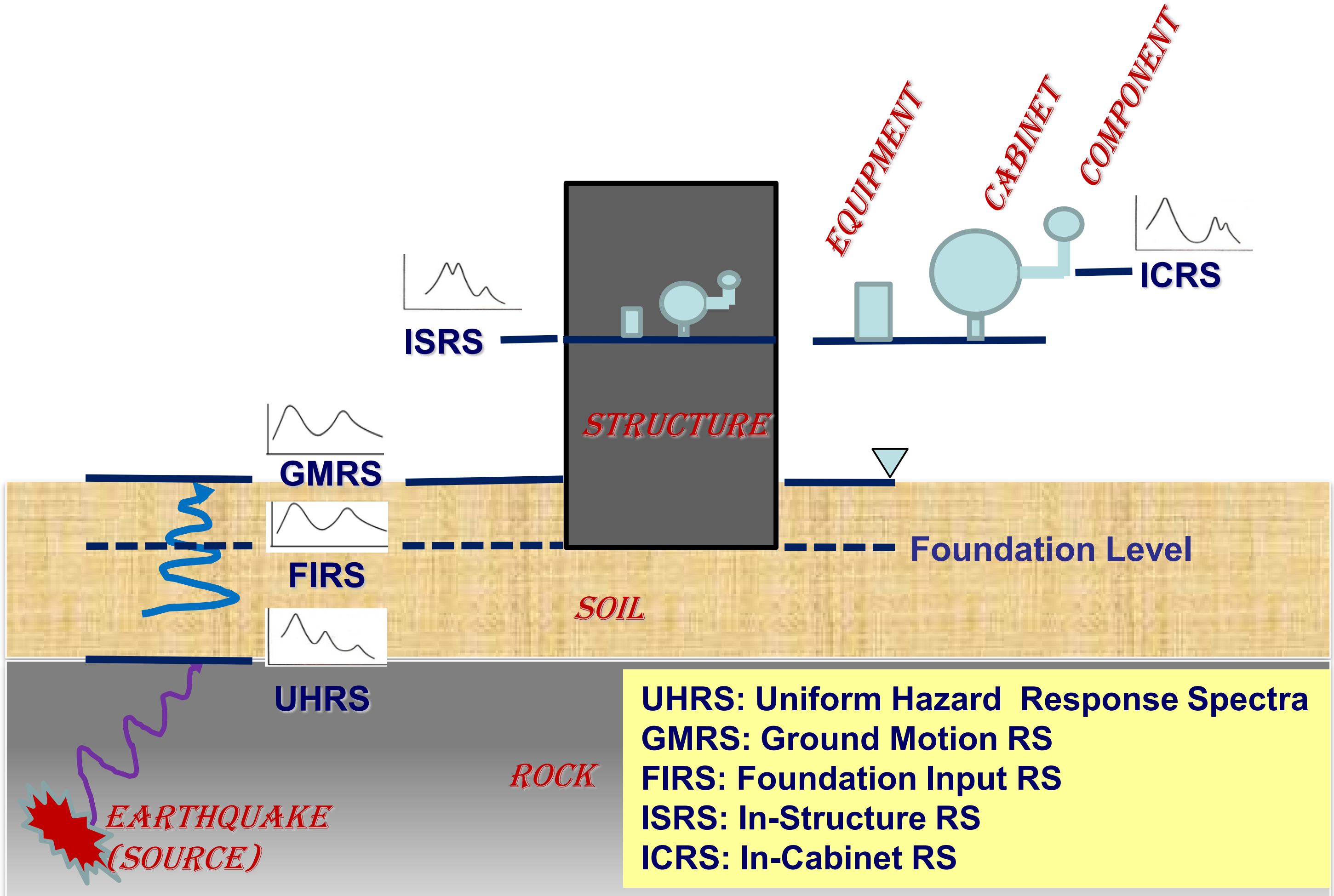
Overview

- To build upon and leverages the existing framework of regulations, NRC and industry guidance, and existing codes and standards, to enable a holistic RIPB approach for seismic safety that integrates risk concepts and engineering design in a manner that is technology neutral and can be consistently used across all NRC regulatory processes involving seismic hazards.

- The work responds to previously stated Commission's goal for a holistic, risk-informed and performance-based regulatory structure as well as to demonstrated industry interest in the RIPB approaches to addressing seismic safety issues.

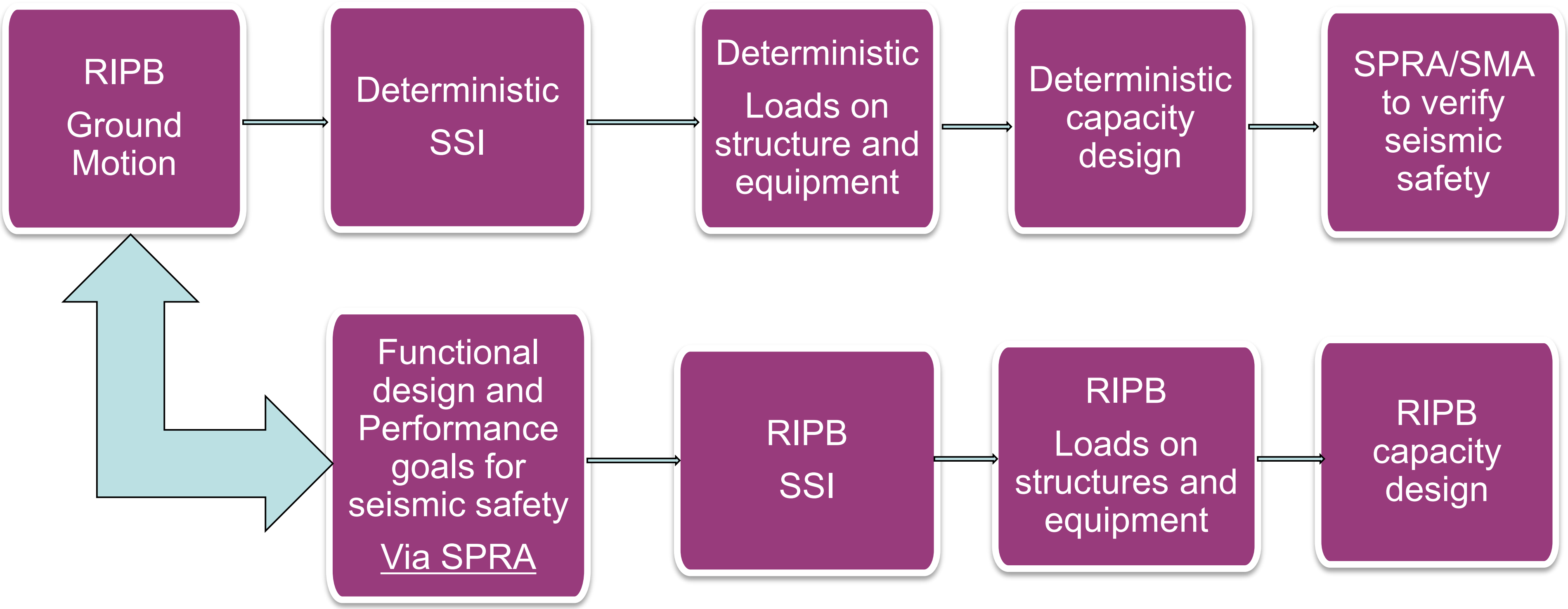
Nuclear Power Plant Seismic Response Analysis and Design

Risk Assessment
↑
Capacity design
↑
Loads on structure and equipment
↑
Soil-Structure Interaction (SSI)
↑
Site Response
↑
Probabilistic Seismic Hazard Analysis (PSHA)



UHRS: Uniform Hazard Response Spectra
GMRS: Ground Motion RS
FIRS: Foundation Input RS
ISRS: In-Structure RS
ICRS: In-Cabinet RS

Gap in RIPB Implementation for Seismic Safety



Alternative implementation to ensure consistent RIPB across all elements

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Protecting People and the Environment

Summary of Approach

- RIPB approach to integrating functional design and physical design
  - Physical design by leveraging performance-based ASCE seismic design and analysis standards to achieve required seismic performance of SSCs
  - Functional design using SPRA to achieve optimal sequence level system seismic performance (more balanced risk profile considering defense-in-depth, diversity, redundancy, safety margin and other non seismic failures)
- Contrast to current approach
  - Current approach
    - Conservative deterministic seismic design of SSCs
    - Assessment of SSCs performance by SPRA to achieve safety goals
  - RIPB approach
    - Using SPRA and safety goals to achieve optimal system level seismic performance and graded approach to SSC design for greater flexibility
    - Performance-based SSCs design to achieve required performance goals

Potential Regulatory Uses

- Risk-informed seismic analysis and design for potential Non-LWR applications
- Risk-informed seismic analysis and design for new LWR reactor applications and SMRs
- Treatment of SSCs in operating reactors thru LARs
- Changes to current licensing basis thru LARs
- Risk-informed plant modifications thru LARs
- Other activities involving seismic hazards
  - Fuel processing facilities and spent fuel for example

Potential Regulatory Benefits

- Integrated approach to design and evaluation to optimize system level seismic performance and enable a graded approach (achieve more balanced seismic risk profile)
- Focus on safety significant seismic sequences and associated SSCs for design and reviews
  - More effective resource allocation
- Practice that provides options to enhance performance
- Enhanced traceability of risk factors
- Increased efficiency and effectiveness by leveraging consensus standards

Acronyms

ASCE	American Society of Civil Engineers
AISC	American Institute of Steel Construction
ALMR	Advanced Liquid Metal Reactor
BEA	Batelle Energy Alliance, Inc.
DG	Draft Regulatory Guide
DOE	Department of Energy
EPRI	Electric Power Research Institute
INL	Idaho National Laboratory
ITER	International Thermonuclear Experimental Reactor
NESCC	Nuclear Energy Standards Coordination Collaborative
NPP	Nuclear Power Plant
RIPB	Risk-Informed Performance-Based
SC	Steel Plate Composite Construction

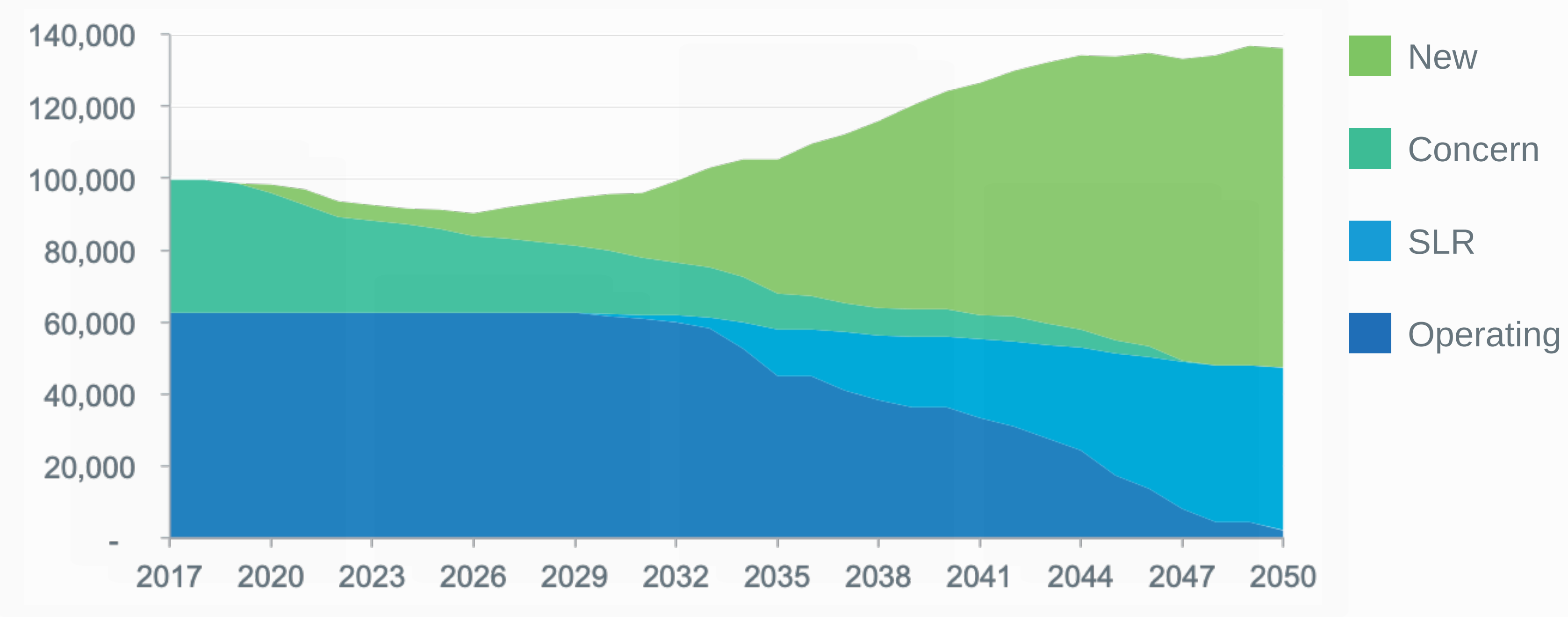
New Plant Cost Reduction and Regulatory Interface

Marc Nichol, Director of New Reactor Deployment

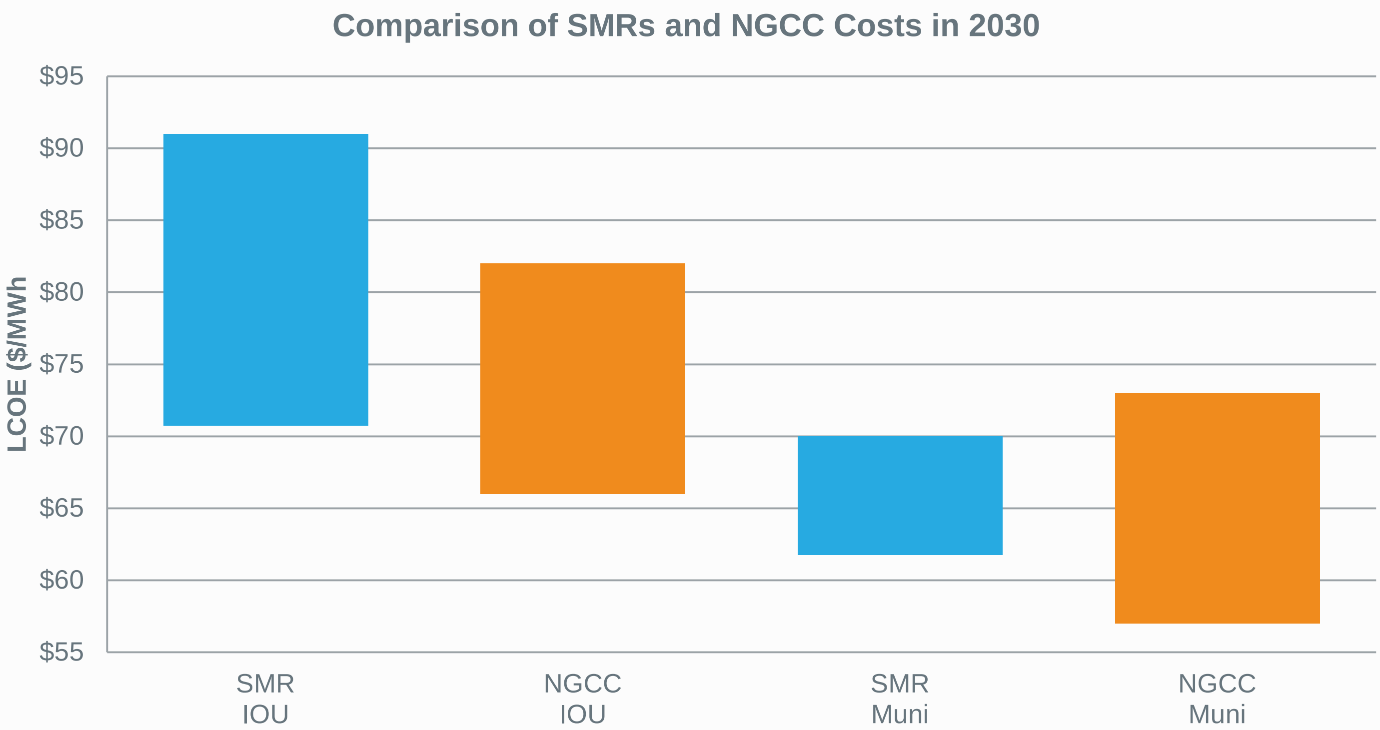
February 7, 2019

Scale of New Build Needed to 2050

Even with subsequent license renewal, retaining 20% market share in 2050 requires adding ~60-90 GW



N^th^-of-a-Kind Cost Competitiveness



Source SMR Start Economic Analysis

Costs are headwinds for nuclear reactors

	First of a Kind SMR	NOAK SMR	NGCC
Facility Size	400 MWe (200MWe x 2 units)		550 MWe
Construction Time	42 months (including 6 months for start-up)		33 months
Deployment Year	2026	2030	2026
Overnight Capital Cost	$5,150/kWe	$4,600/kWe	$1,210/kWe
O&M Costs (2017$)	Fixed O&M: $135/kW-yr Variable O&M: $3/MWh Fuel: $8.5/MWh (includes costs of used fuel disposal at $1/MWh)		Fixed O&M: $27/kW-yr Variable O&M: $4/MWh Fuel: $3.75/Mbtu (equals $24.7/MWh)

Source: SMR Start Economic Analysis

Areas for Cost Improvements

Table 2.2: Cost breakdown for various LWRs

	Cost Breakdown (% of total cost)				
	Generic AP1000	Historic U.S. LWR Median Case	Historic U.S. LWR Best Case	South Korean APR1400	EPR
Nuclear Island Equipment	12.6	9.9	16.5	21.9	18.0
Turbine – Gen. Equipment	4.9	7.0	11.9	5.6	6.3
Yard, Cooling, and Installation	47.5	46.3	49.3	45.5	49.7
Engineering, Procurement, and Construction Cost	15.9	17.6	7.7	20.0	15.3
Owner's Cost	19.1	19.2	14.6	7.0	10.7

Source: MIT Future of Nuclear Study

REDUCING CONSTRUCTION COSTS

- New technologies to reduce costs
  - E.g., concrete, seismic isolation
- Best construction management practices
  - E.g., design completion, experience,
- Regulatory efficiency during construction
  - E.g., changes during construction

VISION FOR ADVANCED MANUFACTURING

- Produce components faster and cheaper
- Enable components with enhanced performance
- Rapidly commercialization of new technologies

NEI’s AMM Roadmap

- Challenge: Advanced manufacturing methods rapidly maturing for use by nuclear industry; however, a timely and clear pathway to regulatory acceptance remains an obstacle for many methods
- Objectives:
    1. Identify the methods of most interest to industry – biggest benefits and nearest-term use
    2. Provide insight to organizations’ assignment of resources toward furthering the commercialization of methods
    3. Establish clarity on an expedited pathway to regulatory acceptance

References

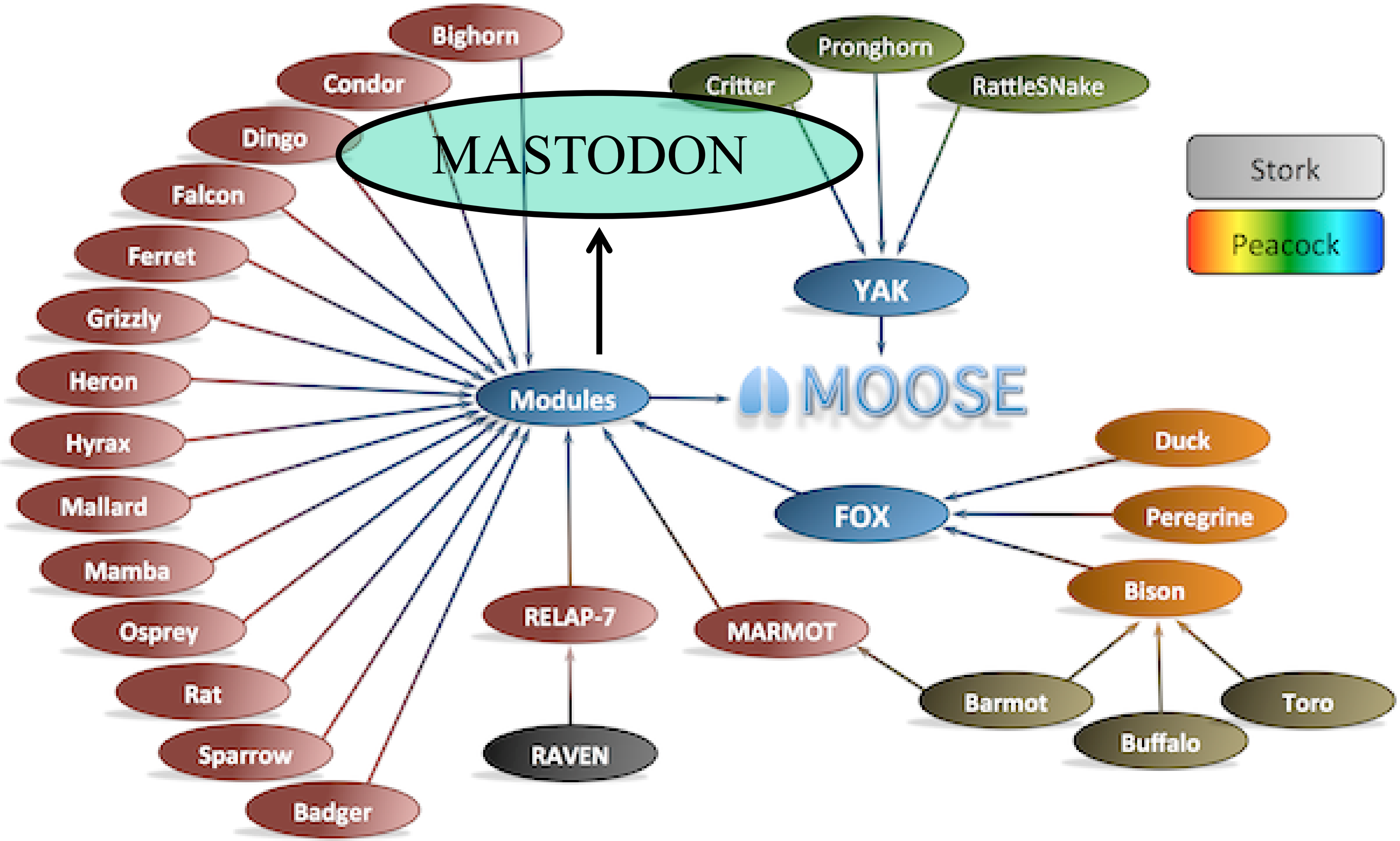
- MIT Future of Nuclear Study: https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf
- ETI Nuclear Cost Drivers: https://www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report
- SMR Start Economics Analysis: http://smrstart.org/wp-content/uploads/2017/09/SMR-Start-Economic-Analysis-APPROVED-2017-09-14.pdf
- NEI Assessment of Licensing Impacts on Construction: https://www.nei.org/CorporateSite/media/filefolder/resources/reports-and-briefs/assessment-licensing-impacts-construction-changes-part-52-20181001.pdf

Design Optimization for Safety and Cost Using MASTODON

Chandu Bolisetti
Facility Risk Group
Idaho National Laboratory

February 7th, 2019

MOOSE and Applications

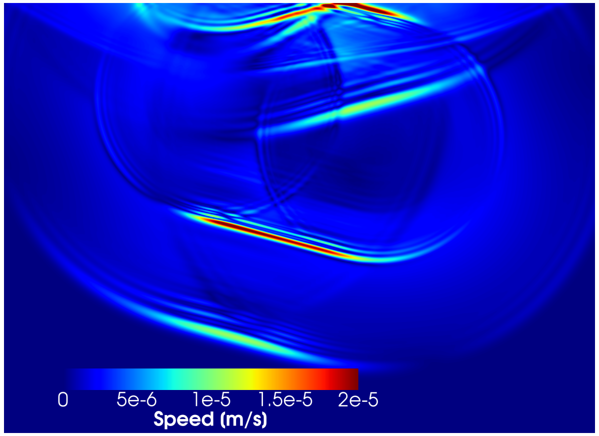


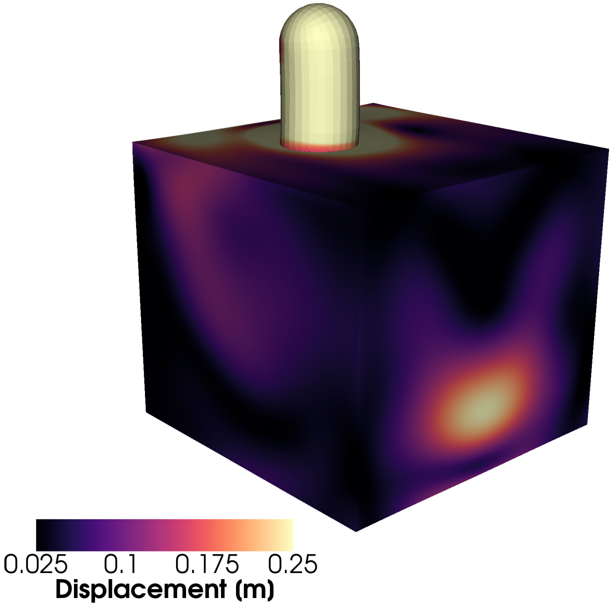
https://mooseframework.org

https://mooseframework.org/mastodon

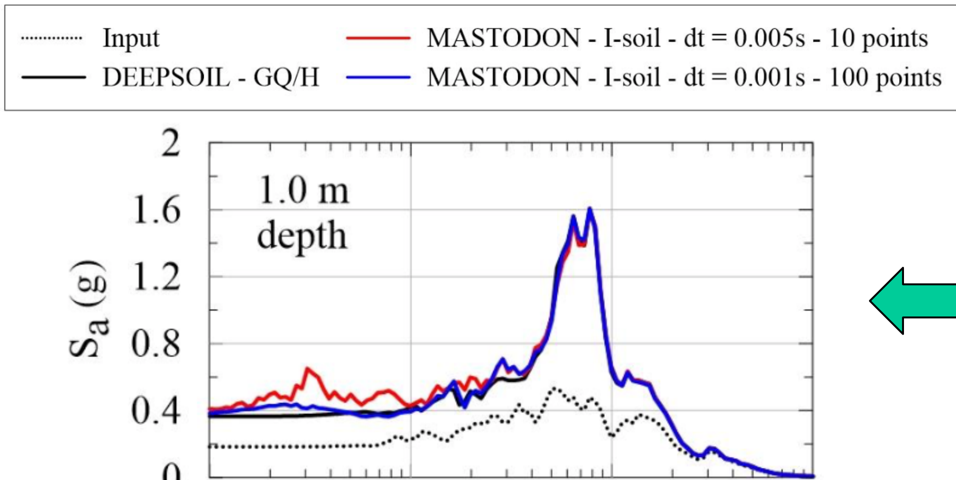
MASTODON Capabilities

- **Source-to-site simulation**
  - Fault rupture, complex wave-field input through Domain Reduction Method
- **Nonlinear soil-structure interaction**
  - iSoil - 3D multilinear, pressure-dependent hysteretic behavior
  - Gapping, sliding and uplift
- **Probabilistic risk assessment**
  - Automated PRA
  - Design optimization for safety and cost
- **SQA**
  - 'Documentation is code'
  - NQA-1

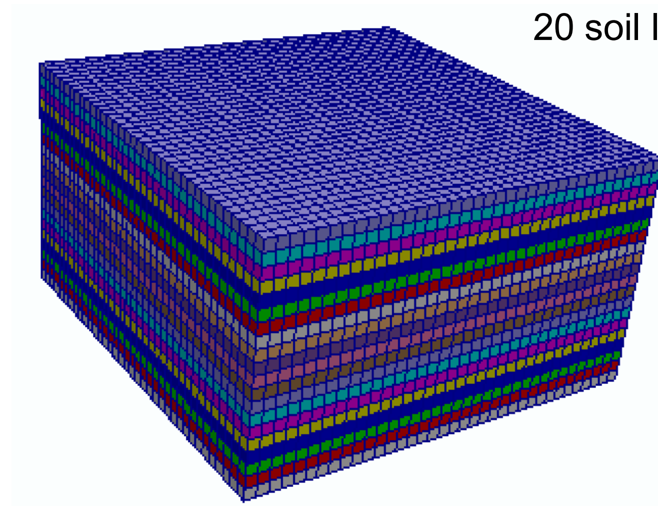


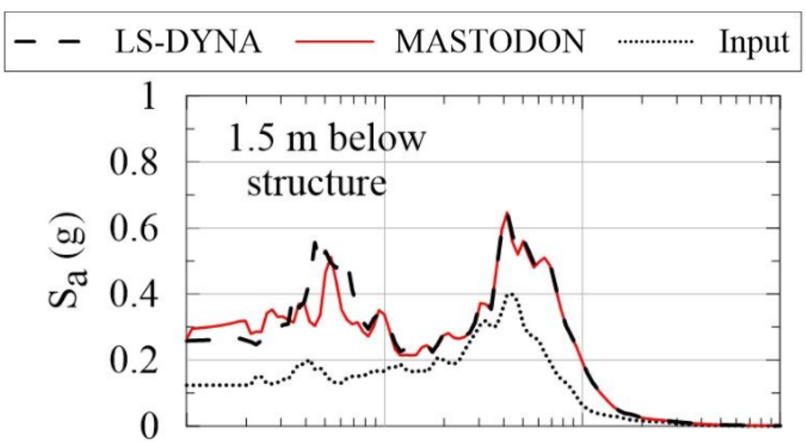


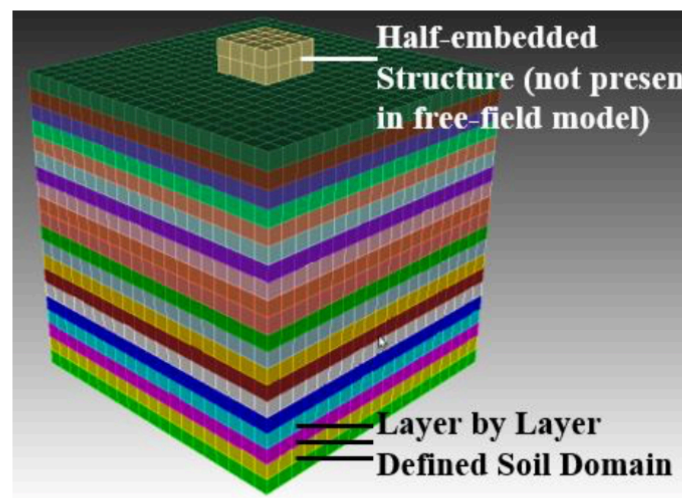
Nonlinear site-response and SSI analysis



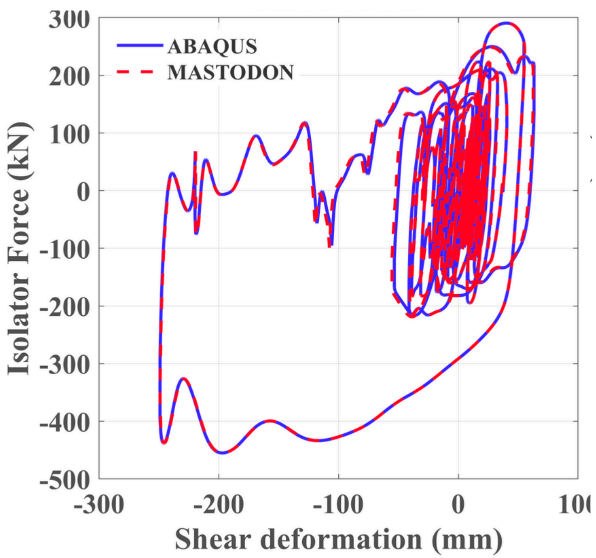
36 m x 36 m x 20 m
20 soil layers



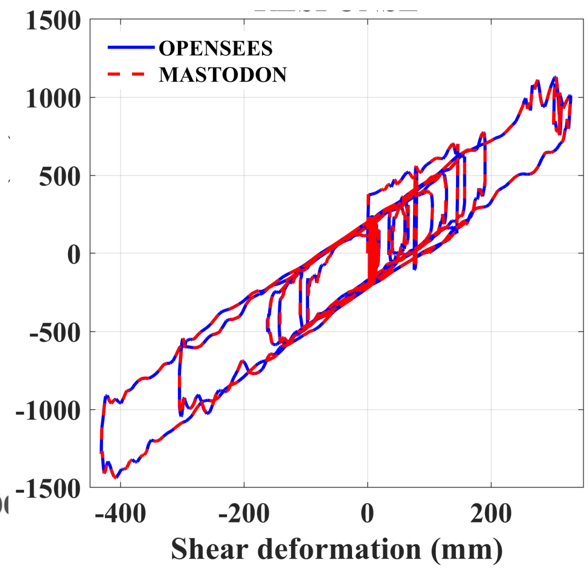




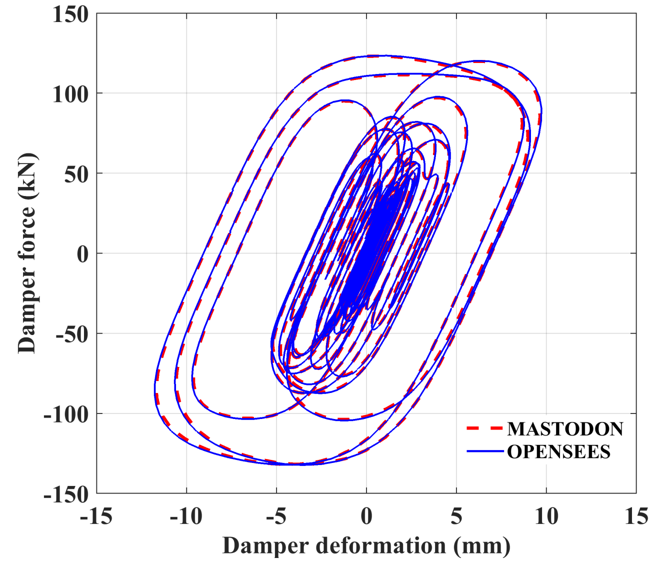
Seismic Protective Systems



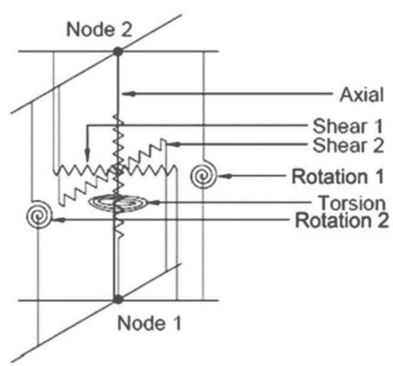
Lead-Rubber Bearing
Kumar et al (2014)

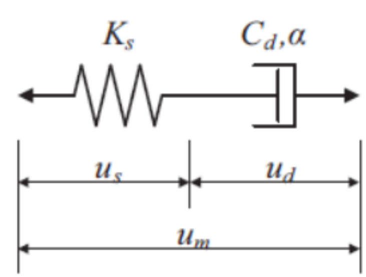


Friction-Pendulum Bearing
Kumar et al (2015)



Nonlinear Fluid-Viscous Damper (Maxwell model)





Idaho National Laboratory

Automation of SPRA calculations

Preprocessing

Probabilistic sampling of the input model

- Inputs seismic hazard curve for time-based assessment
- Sampling using LHC, Monte Carlo, etc., and automatically parallelized

↓

Simulation

Running simulations

↓

Postprocessing

Calculating fragilities

↓

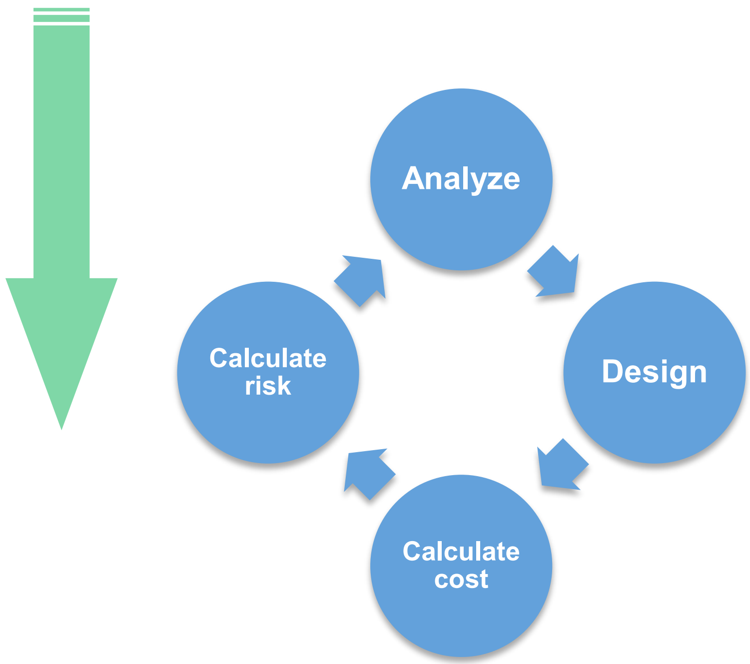
Fault-tree analysis and risk calculation

- **Inputs:** SSC capacities, fault trees and event trees
- **Outputs:** Component fragilities, minimal cutsets, associated probabilities, component importance measures, system fragilities and system risk *(benchmarked with Saphire)*

Risk+Cost-Based Design

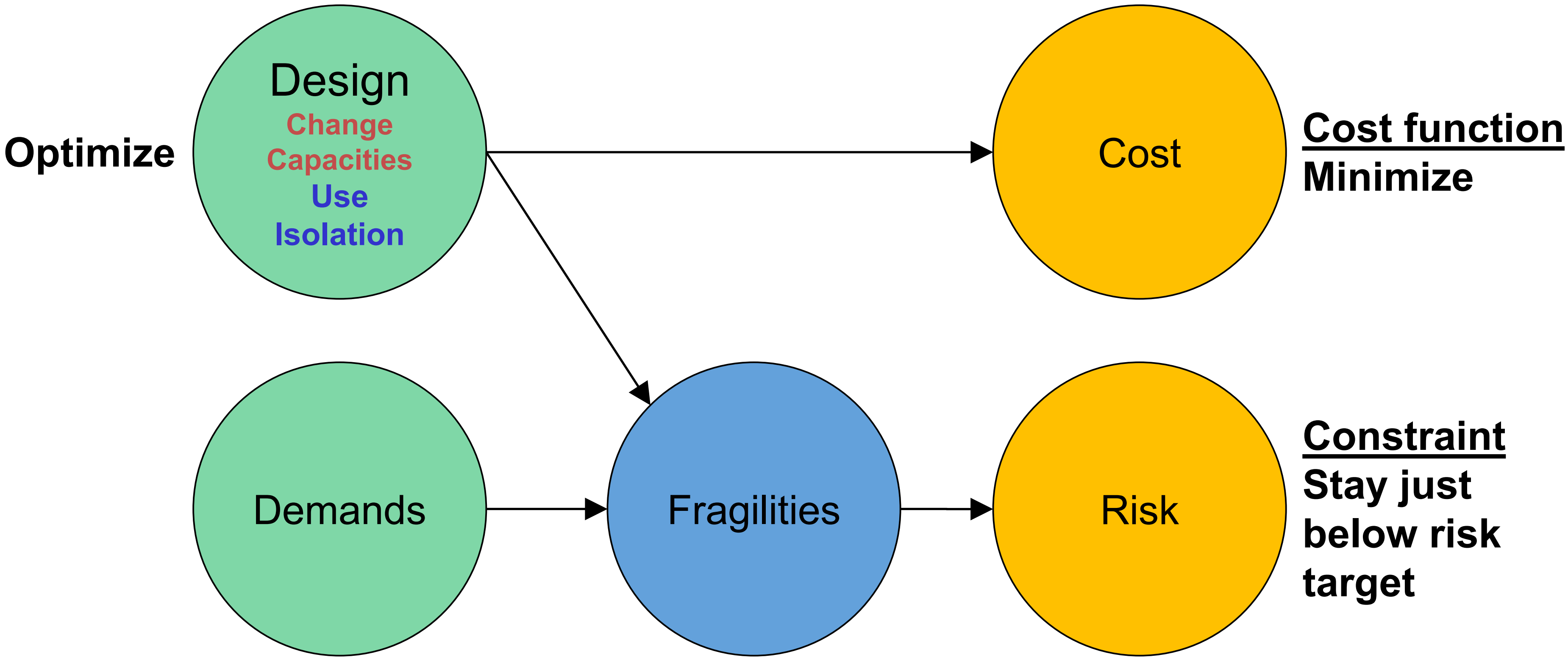
- Advance from risk-informed design to a risk-based design
- Optimize the design for both safety AND cost
- Enable strategic use of risk mitigation techniques such as seismic isolation and other energy dissipation mechanisms, as well as NLSSI modeling, to reduce capital cost while meeting safety goals
- Provide a ***decision-making*** tool and not just an analysis tool

Risk - informed design



Risk+cost - based design

Design optimization - Problem



Current projects

- Technology Commercialization Fund (TCF)
  - INL, MCEER, Southern Company, X-Energy, TerraPower
  - Fragility analysis using MASTODON
  - Safety & Cost optimization using MASTODON and DAKOTA
- ARPA-E Resource Team
  - Provide software tools to aid the progress of the project
  - Elements for seismic protective systems (LR Isolator, FP Isolator and Nonlinear Fluid Viscous Damper)
  - Explicit-implicit co-simulation to maximize computation speed

Acknowledgments

- Saran Bodda and Abhinav Gupta, NCSU
- Sharath Parsi and Andrew Whittaker, UB
- Will Hoffman and Justin Coleman, INL
- Advanced nuclear industry partners

How to work with us?

- GAIN [www.gain.inl.gov]
  - DOE NE vouchers
  - Technology Commercialization Funds
  - SBIR
  - Industry FOAs

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Application of seismic protective systems to advanced nuclear reactors

Andrew Whittaker, Ph.D., S.E.

SUNY Distinguished Professor

Director, MCEER

Department of Civil, Structural and Environmental Engineering

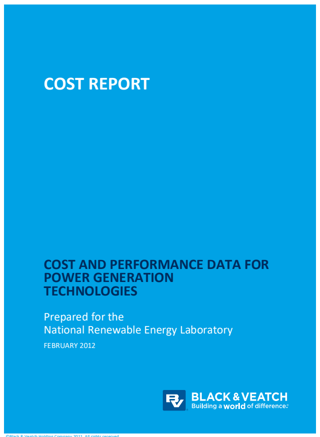
University at Buffalo

EARTHQUAKE ENGINEERING TO EXTREME EVENTS

Outline

- New build plants: cost drivers, performance
- Seismic isolation hardware and applications
- Key developments in the US
- Technology readiness
- Seismic isolation
    - Benefits
    - Guidance for analysis, design and testing
    - Numerical tools
    - Seismic probabilistic risk assessment
- Ongoing studies

New build nuclear power plants


COST REPORT

COST AND PERFORMANCE DATA FOR POWER GENERATION TECHNOLOGIES

Prepared for the
National Renewable Energy Laboratory

FEBRUARY 2012

BLACK & VEATCH
Building a world of difference.

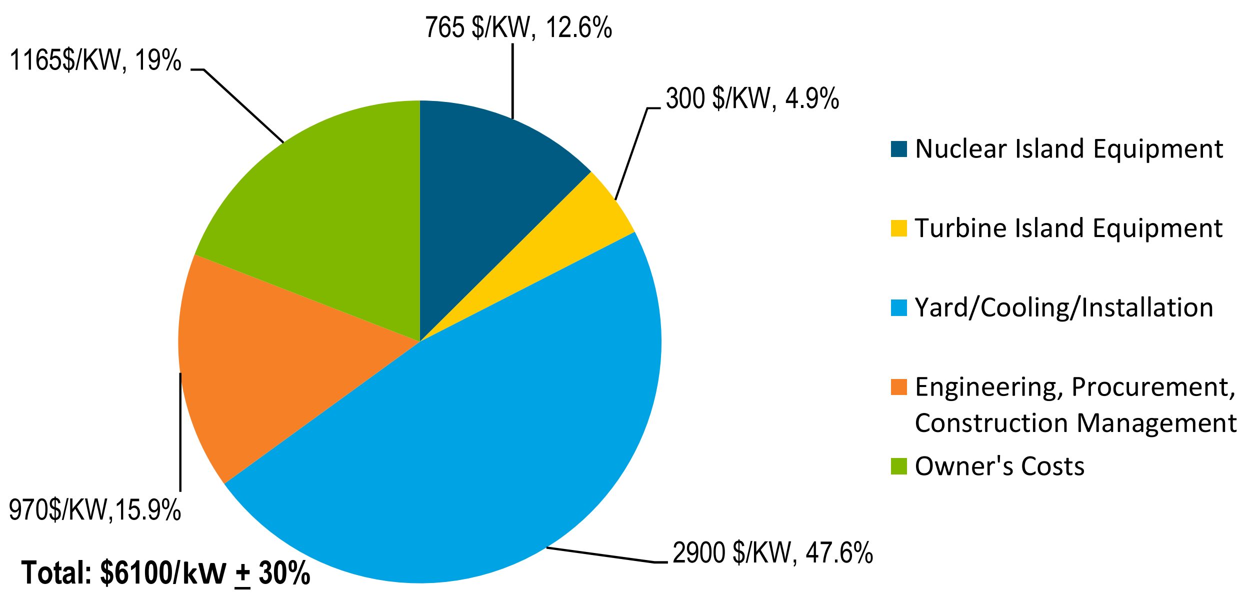
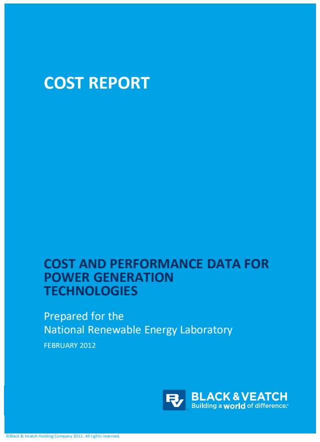


Figure 1. Capital cost breakdown for a nuclear power plant

New build nuclear power plants

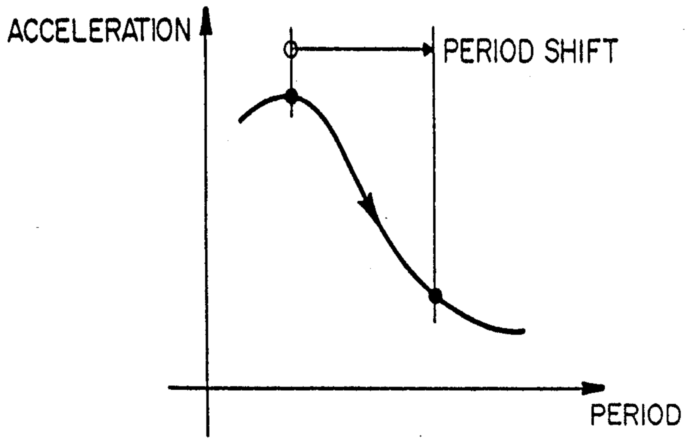
- Cost drivers for new build NPPs
  - Site-specific analysis, design and construction
  - Site-specific equipment designs and qualification
  - Regulatory review
  - Legacy methods for design and construction
  - Supply chains
  - Seismic load effects, vary by site
    - 30+% of overnight capital cost
    - 10+% to time to construct

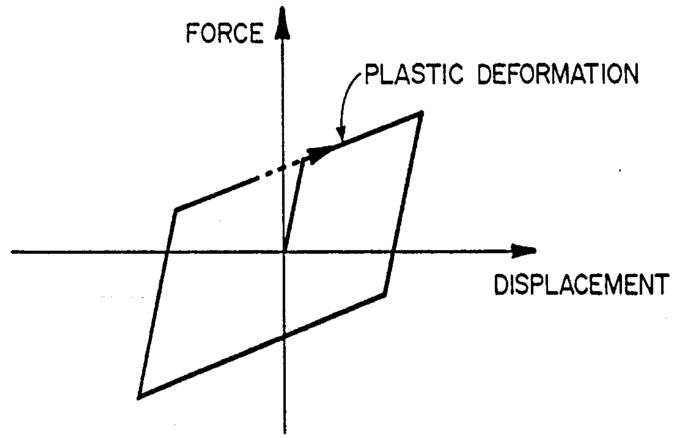


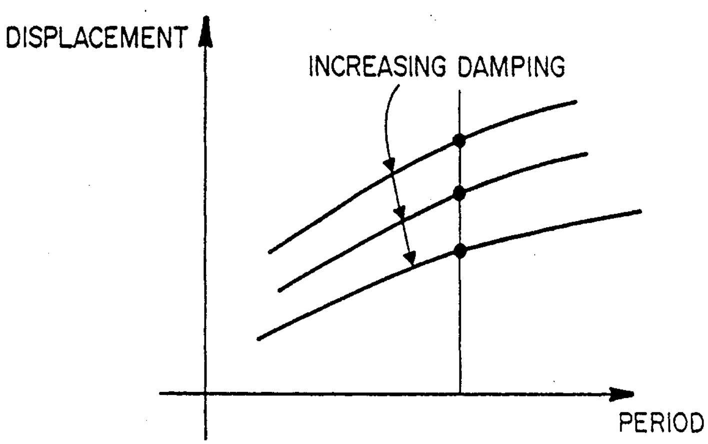
New build nuclear power plants

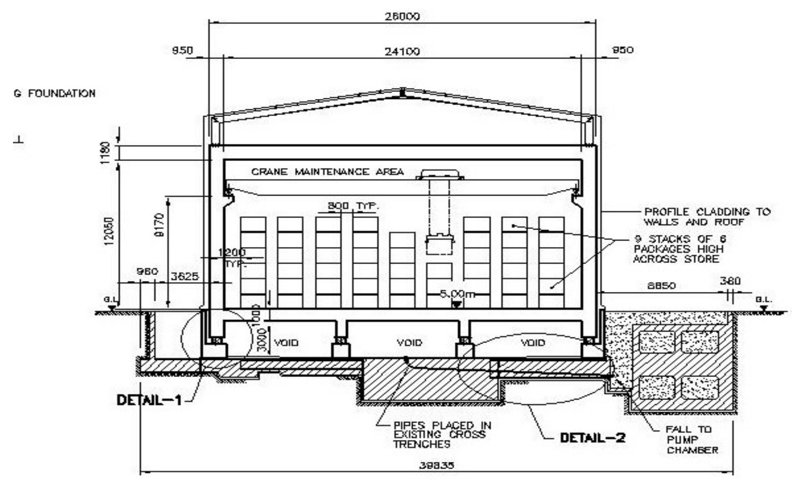
- Performance expectations
  - Performance metrics: function of reactor type
  - 1% NEP of unacceptable performance | DBE shaking
  - 10% NEP of unacceptable performance | BDBE shaking
  - DBE shaking: RP between 20000 and 50000 years
  - MAFE core damage < 0.000001
  - MAFE radiation release <0.0000001
  - Performance confirmed by seismic PRA

Seismic isolation

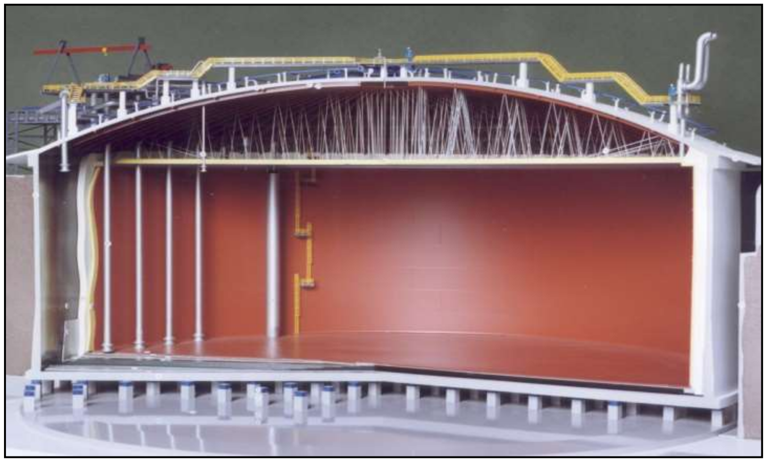




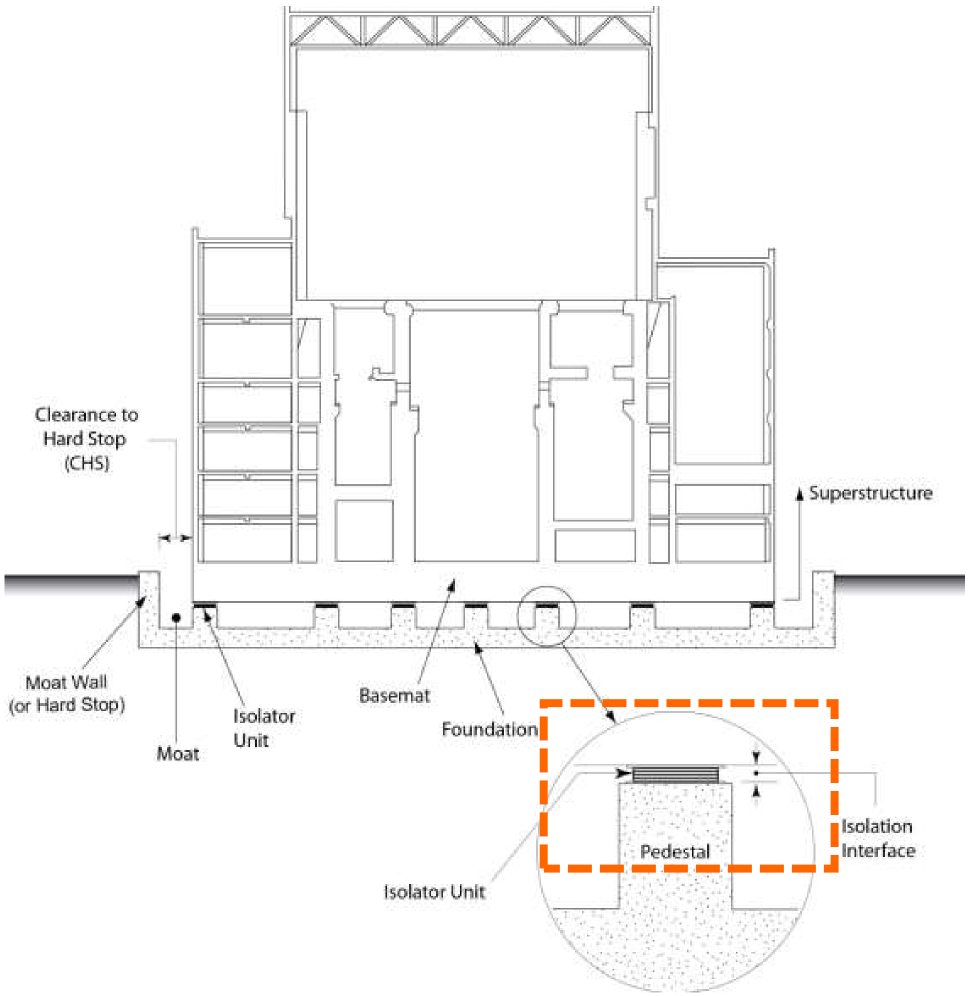


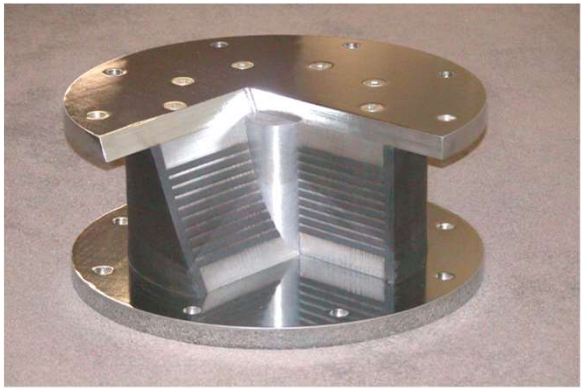


Seismic isolation



Seismic isolation





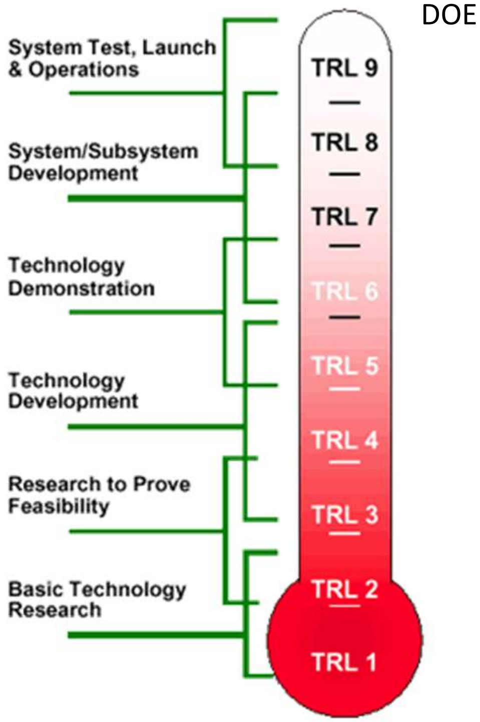
Key developments in the US

- Standards
  - ASCE 4-16
  - ASCE 43-19
- Reports
  - NUREG/CRs
  - INL
  - MCEER
- Journal articles
  - JSE, NED, ES
- SMiRT papers

- Topics covered
  - Modeling isolators
    - Elastomeric
    - Sliding
    - V+V
    - Implementation
  - Analysis, design, SSI
    - Isolators, superstructure
  - Seismic probabilistic risk assessment
  - Aircraft impact
  - Cost-benefit analysis

Technology readiness

- Proven technology and supply chain
- US utilized technology
  - LR bearings (Dynamic Isolation Systems)
  - FP bearings (Earthquake Protection Systems)
  - ISO QA procedures used to date
  - Commercial grade dedication or NQA-1
- Very high confidence in isolator behavior
  - Dynamic testing of prototype testing
  - All production bearings tested for DBE demands
- Deployed in mission-critical buildings in CA
  - Very high seismic hazard
  - 30+ year history of applications from both vendors
  - Design and testing all peer reviewed

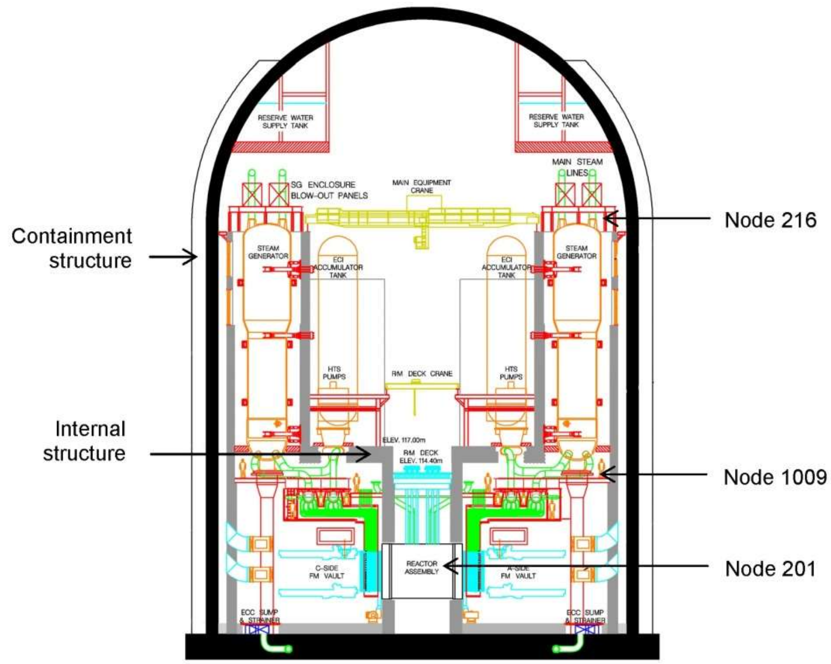


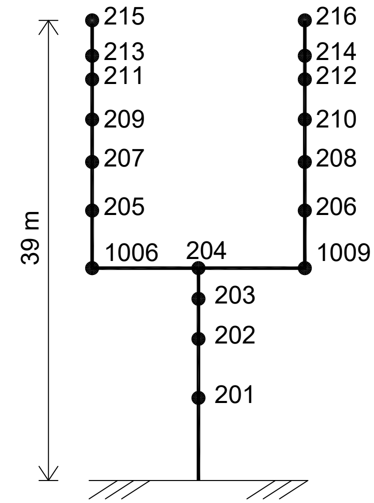
Benefits of isolation

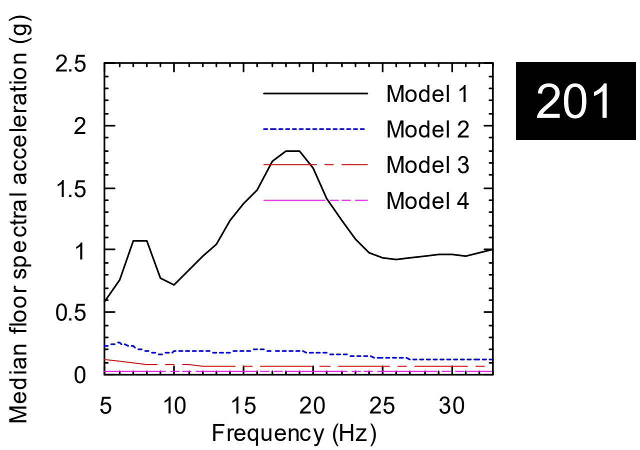
- Standardize buildings and internal SSCs
  - For CIS, horizontal spectral demand approximately constant with height
    - Increases substantially for conventional NPPs
  - Site-specific designs to address ONLY the isolation system
    - Internal equipment optimized for operation
      - No seismic penalty; one time qualification, if needed at all
      - Site independent; dramatic cost savings across *N* plants
    - Greatly simplified building design and seismic PRA
    - Reduced construction time, regulatory review
  - *Insurance* against increasing hazard at site
  - Enables construction of NPPs anywhere in the US

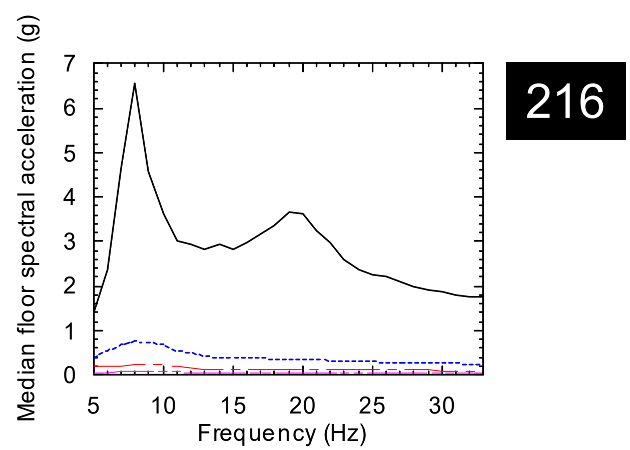
Benefits of isolation

- Reduce seismic risk
  - Isolation of a conventional NPP will reduce seismic risk by a factor of between 1000 and 1,000,000
    - Studies by Huang et al. in the late 2000s
    - Kumar et al. in 2016
    - Yu et al. in 2016
    - Explicit consideration of accident sequences triggered by failure of the isolation system
    - Can trade risk with overnight capital cost
  - Enables a more balanced risk portfolio across external hazards


Containment structure
Internal structure
Node 216
Node 1009
Node 201

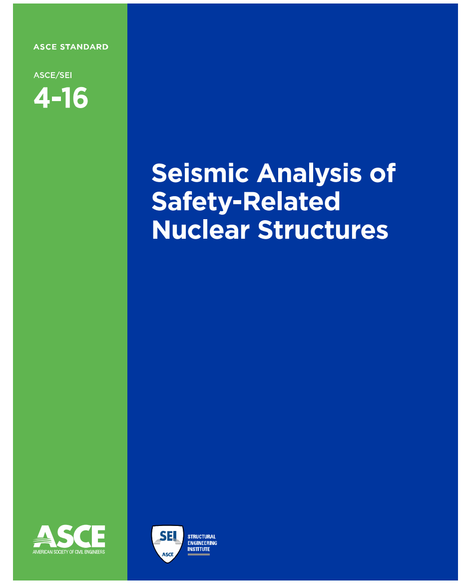

215
213
211
209
207
205
1006
204
1009
216
214
212
210
208
206
203
202
201
39 m


201
Median floor spectral acceleration (g)
Frequency (Hz)
Model 1
Model 2
Model 3
Model 4
0
0.5
1
1.5
2
2.5
5
10
15
20
25
30


216
Median floor spectral acceleration (g)
Frequency (Hz)
0
1
2
3
4
5
6
7
5
10
15
20
25
30

Technology readiness

- Regulatory guidance available
  - ASCE
    - Chapter 12 of ASCE 4-16
      - Analysis of isolated NPPs
    - Chapter 9 of ASCE 43-19
      - Design/testing of isolated NPPs
- NUREG/CRs
  - Technical considerations (7253)
  - Isolation of NPPs with sliding bearings (7254)
  - Isolation of NPPs with sliding bearings (7255)
- MCEER reports
  - 08-0019, 09-0008, 15-0006, 15-0008
  - http://www.buffalo.edu/mceer/publications-and-research.html



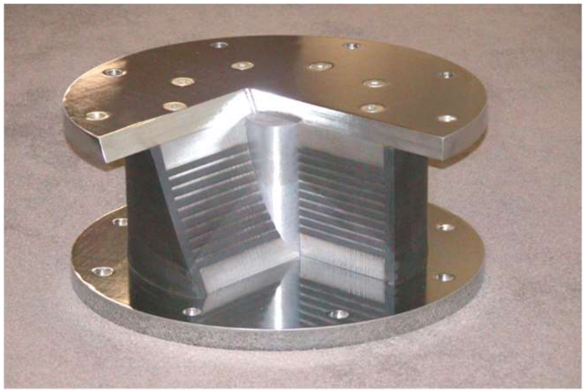
Risk-informed, performance-based

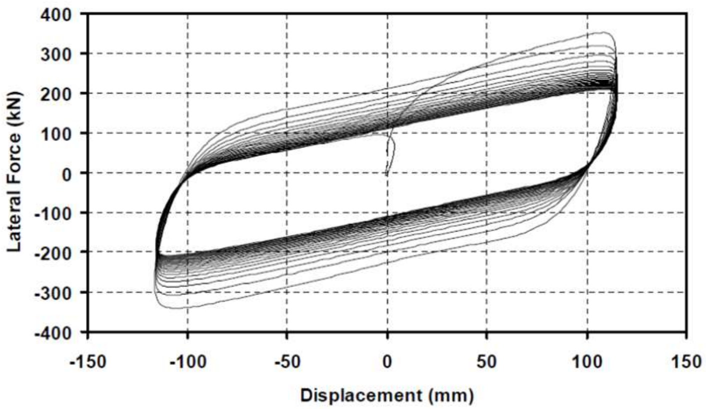
Hazard	Use	Isolation system			Superstructure	Other SSCs	Umbilical lines	Stop or Moat
		Isolation system displacement	Performance	Acceptance criteria	Performance	Performance		
DBE Response spectrum per Chapter 2	Production testing of isolators. Design loads for isolated superstructure. In-structure response spectra (ISRS).	Mean and 80^{th} percentile isolation system displacements.	No damage to the isolation system for DBE shaking.	Production testing of each isolator for the 80^{th} percentile isolation system displacement and corresponding axial force. Isolators damaged by testing cannot be used for construction.	Conform to consensus materials standards for 80^{th} 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 80^{th} 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).	90^{th} 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 90^{th} 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 90^{th} percentile displacement. Damage to the moat is acceptable in the event of contact.

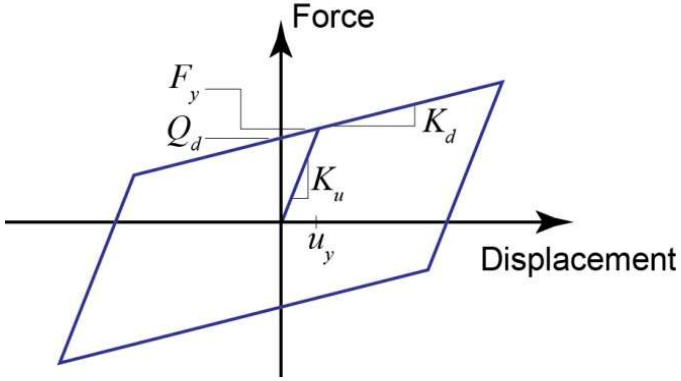
1. Can be achieved by satisfying the requirement for BDBE shaking.
2. 90^{th} percentile BDBE displacements may be calculated by multiplying the mean DBE displacement by a factor of 3.
3. The number of prototype isolators to be tested shall be sufficient to provide the required 90+% confidence.

Numerical modeling tools

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



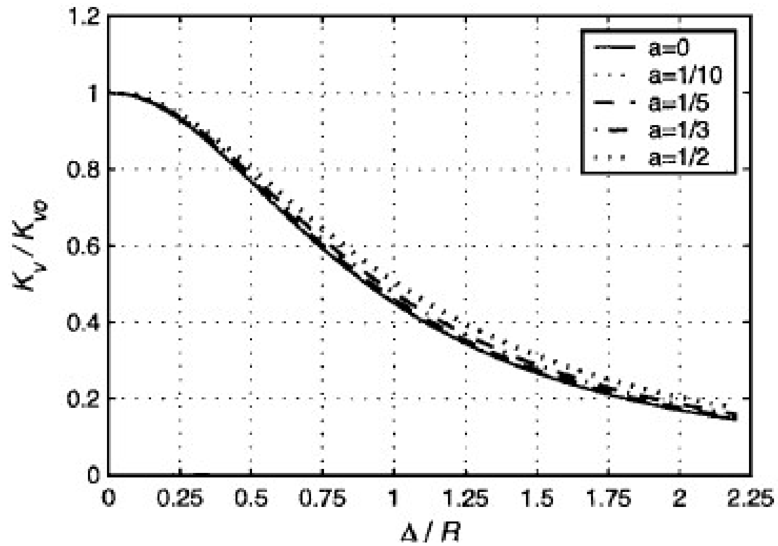


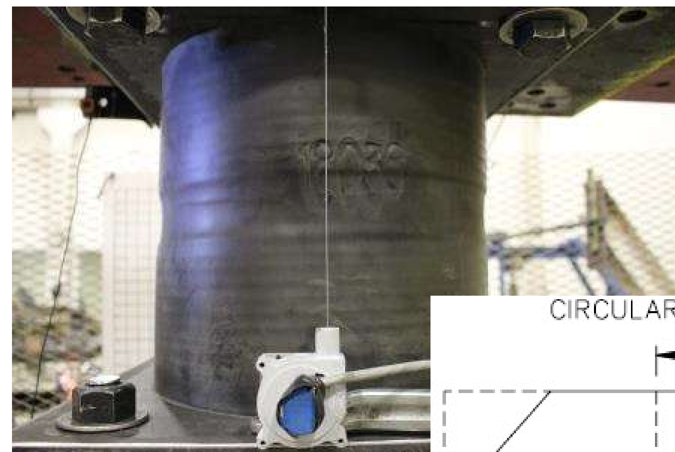


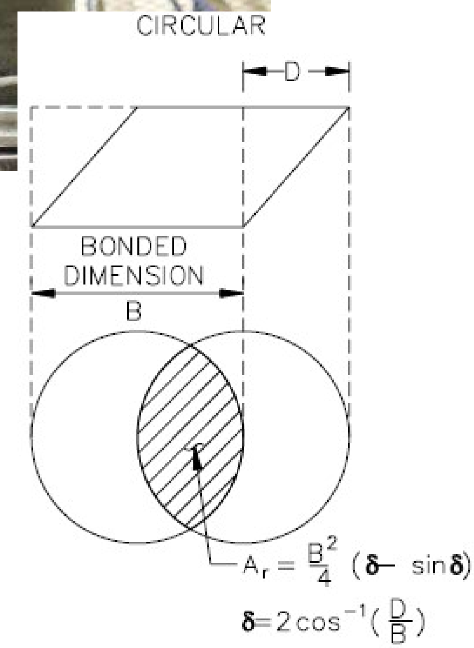
Numerical modeling tools

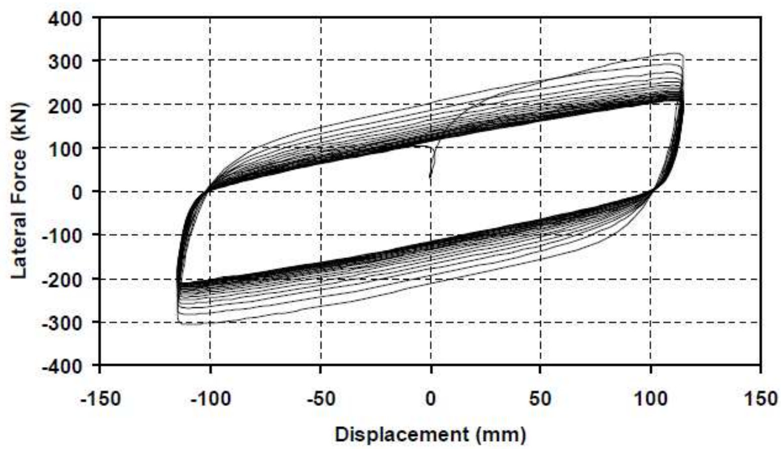
Properties	3DBASIS	SAP2000	PERFORM3D	LSDYNA	ABAQUS	OpenSees	New
Coupled horizontal directions	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Coupled horizontal and vertical directions	No	No	No	No	No	No	Yes
Different tensile and compressive stiffness	No	No	Yes	Yes	Yes	Yes	Yes
Nonlinear tensile behavior	No	No	No	No	Yes	Yes	Yes
Cavitation and post-cavitation	No	No	No	No	No	No	Yes
Nonlinear compressive behavior	No	No	No	No	Yes	Yes	Yes
Varying buckling capacity	No	No	No	No	No	No	Yes
Heating of lead core	No	No	No	No	No	No	Yes

Numerical modeling tools



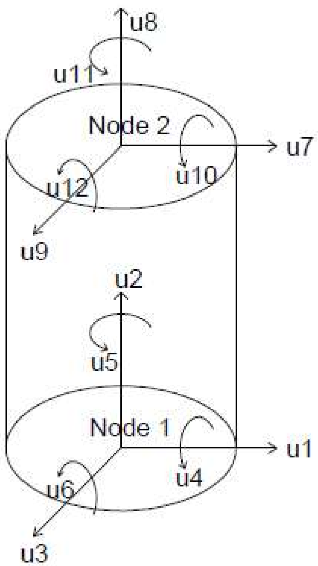




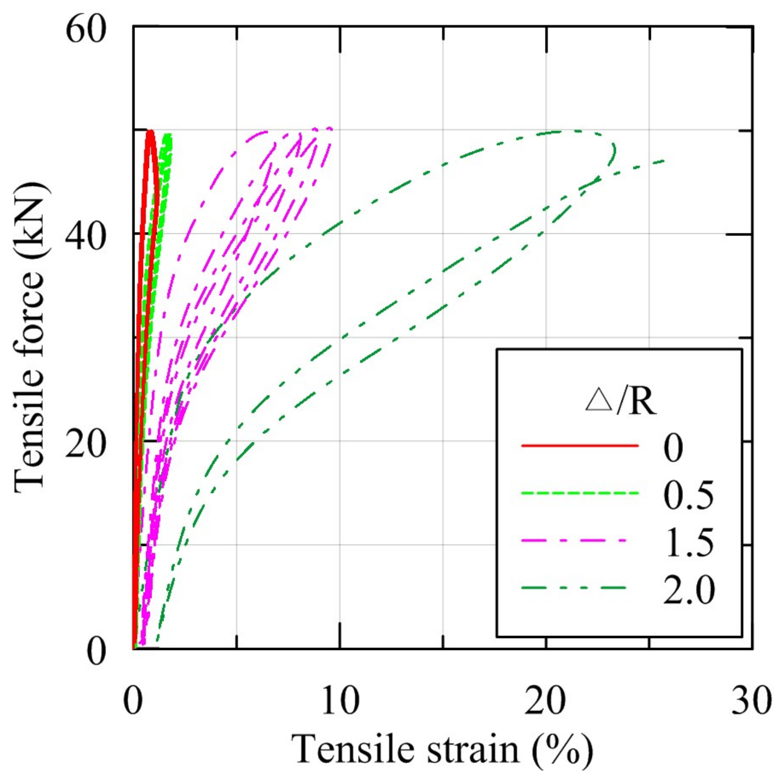


Numerical modeling tools

- User elements in OpenSees and ABAQUS
  - ElastomericX for LDR bearing
  - LeadRubberX for LR bearing
  - HDRX for HDR bearing
- Models in LS-DYNA
- Two node, 12 DOF, 3D element
- Features
  - Strength degradation in shear due to lead core heating
  - Variation in buckling load due to horizontal displacement
  - Cavitation and post-cavitation behavior due to tensile loading
  - Variation in axial stiffness due to horizontal displacement
  - Variation in shear stiffness due to axial load
- Verification and validation per ASME 2006

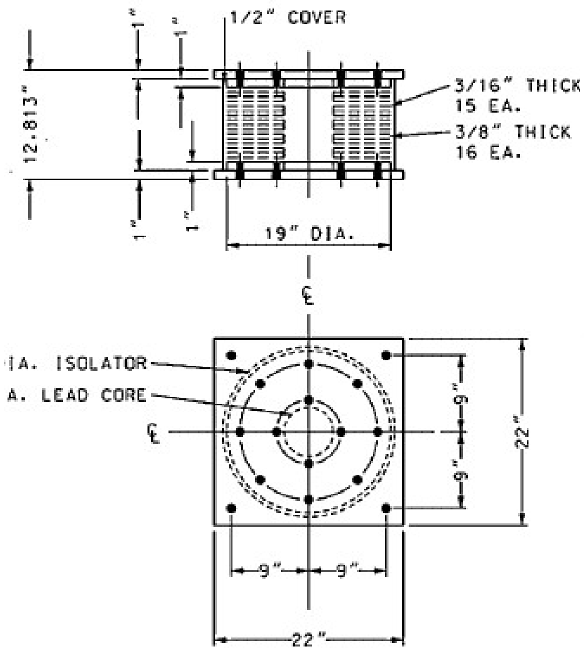


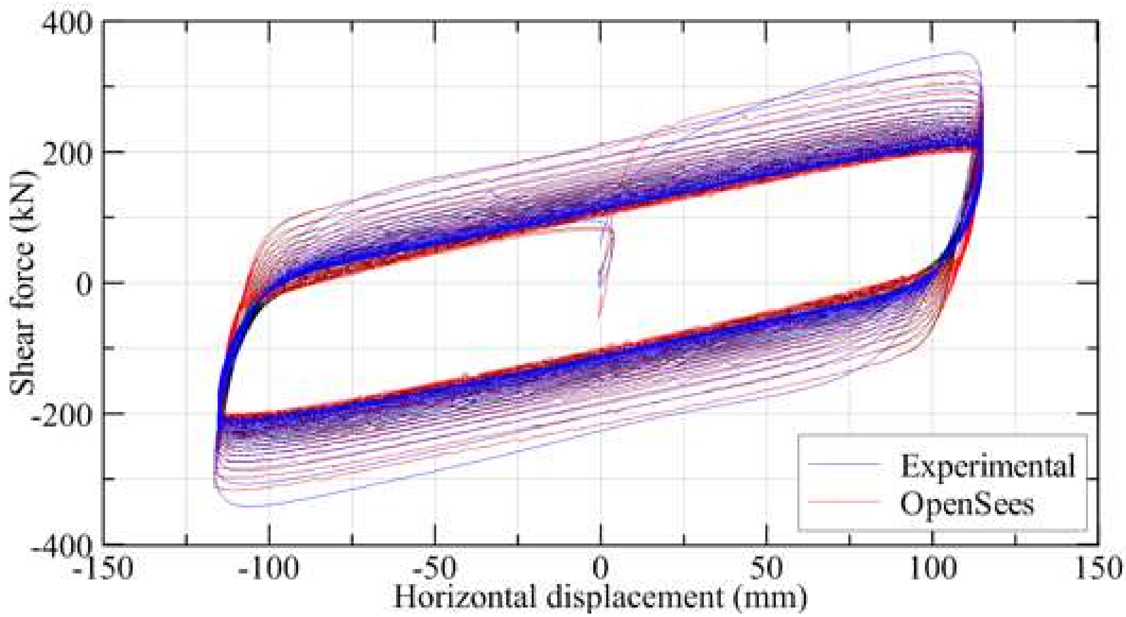
Numerical modeling tools



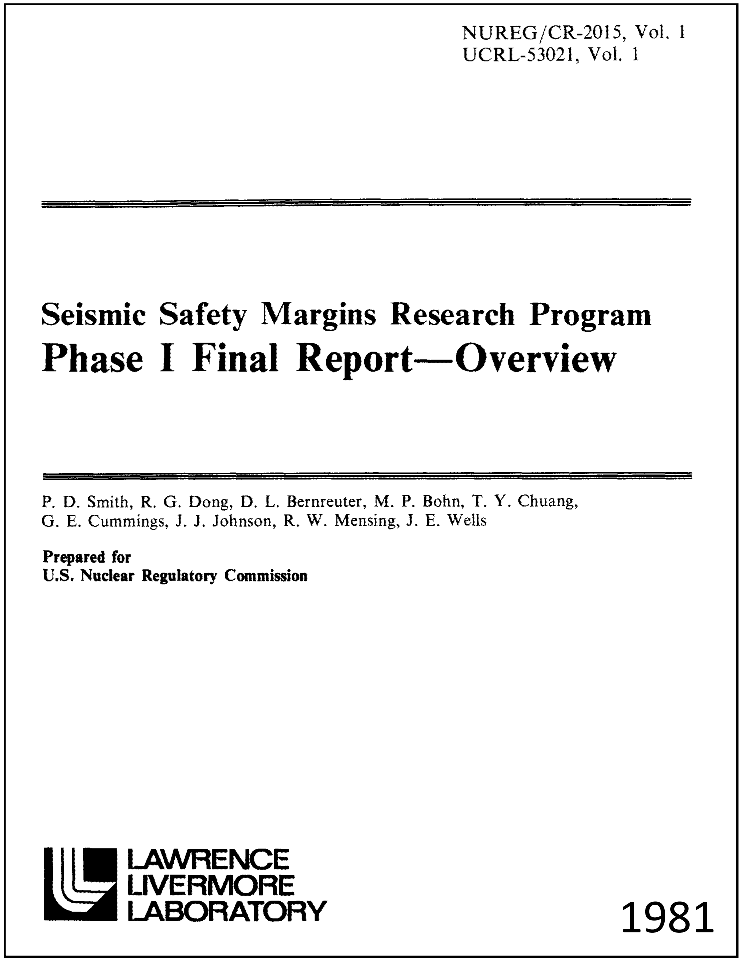
EARTHQUAKE ENGINEERING TO EXTREME EVENTS

Numerical modeling tools





Advanced seismic PRA


NUREG/CR-2015, Vol. 1
UCRL-53021, Vol. 1

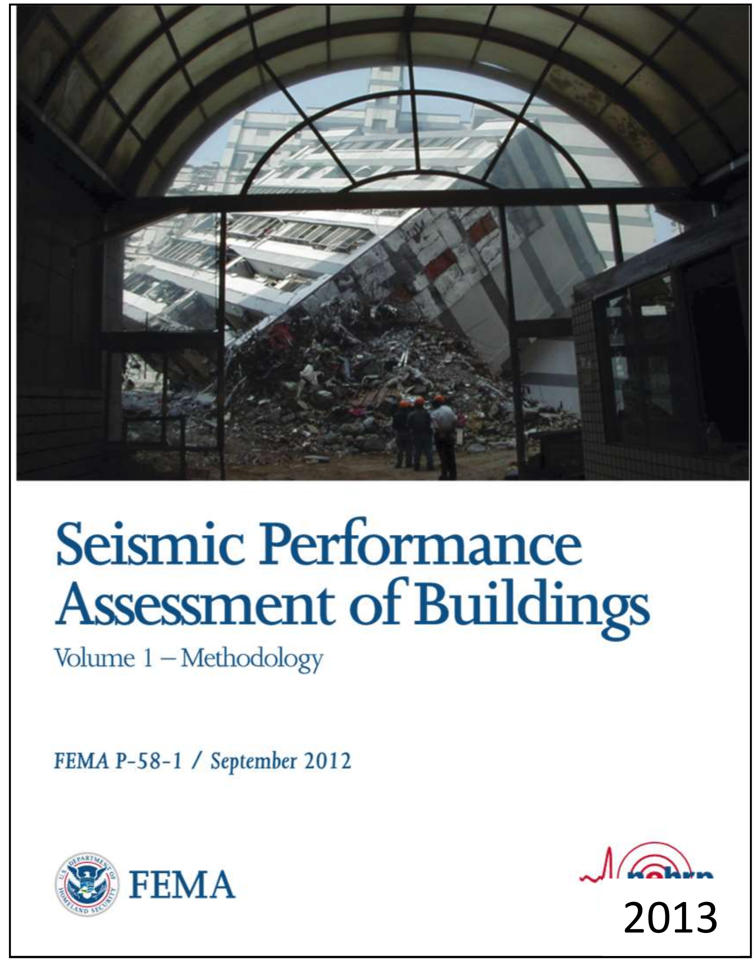
Seismic Safety Margins Research Program
Phase I Final Report—Overview

P. D. Smith, R. G. Dong, D. L. Bernreuter, M. P. Bohn, T. Y. Chuang, G. E. Cummings, J. J. Johnson, R. W. Mensing, J. E. Wells

Prepared for
U.S. Nuclear Regulatory Commission

LAWRENCE LIVERMORE LABORATORY

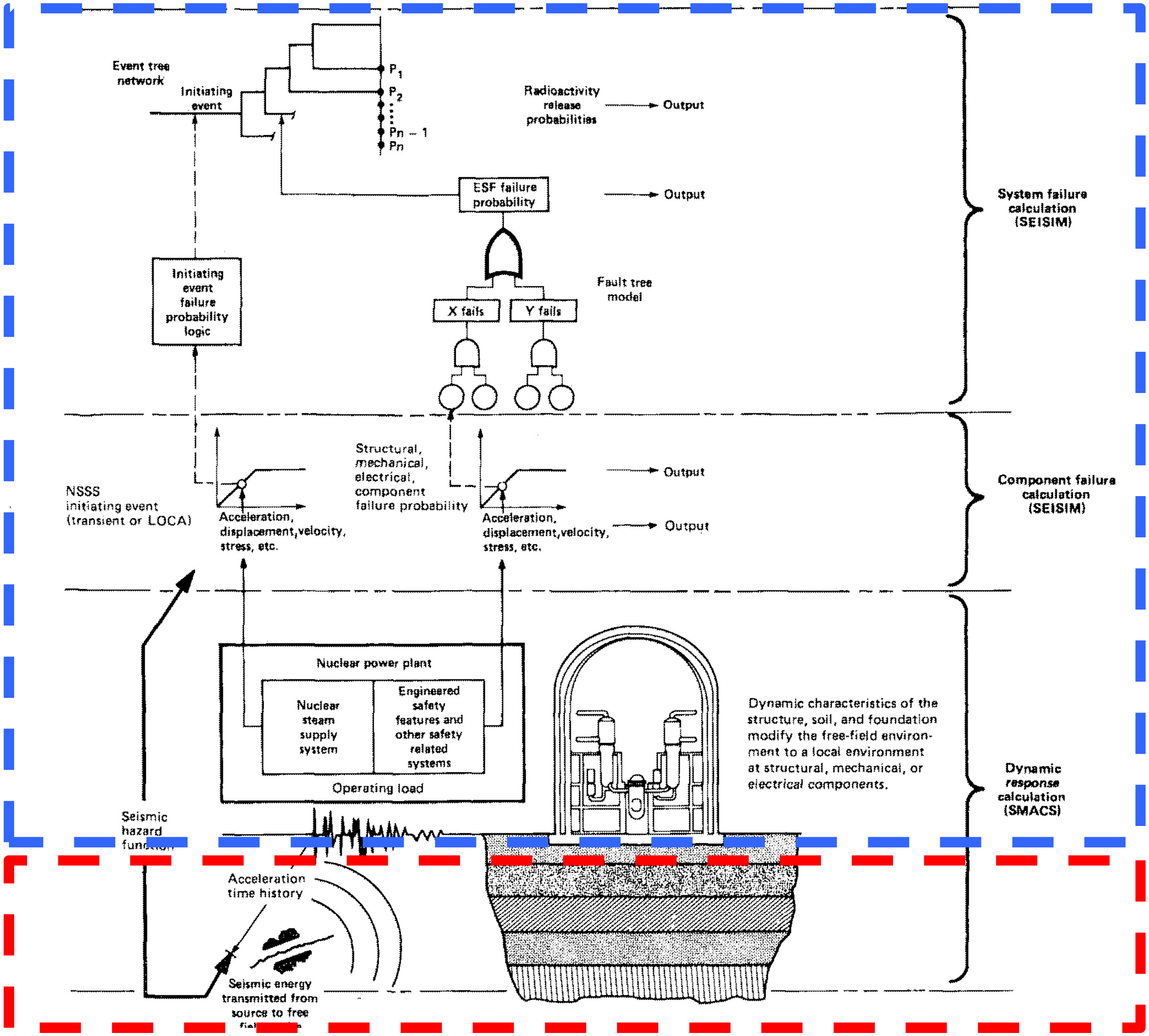
1981


Seismic Performance Assessment of Buildings
Volume 1 – Methodology

FEMA P-58-1 / September 2012

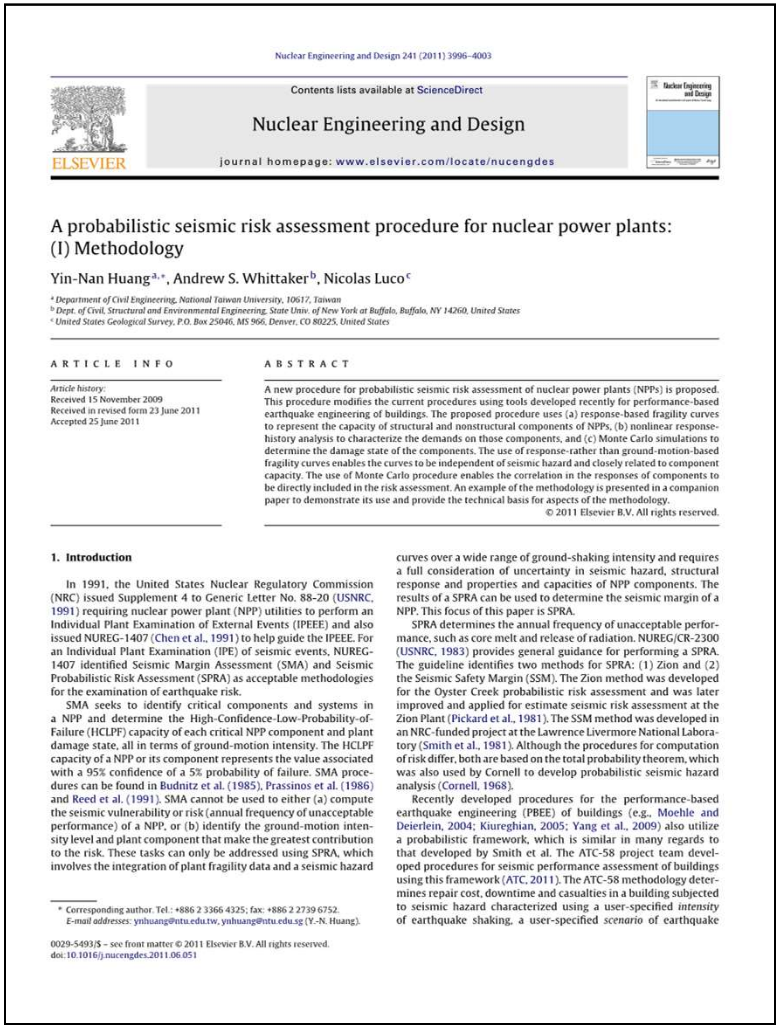
FEMA

2013



Event tree network
Initiating event
P1
P2
Pn – 1
Pn
Radioactivity release probabilities
Output
ESF failure probability
Output
Fault tree model
X fails
Y fails
Initiating event failure probability logic
System failure calculation (SEISIM)
Structural, mechanical, electrical, component failure probability
Output
Output
NSSS initiating event (transient or LOCA)
Acceleration, displacement, velocity, stress, etc.
Acceleration, displacement, velocity, stress, etc.
Component failure calculation (SEISIM)
Nuclear power plant
Nuclear steam supply system
Engineered safety features and other safety related systems
Operating load
Dynamic characteristics of the structure, soil, and foundation modify the free-field environment to a local environment at structural, mechanical, or electrical components.
Dynamic response calculation (SMACS)
Seismic hazard
Acceleration time history
Seismic energy transmitted from source to free

Advanced seismic PRA



Nuclear Engineering and Design 241 (2011) 3996–4003

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A probabilistic seismic risk assessment procedure for nuclear power plants: (I) Methodology

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ABSTRACT

A new procedure for probabilistic seismic risk assessment of nuclear power plants (NPPs) is proposed. This procedure modifies the current procedures using tools developed recently for performance-based earthquake engineering of buildings. The proposed procedure uses (a) response-based fragility curves to represent the capacity of structural and nonstructural components of NPPs, (b) nonlinear response-history analysis to characterize the demands on those components, and (c) Monte Carlo simulations to determine the damage state of the components. The use of response-rather than ground-motion-based fragility curves enables the curves to be independent of seismic hazard and closely related to component capacity. The use of Monte Carlo procedure enables the correlation in the responses of components to be directly included in the risk assessment. An example of the methodology is presented in a companion paper to demonstrate its use and provide the technical basis for aspects of the methodology.

1. Introduction

In 1991, the United States Nuclear Regulatory Commission (NRC) issued Supplement 4 to Generic Letter No. 88-20 (USNRC, 1991) requiring nuclear power plant (NPP) utilities to perform an Individual Plant Examination of External Events (IPEEE) and also issued NUREG-1407 (Chen et al., 1991) to help guide the IPEEE. For an Individual Plant Examination (IPE) of seismic events, NUREG-1407 identified Seismic Margin Assessment (SMA) and Seismic Probabilistic Risk Assessment (SPRA) as acceptable methodologies for the examination of earthquake risk.

SMA seeks to identify critical components and systems in a NPP and determine the High-Confidence-Low-Probability-of-Failure (HCLPF) capacity of each critical NPP component and plant damage state, all in terms of ground-motion intensity. The HCLPF capacity of a NPP or its component represents the value associated with a 95% confidence of a 5% probability of failure. SMA procedures can be found in Budnitz et al. (1985), Prassinos et al. (1986) and Reed et al. (1991). SMA cannot be used to either (a) compute the seismic vulnerability or risk (annual frequency of unacceptable performance) of a NPP, or (b) identify the ground-motion intensity level and plant component that make the greatest contribution to the risk. These tasks can only be addressed using SPRA, which involves the integration of plant fragility data and a seismic hazard curves over a wide range of ground-shaking intensity and requires a full consideration of uncertainty in seismic hazard, structural response and properties and capacities of NPP components. The results of a SPRA can be used to determine the seismic margin of a NPP. This focus of this paper is SPRA.

SPRA determines the annual frequency of unacceptable performance, such as core melt and release of radiation. NUREG/CR-2300 (USNRC, 1983) provides general guidance for performing a SPRA. The guideline identifies two methods for SPRA: (1) Zion and (2) the Seismic Safety Margin (SSM). The Zion method was developed for the Oyster Creek probabilistic risk assessment and was later improved and applied for estimate seismic risk assessment at the Zion Plant (Pickard et al., 1981). The SSM method was developed in an NRC-funded project at the Lawrence Livermore National Laboratory (Smith et al., 1981). Although the procedures for computation of risk differ, both are based on the total probability theorem, which was also used by Cornell to develop probabilistic seismic hazard analysis (Cornell, 1968).

Recently developed procedures for the performance-based earthquake engineering (PBEE) of buildings (e.g., Moehle and Deierlein, 2004; Kiureghian, 2005; Yang et al., 2009) also utilize a probabilistic framework, which is similar in many regards to that developed by Smith et al. The ATC-58 project team developed procedures for seismic performance assessment of buildings using this framework (ATC, 2011). The ATC-58 methodology determines repair cost, downtime and casualties in a building subjected to seismic hazard characterized using a user-specified *intensity* of earthquake shaking, a user-specified *scenario* of earthquake

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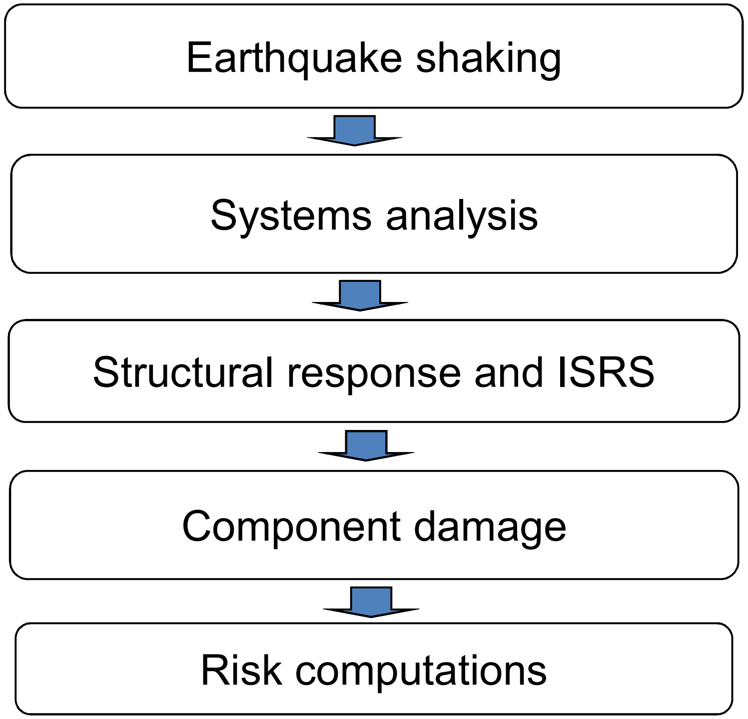
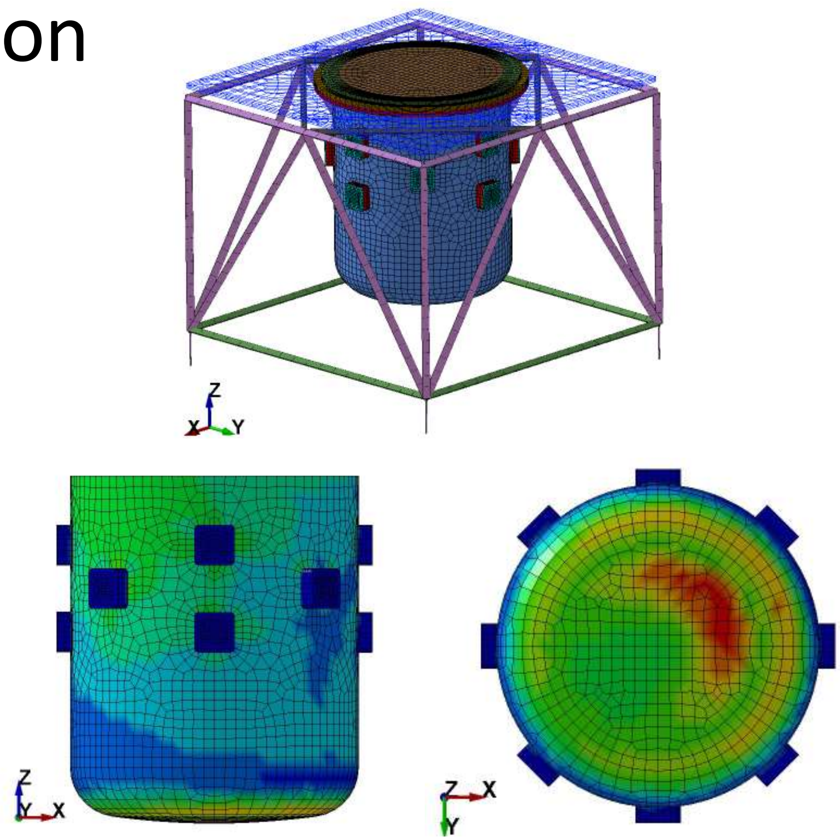


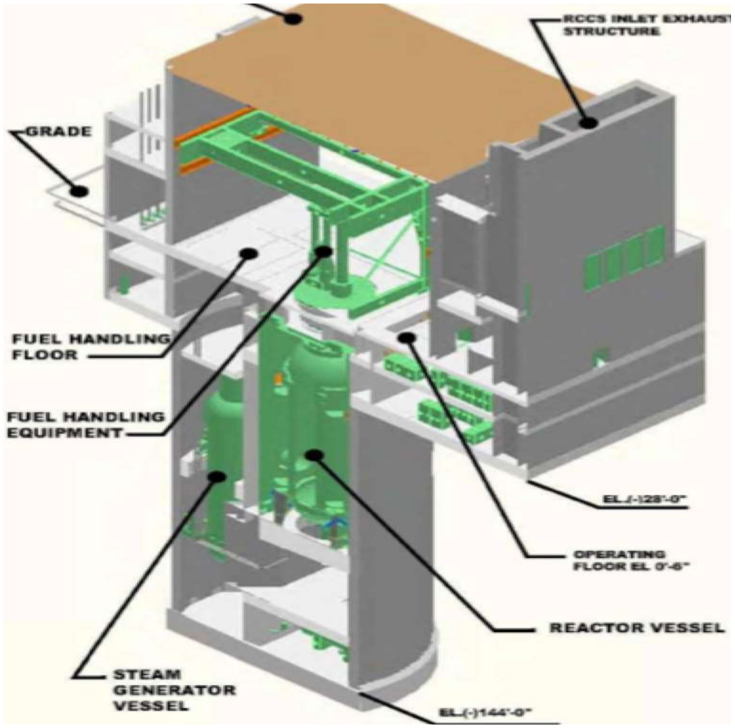
On-going: DOE + TerraPower

- Fluid-structure interaction
  - Liquid metal reactors
  - Analytical solutions
  - Verification
  - Validation
    - Simulator testing
  - Benefits of isolation
  - Seismic qualification
  - SMiRT25



On-going: EPRI

- Seismic isolation of advanced reactors
  - Literature review
  - Costs and benefits
    - Building isolation
    - Equipment isolation
    - Overnight capital cost
  - Future research needs
  - SMiRT25



On-going: DOE TCF

- Seismic optimization of advanced reactor designs
  - INL, Southern Company, TerraPower, X-energy, MCEER
  - Protective systems: 2D and 3D isolators, dampers
  - MASTODON
    - Open source time domain code
    - Response-history analysis, PRA, optimization
    - SQA, NQA-1
    - LR bearing, nonlinear FVD, FP bearing
    - Verified and validated models
  - PRA tools under development
  - Optimization tools under development
    - Minimize a combination of cost and seismic risk
  - SMiRT25

On-going: ARPA-E

- Equipment-based seismic protective systems
  - MIT, EPRI, TerraPower, X-Energy, SC Solutions, Exponent
  - Optimize equipment for operational performance
  - Eight integrated tasks, including
    - Design spaces for safety-class equipment
    - Develop, prototype and testing of *protective packages*
    - V+V numerical models of *protective packages*
    - MIL qualification procedures
    - Standards development (ASCE 4 and 43) and TTO
  - SMiRT25

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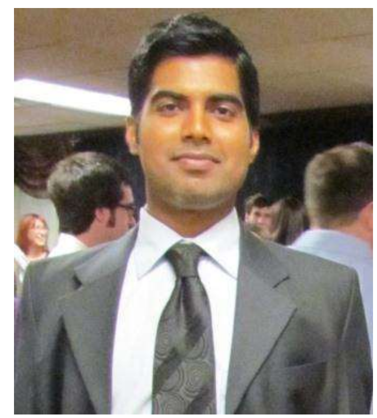
- TerraPower, X-energy, Southern Company
- Electric Power Research Institute
  - Dr. David Scott



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Protecting People and the Environment

Development of Generic Seismic Hazard Curves to Support Design Process

Martin Stutzke
Division of Safety Systems, Risk Assessment, and Advanced Reactors
Office of New Reactors

February 7, 2019

Background

- Current staff position for LWR licensing:
  - Submit results of PRA-based SMA with application
  - Risk-informed acceptance guideline: plant-level HCLPF ≥ 1.67 SSE
  - Complete seismic PRA 6 months prior to initial fuel loading
- LMP Guidance Document (NEI 18-04) PRA scope for non-LWR licensing:
  - All radiological sources
  - All hazards, e.g., seismic PRA (not PRA-based SMA)
  - All operating modes
  - Multi-module and multi-source risks

Observations and Challenges

- SMA does not directly support the LMP process because it does not estimate sequence frequencies, risks, or risk surrogates (CDF, LRF)
- The current HCLPF acceptance guideline is based on an understanding of LWR seismic risk surrogates when the guideline was originally adopted (SRM to SECY-93-087, 7/21/1993). However, our understanding of seismic hazard has evolved:
  - Generic Issue 199, "Implications of Updated Probabilistic Seismic Hazard Estimates in Central and Eastern U.S. for Existing Plants," 6/9/2005
  - Fukushima NTTF Rec. 2.1, 7/12/2011
- Very limited understanding of non-LWR seismic risks.
- **How to do a seismic PRA without identifying a site?**

One Possible Approach

- Compile updated seismic hazard estimates for all existing sites from the licensee responses to the 50.54(f) letter concerning Fukushima NTTF Rec. 2.1.
- Assume that the set of existing sites forms a random sample from the population of potential sites.
- Determine pointwise 80%/95% upper tolerance limits (UTLs):
  - 80% population coverage
  - 95% confidence level
  - There is an UTL for each triple (spectral frequency, acceleration, statistic – mean and fractiles).

Example: For the 100 Hz (PGA) seismic hazard curve at 0.3 g, the mean annual exceedance frequency (AEF) is less than or equal to "x" (x is the UTL) for 80% of the population of potential sites, with 95% confidence.

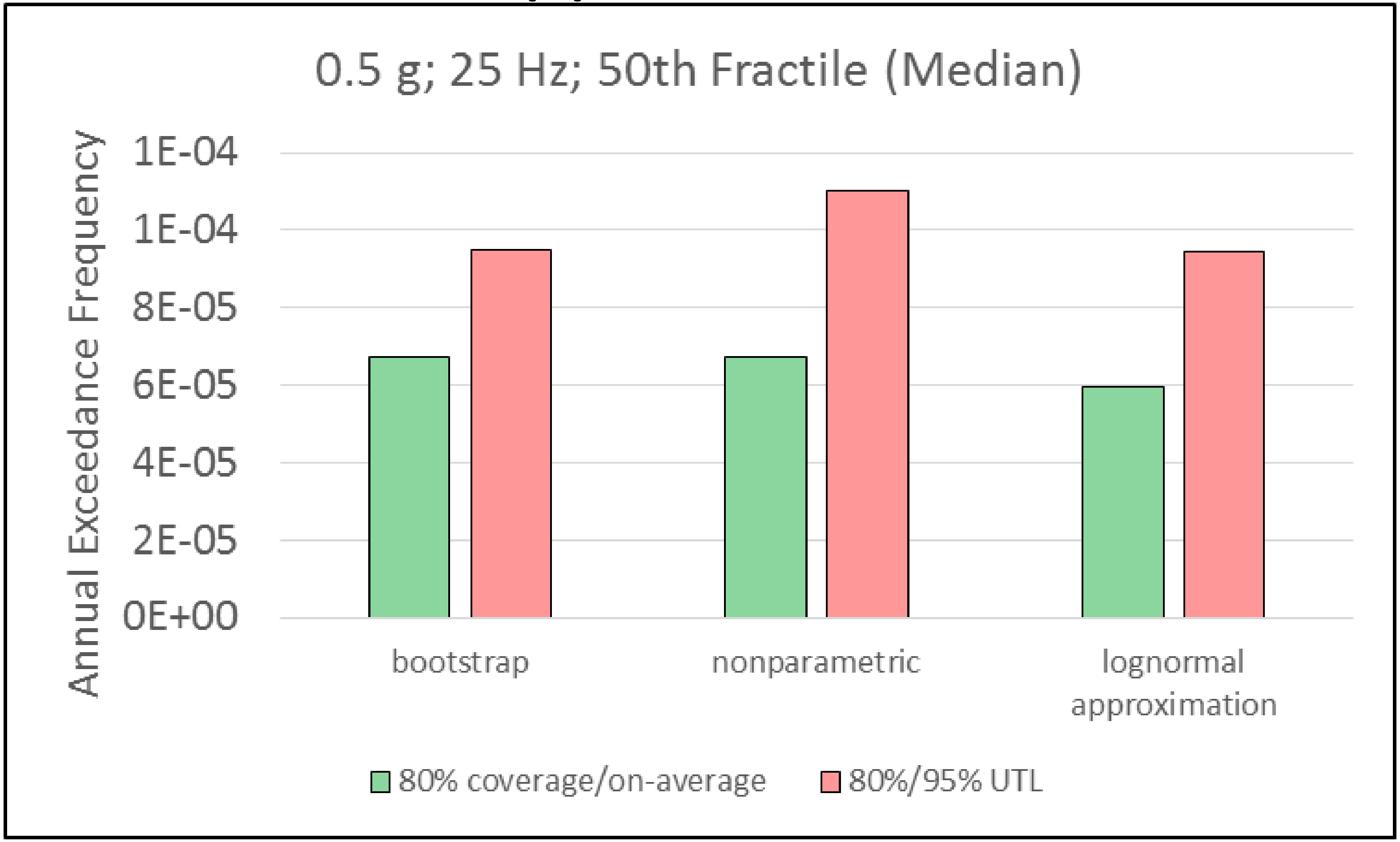
Information Sources

- Licensee responses to the 10 CFR 50.54(f) letter concerning Fukushima NTTF Rec. 2.1.
- Sites (59 total):
  - Co-located plants treated as a single site
  - Includes all issued ESPs (all are co-located with existing sites)
- Accelerations (13 total):
  - 0.01, 0.015, 0.03, 0.05, 0.075, 0.1, 0.15, 0.3, 0.5, 0.75, 1, 1.5, 3 g
  - Log-log linear interpolation for seven sites
  - No extrapolation
- Spectral frequencies (7 total):
  - 100 (PGA), 25, 10, 5, 2.5, 1, 0.5 Hz
  - Log-log rational function interpolation to estimate the 25 Hz curve for two sites
- Statistics (6 total): mean and five fractiles (5th, 16th, 50th, 84th, and 95th)

Upper Tolerance Limits

- Methods
  - Bootstrap percentile method
  - Nonparametric method
  - Lognormal approximation
- Overall observations
  - All methods produce similar numerical results
  - Anderson-Darling hypothesis tests indicate that the lognormal approximation is not always valid

Results – Comparison of On-Average Values to Upper Tolerance Limits



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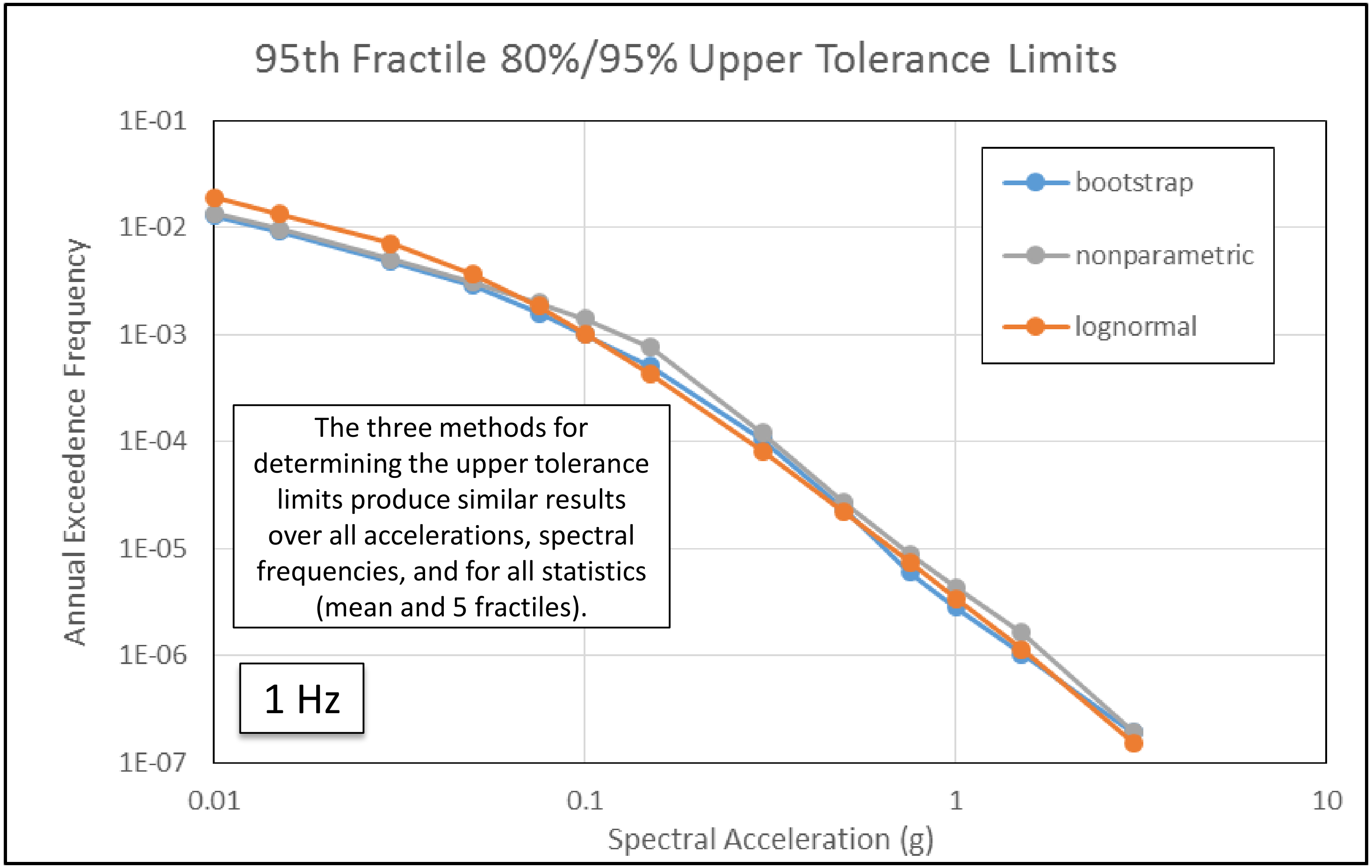
Results – Comparison of ULT Methods



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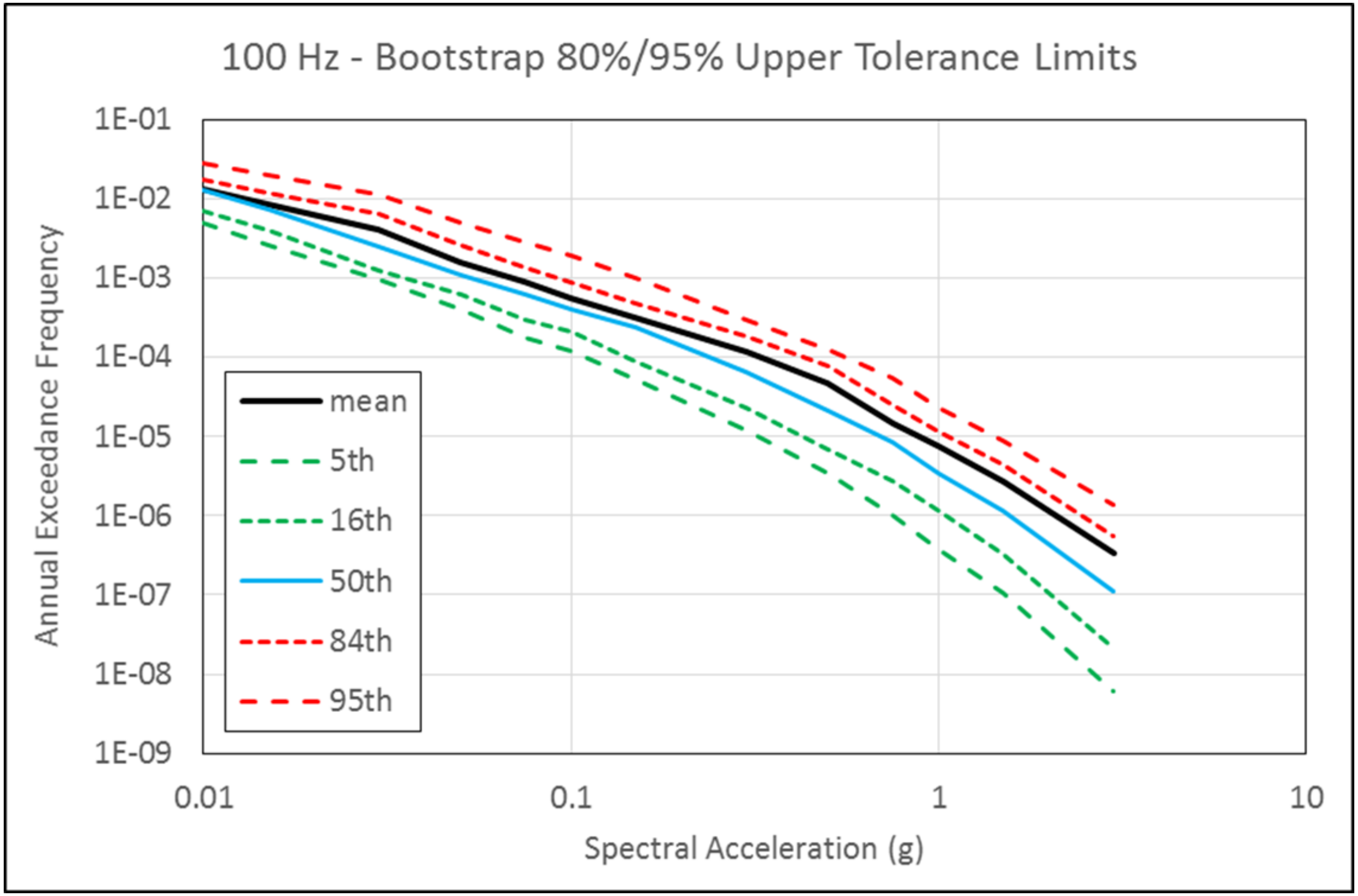
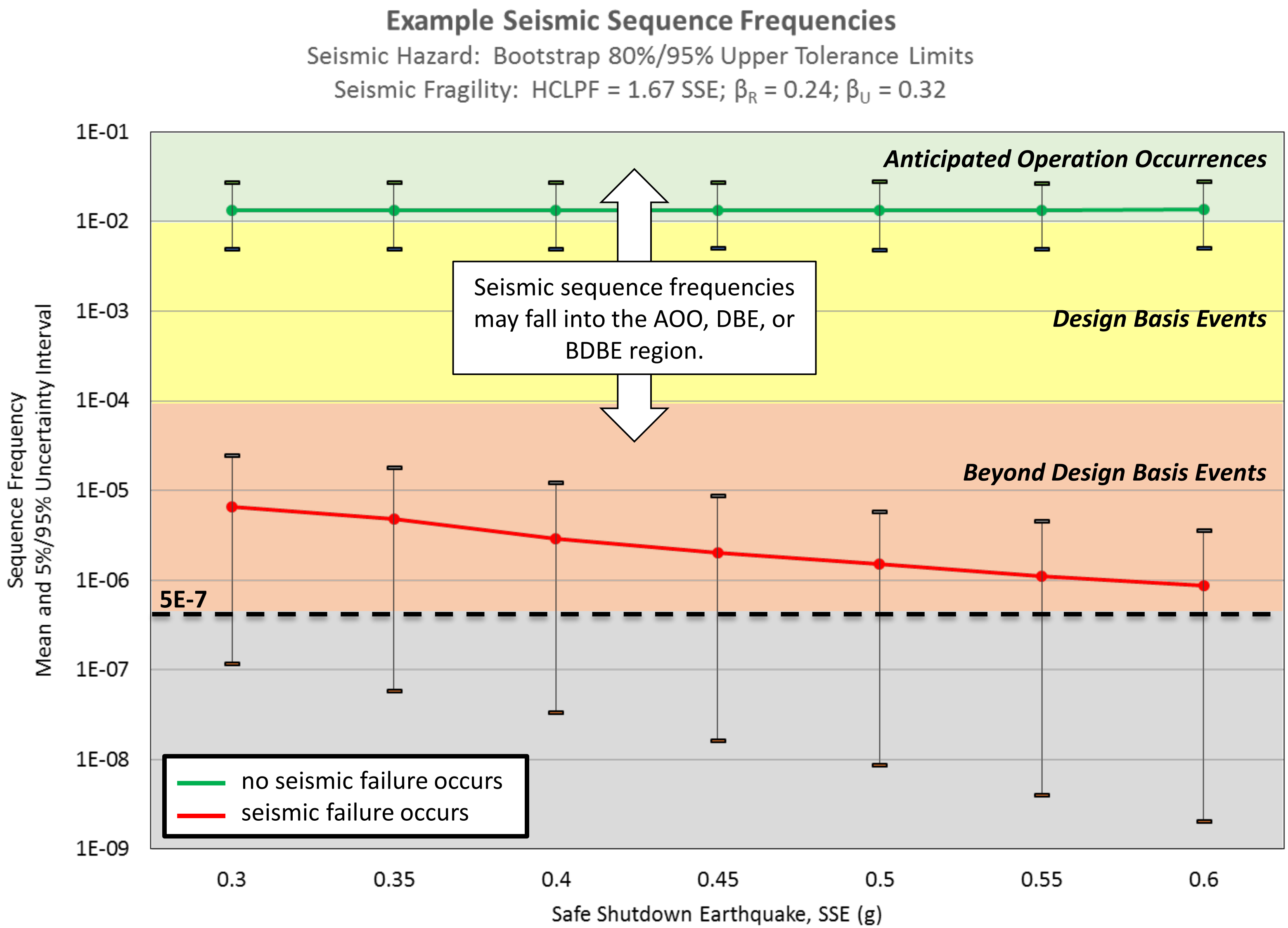
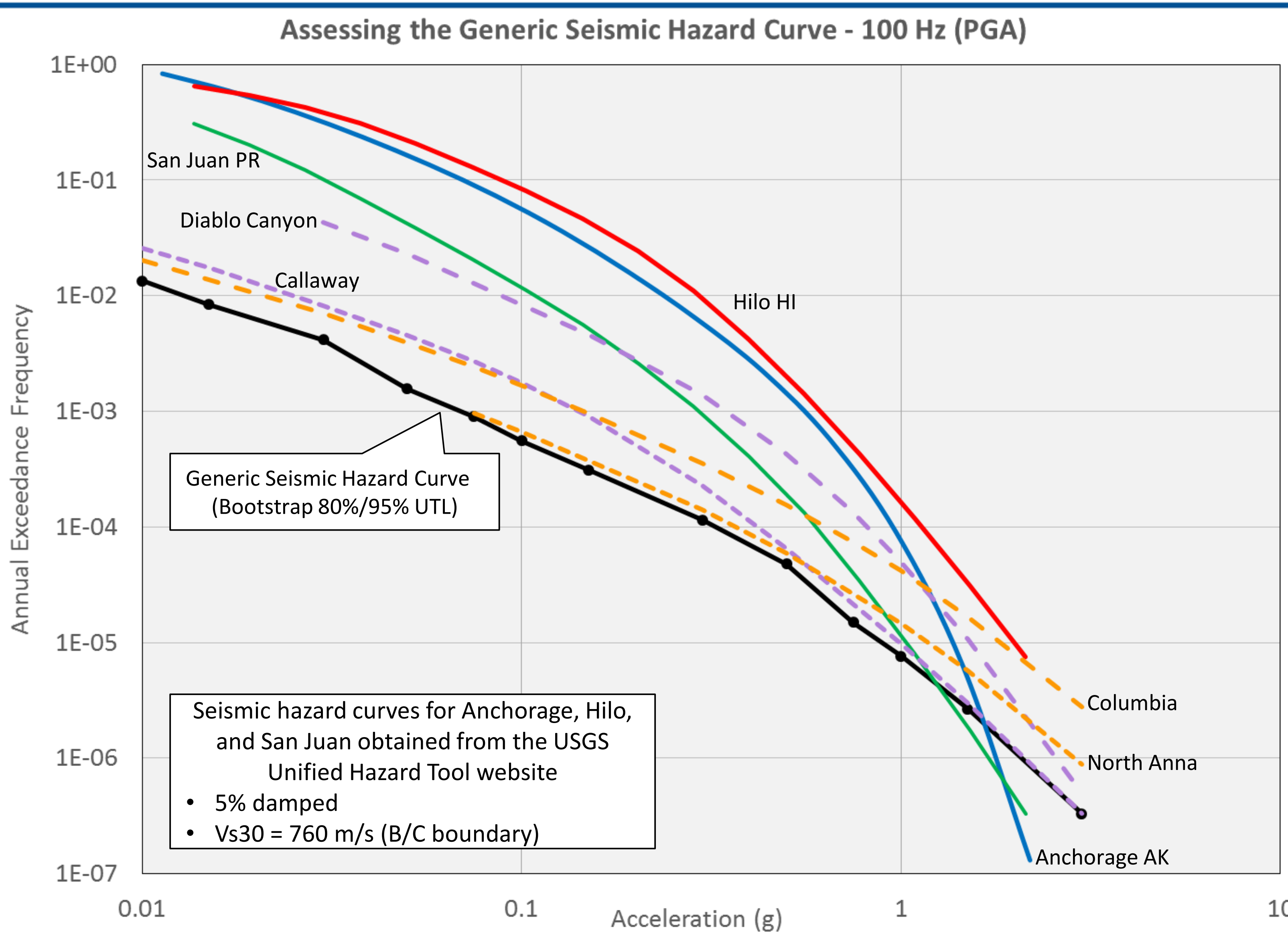
Results - Generic Seismic Hazard Curves




Example Seismic Sequence Frequencies
Seismic Hazard: Bootstrap 80%/95% Upper Tolerance Limits
Seismic Fragility: HCLPF = 1.67 SSE; β_R = 0.24; β_U = 0.32
Anticipated Operation Occurrences
Design Basis Events
Beyond Design Basis Events
Seismic sequence frequencies may fall into the AOO, DBE, or BDBE region.
5E-7
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E-09
Sequence Frequency
Mean and 5%/95% Uncertainty Interval
0.3
0.35
0.4
0.45
0.5
0.55
0.6
Safe Shutdown Earthquake, SSE (g)
no seismic failure occurs
seismic failure occurs


Assessing the Generic Seismic Hazard Curve - 100 Hz (PGA)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
Annual Exceedance Frequency
0.01
0.1
1
10
Acceleration (g)
San Juan PR
Diablo Canyon
Callaway
Hilo HI
Columbia
North Anna
Anchorage AK
Generic Seismic Hazard Curve
(Bootstrap 80%/95% UTL)
Seismic hazard curves for Anchorage, Hilo, and San Juan obtained from the USGS Unified Hazard Tool website
• 5% damped
• Vs30 = 760 m/s (B/C boundary)

Concluding Thoughts

- DC, SDA, and ML applications:
  - Include a description of the peer reviewed, design-specific seismic PRA and its results
  - Applicant to develop seismic hazard curves appropriate for anticipated future site locations
    - The development of generic seismic hazard curves using the upper tolerance limit approach may be one acceptable approach
    - Other approaches may also be acceptable
- COL and CP/OL applications:
  - Include a description of the peer reviewed, site-specific seismic PRA and its results
  - If the COL application is based on a DC, SDA, or ML, it is essential to identify and address differences between the design-specific seismic PRA and the site-specific seismic PRA <u>early in the licensing process</u>

Acronyms and Initialisms

AEF	annual exceedance frequency
CDF	core damage frequency
GMRS	ground motion response spectrum
HCLPF	high confidence of low probability of failure
LERF	large early release frequency
LMP	Licensing Modernization Project
LRF	large release frequency
NEI	Nuclear Energy Institute
NTTF	Near Term Task Force
PGA	peak ground acceleration
PRA	probabilistic risk assessment
SSE	safe shutdown earthquake
SMA	seismic margins analysis
UHS	uniform hazard spectrum
UTL	upper tolerance limit