INL/EXT-14-33234

Seismic Isolation Working Meeting Gap Analysis Report

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September 2014
(DRAFT)

U.S. Department of Energy
Office of Nuclear Energy

INL/EXT-14-33234

Seismic Isolation Working Meeting Gap Analysis Report Development

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September 2014

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

EXECUTIVE SUMMARY

The ultimate goal in nuclear facility and nuclear power plant operations is operating safely during normal operations and maintaining core cooling capabilities during off-normal events including external hazards. Understanding the impact of external hazards, such as flooding and earthquakes, have on nuclear facilities and NPPs is critical to deciding how to manage these hazards to expectable levels of risk. From a seismic risk perspective the goal is to manage seismic risk. Seismic risk is determined by convolving the seismic hazard with seismic fragilities (capacity of systems, structures, and components (SSCs)). There are large uncertainties associated with evolving nature of the seismic hazard curves. Additionally there are requirements within DOE and potential requirements within NRC to reconsider updated seismic hazard curves every 10 years. Therefore opportunity exists for engineered solutions to manage this seismic uncertainty. One engineered solution is seismic isolation. Current seismic isolation (SI) designs (used in commercial industry) reduce horizontal earthquake loads and protect critical infrastructure from the potentially destructive effects of large earthquakes. The benefit of SI application in the nuclear industry is being recognized and SI systems have been proposed, in the American Society of Civil Engineers (ASCE) 4 standard, to be released in 2014, for Light Water Reactors (LWR) facilities using commercially available technology. However, there is a lack of industry application to the nuclear industry and uncertainty with implementing the procedures outlined in ASCE-4. Opportunity exists to determine barriers associated with implementation of current ASCE-4 standard language.

Based on discussions with nuclear vendors there is opportunity to apply SI solutions for systems and components in nuclear facilities and NPPs. There may be a need to seismically isolate systems and components such as diesel generators and reactor pressure vessels. However, SI procedures and designs proposed for SI of an entire facility may not be appropriate because the mass of many systems and/or components is relatively small, and their geometry is very different. For these systems and/or components there may be a need to provide three-dimensional seismic isolation in addition to lateral SI.

To start this activity a working meeting was convened on August 19th 2014 with representatives from DOE, National Laboratories, Industry, EPRI, and NRC to discuss three SI topics: 1) general background on current SI progress in the U.S., 2) limitations associated with implementing procedures outlined in ASCE-4 for SI solutions of entire nuclear power plant, and 3) to determine potential SI solutions for systems and components and gaps associated with developing standardized technologies, methods, and numerical tools for these solutions. Additionally, the working meeting highlights what systems and/or components could benefit from SI. Issues related to implementation of SI were discussed at the meeting and these issues help in identification of areas and needs to perform research and development (R&D).

ACKNOWLEDGEMENTS

The authors would like to thank the participants (list provided in the Appendix) for making the meeting a success by providing insight and sharing their knowledge and also, appreciate the feedback that authors got on the report. We would also like to thank the DOE for its support. Any opinions, findings, conclusions or recommendations expressed are those of the author(s) and do not necessarily reflect the view of the Department of Energy Office of Nuclear Energy

CONTENTS

ACRONYMS

BDBE	Beyond Design Basis Earthquake
DBE	Design Basis Earthquake
DOE	Department of Energy
INL	Idaho National Laboratory
NLSSI	NonLinear Soil Structure Interaction
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
NPP	Nuclear Power Plant
NTTF	Near Term Task Force
SASSI	System for Analysis of Soil-Structure Interaction
SSI	Soil-Structure Interaction

Seismic Isolation Working Meeting Gap Analysis Report

1. Introduction

Seismic Isolation (SI) is gaining importance in the nuclear arena, mainly after the Fukushima accident in 2011that increased awareness in the nuclear community about uncertainties associated with designing and constructing nuclear power plants (NPPs) capable of withstanding large earthquake ground motions. The use of modern seismic (or base) isolation devices has increased in recent decades. SI has been used in the design and construction of NPPs in France and South Africa and was recently used to isolate new emergency response centers located at NPPs in Japan. As a result of international implementation at NPP sites, SI is currently being considered for nuclear facilities in the United States (NUREG, Draft).

Thus, the working meeting was held to discuss the current state of SI for nuclear facilities in the U.S. and to discuss the current state, challenges and gaps associated with implementation of SI at NPP's in the US. Currently, small modular reactors are being considered as the next generation reactors, so this effort is very timely such that the design could incorporate SI systems in order to enhance safety with respect to seismic hazards (such as earthquakes).

Horizontal SI effectively reduces the horizontal acceleration that develops in safety structures, systems, and components, such as containment and internal structures, to values well below those in conventional (non-isolated) nuclear construction. Vertical isolation seems an area where more research and development (R&D) might be needed and the challenge of isolating a component versus the entire structure are main areas that would need to be addressed in the future.

Seismic isolation systems have been widely implemented in the commercial industry to mitigate seismic effects at commercial facilities, natural gas storage facilities, and bridges. However, implementation at nuclear power plants has not been considered due to lack of standardization for nuclear applications and uncertainty associated with the regulatory process. NPP application is gaining interest due to standardized of SI systems for LWRs in the forthcoming American Society of Civil Engineers (ASCE) 4 and Nuclear Regulatory Commission (NRC) research that has funded the publication a NUREG. When released, this NUREG would be the first document released by the US NRC that provides information on SI of nuclear power plant facilities, with a focus on LWRs.

With industry interest in application of seismic isolation at NPPs, both existing and advanced reactor designs, it is important to determine what research and development (R&D) could be performed to provide standardized SI methods, tools, and technologies to enable deployment. To start this activity a working meeting was convened on August 19th 2014 with representatives from DOE, National Laboratories, Industry, EPRI, and NRC to discuss the following:

1. General background on current SI progress in the U.S
2. Limitations associated with implementing procedures outlined in ASCE-4
3. Determine potential SI solutions for systems and components
4. Determine gaps associated with developing standardized technologies, methods, and numerical tools for these solutions.
5. Systems and/or components that could benefit from SI

The issues related to implementation of SI were discussed and identified for future R&D needs.

1.1 Industry Support for Seismic Isolation

Due to the potential to reduce the effects of earthquake loadings on SSCs and thus reduce the seismic risk the nuclear industry has already demonstrated a willingness to participate in seismic isolation research. TerraPower, LLC is participating with the INL through a Cooperative Research and Development

Agreement (CRADA) to develop an industry acceptable methodology for evaluating the potential benefits of seismic isolation of suspended systems. The focus here is to couple a NonLinear Soil-Structure Interaction (NLSSI) methodology with numerical models of seismic isolators. This methodology is currently being developed at INL with funding provided by Department of Energy (DOE) National Nuclear Security Administration (NNSA).

Additionally, NuScale has expressed interest in participating in a program that develops a family of seismic isolation solutions for systems and/or components at nuclear facilities. Methods and tools for evaluating the performance of seismic isolation systems for systems and components as well as SI technologies would be documented in a consensus code standard.

1.2 The Need for Seismic Isolation of Systems and/or Components

Seismic hazard curves used in evaluating risk at nuclear facilities are continuously evolving. There are large uncertainties associated with the magnitude and frequency of the many seismic events that are used to define the hazard curves. Additionally there are requirements within DOE and potential requirements within NRC to re-evaluate site specific seismic hazard curves every 10 years (NTTF). The evolving nature of the seismic hazard curves and the requirement to re-evaluate those curves every 10 years creates the possibility that a number of these seismic hazard curves will increase (which they generally do as research continues on seismic source characterization, empirical ground motion attenuation equations, and local site effects).

Therefore opportunity exists for engineered solutions to manage this seismic uncertainty. One engineered solution is seismic isolation. SI has the potential to reduce horizontal earthquake loads for nuclear structures, systems, and components (SSCs). A substantial reduction in horizontal earthquake loading has the potential to increase the safety of nuclear SSCs by managing the risk associated with large seismic events. Isolation is typically achieved by installing horizontally flexible and vertically stiff seismic isolators between the superstructure and its foundation. Isolators serve two key functions: 1) supporting gravity loads, and 2) protection of the supported structure and its systems and components from the damaging effects of horizontal earthquake ground motion.

ASCE 4 provides standard procedures for providing robust seismic isolation systems for the entire NPP as shown in Figure 1. In addition to SI systems for LWRs (such as those shown in Figure 2), there is a need in the nuclear industry for seismic isolation of nuclear facility (both near surface facilities and deeply embedded facilities) related systems and/or components such as diesel generators, reactor pressure vessels, steam generators, spent fuel pools, and critical response facilities such as FLEX (maintaining back up safety equipment at a secure offsite location).

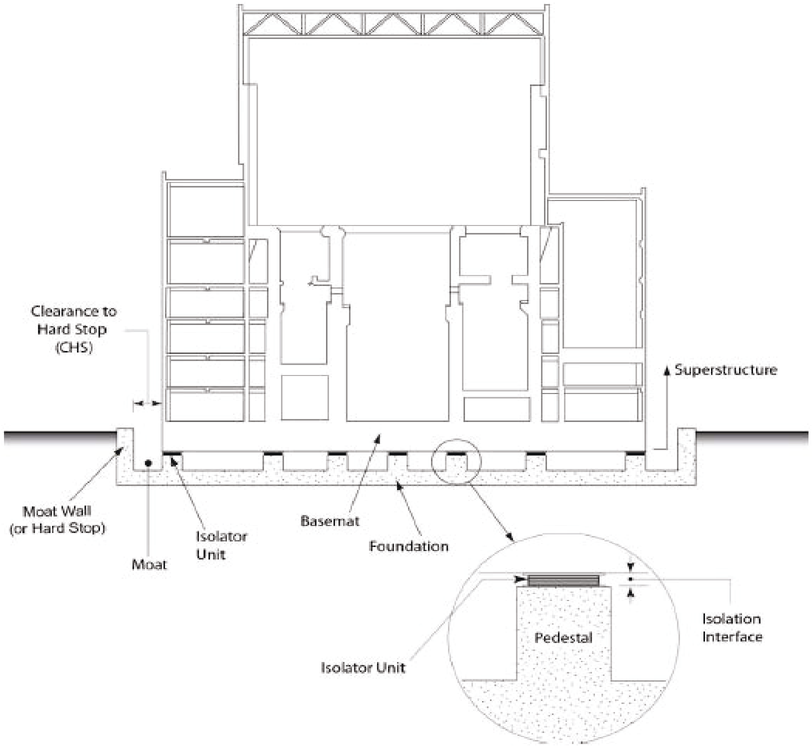
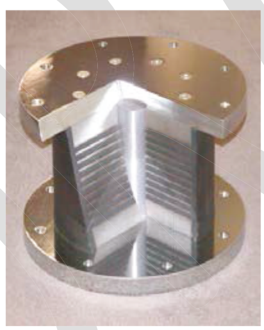


Figure 1: Proposed Seismic Isolation of LWR per ASCE 4



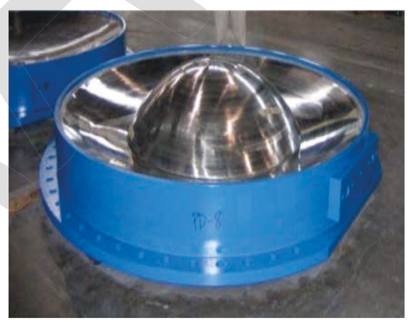


Figure 2: Seismic isolators a) lead-rubber bearing (courtesy of DIS) b) Friction Pendulum bearing (courtesy of EPS)

The isolation solution shown in Figure 1 would not be cost effective for deeply embedded NPPs. Since this would require over-excavation of the soil, and installation of a moat system to accommodate the lateral displacement of the facility. Therefore the likely benefit for deeply embedded structures would be systems and/or components internal to the NPP. For these systems and/or components there may be a need to provide three-dimensional seismic isolation in addition to lateral SI. Due to the potential difference in the isolation environment (i.e. isolators may be located in the nuclear power plant instead of isolating the nuclear power plant) and the potential need to provide three-dimensional SI, it is necessary to provide required and improved numerical methods and consensus standards for SI of systems and/or components.

1.3 Seismic Isolation Implementation The Need for Seismic Isolation of Systems and/or Components

There are some nuclear applications of seismic isolation in countries outside of the U.S. The draft NUREG provides an overview of these isolation systems and a brief description is provided in this section:

1. A total of six NPP units have been seismically isolated in Cruas, France and Koeberg, South Africa in 1983 and 1984.
2. The six seismically isolated reactors are located at two sites and all six are Pressurized Water Reactor (PWR) units constructed in the 1980s. Four reactors are located at the Cruas-Meysse site in France and two are located at the Koeberg site in South Africa. Isolation systems in these NPPs use neoprene as the elastomer.
3. The Tokamak fusion reactor, ITER, and the Jules Horowitz research reactor (JHR), both being constructed in Caderache, France will also be seismically isolated, as shown in Figure 3.

Figure 3 Seismic Isolation for ITER and JHR

In response to changes in the Japanese Seismic Nuclear Regulations and experience data gathered from the 2007 Niigataken-Chuetsu-Oki earthquake that impacted the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP), Japanese utilities decided to seismically isolate emergency operations buildings. This unique application of seismic isolation at a NPP does not focus on SI of the nuclear island but rather emergency response centers that coordinate the response post earthquake. This unique approach could be applied to FLEX centers in the U.S.

2. Seismic Isolation Working Meeting Discussion

The main objective of this working meeting was to discuss the current state and need for seismic isolation for nuclear rectors (structures, systems, and components) and identify the challenges and gaps.

2.1 Discussions Notes From Meeting

The meeting provided a high level overview of current state of SI in the U.S. This meeting was organized with a morning of presentations and an afternoon of discussion, detailed information is provided in the report appendices.

Purpose of morning session was to discuss current state of practice for seismic isolation of nuclear facilities:

Presenter: Justin Coleman, INL

Role of Presentation: Meeting expectations and outcome

Presenter: Michael Salmon, LANL

Role of Presentation: ASCE-4 and 43 implementation process and NRC acceptance

Presenter: Andrew Whittaker, UB

Role of Presentation: Technical considerations for seismic isolation in the U.S. and current ASCE 4 implementation

Presenter: Jose Pires, NRC

Role of Presentation: NRC research in seismic isolation

Presenter: John Richards, EPRI

Role of Presentation: EPRI research in seismic isolation

Presenter: Piyush Sabharwall, INL

Role of Presentation: Safety systems for nuclear reactors

Purpose of the afternoon discussions was to determine what seismic isolation gaps exist and what research and development (R&D) activities could fill those gaps. Some topics for consideration include:

- Advanced numerical methodologies
- Seismic isolation technologies for systems and components
- Cliff edge affects
- Issues associated with piping and lines that cross the isolated non-isolated interface

More detailed meeting notes are provided in Appendix B, with presentations in Appendix D. Gaps identified in the working meeting are addressed in Sections 2.2, 2.3, and 2.4 with more details provided in Appendix C. Some highlights from the meeting are:

- Reduction in structure response to a horizontal ground motion could be achieved with seismic isolation and thus could enhance safety for NPP SSC's potentially reducing seismic risk.
- Hard stops are designed in order to prevent any further displacement than the SI is designed for.
- Site specific seismic hazards are a moving target and tend to increase
- SI could mitigate risk associated with increasing site specific seismic hazards
- For NPP (such as SMRs) SI could provide following benefits:
- Reduction in downtime, will be a great cost benefit
- SI system could be considered as an added defense in depth for loosing critical components
- SPRA needs to provide best possible risk numbers increasing the need for realistic numerical models and quantifying uncertainty. Whereas for seismic design and analysis for plant NPPs the design should provide a conservative result thus requiring less numerical accuracy.
- Using high fidelity codes (when needed) to predict/model SI accurately with high confidence level

- Time domain analysis can assist with looking at effect of concrete cracks, inclined wave effects, non-linear effect of soil, effect of embedment
- Before using SI for nuclear structures/components, in order to gain confidence we should look into smaller systems or building (emergency response building) and consolidated storage facilities→ will help gain nuclear community and general public confidence
- Aircraft Impact to the Main Containment building with SI: since the relative size/mass of the containment is much greater than aircraft, hardly any movement will be noticed
- effect for embedded system (should not be much of an issue but analysis not done yet), could also depend on depth of embedment
- size of the structure (could be an issue for smaller structures, like SMR containment, because of aircraft impact will be more like an impulse (here the issue is of momentum transfer)

2.2 Identified Gaps

The working meeting highlighted gaps in several areas, which are presented in sections 2.3 and 2.4 below. Gaps identified in this working meeting fit into two areas, isolating the entire nuclear facility, and isolation of systems and components. A systematic process was developed in sections 2.3 and 2.4 to state the gap, it's importance to industry, current state of knowledge and research and development, and need (ranked as high, medium, low).

2.3 Entire Nuclear Facility

2.3.1 Hard Stop Cliff Edge Effects

ASCE 4 committee hasn't addressed the potential cliff edge effects (and therefore unanalyzed damaged to the nuclear structures, systems, and/or components (SSCs)) during beyond design basis earthquake (BDBE). This is an important parameter to consider in the SI application for a safe design.

Importance to Industry

Cliff edge concerns would cause potential limitations of SI use in industry.

Current State of Knowledge

Limited

Current Research and Development

No research activities have been funded to understand the potential cliff edge effects of hitting the moat wall.

Limited

Need

Medium

R&D would produce tools, methods, and technologies for addressing cliff edge effects. These would be implemented as guidance in industry consensus codes such as ASCE 4. Understanding of cliff edge effects (if any) and proposed solutions for design changes (if necessary) and demonstrating the reduction of in-structure nuclear facility response has potential to increase nuclear safety.

2.3.2 Hard Stop Requirements

Is the hard stop needed? Currently ASCE-4 requires implementation of a hard stop to prevent displacement of the nuclear facility beyond what would cause tearing of the isolation system and catastrophic damage.

Importance to Industry

Industry is concerned that the hard stop creates potential design issues since they must demonstrate what happens when the facility hits the hard stop. There is also a concern that for irregular geometries that facility impact with the hard stop may create potential challenges.

Current State of Knowledge

Limited

Current Research and Development

University at Buffalo is currently performing research to develop a SPRA approach, which would allow the moat to be screened out.

Need

Current state of knowledge is presented in ASCE-4, which requires implementation of the hard stop. ASCE-4 states:

High

2.3.3 Seismic isolation methods and solutions for mitigating Vertical Ground Motion

SI of entire nuclear facility is standardized in forthcoming version of ASCE-4. These are horizontal isolation systems. Vertical seismic response is an issue at some sites and thus there may be a need for vertical isolation. Currently there is relatively little knowledge in the U.S. on designing robust vertical isolation. Need to understand what the need is for vertical isolation and develop methods and solutions for vertical isolation.

Importance to Industry

For some soil sites vertical ground motion is significant. These may cause large in-structure vertical response which may require robust seismic designs. Significant cost savings could be achieved by coming up with methods and solutions for vertical isolation.

Current State of Knowledge

Currently only horizontal isolation has been accepted in codes and standards. Vertical isolation concepts have not been implemented in any nuclear facilities in the world.

Limited

Current Research and Development

Limited

Need

Vertical seismic response is an issue at some sites and thus there may be a need for vertical isolation.

Medium

2.3.4 Understanding margins in Seismic Analysis

Margins that may exist in seismic analysis are something that are not clearly understood. Three recent earthquakes in the last seven years have exceeded their design basis earthquake values (so damage to SSC's should have occurred). These seismic events were recorded at Kaswazaki-Kariwa (2007), Fukushima Daichii and Daini (March 2011), and North Anna (August 2011). However, seismic walk downs at some of these plants indicate that very little damage occurred to safety class systems and components due to the seismic motion. Therefore it is necessary to gather the applicable data to quantify the margins in current seismic analysis techniques (linear analysis) at nuclear power plants.

Importance to Industry

Overly conservative seismic analysis and SPRA may cause NPP venders to focus too much money on seismically hardening their design. This could also cause NPP venders to make decisions to seismically isolation SSCs based on overly conservative information (SI may not be needed).

Current State of Knowledge

Data is available at NPP sites however to our knowledge no one has gathered the data for use in determining seismic margins in current analytical procedures and methods.

Limited

Current Research and Development

INL is currently involved in an activity to develop a NonLinear Soil Structure Interaction (NLSSI) methodology. As part of this process INL is comparing linear analysis with non-linear analysis at increasing levels of ground motion to demonstrate importance of including nonlinear effects.

The decisions to implement SI should occur after realistic seismic analysis has been performed.

Limited

Need

High

2.3.5 Cost Benefit (Economic Viability) for SI of entire nuclear plant

To our knowledge no one has performed a cost benefit analysis in the U.S. on an isolated versus non-isolated nuclear systems and components. A cost benefit analysis could provide valuable insight for venders interested in application of seismic isolation to manage seismic risk at their nuclear facilities.

Importance to Industry

Provides industry with information on potential cost savings when SI is implemented in new nuclear facility design and/or modification of existing nuclear facilities.

Current State of Knowledge

Limited

Current Research and Development

Limited

Need

DOE and industry need to understand the cost benefit of implementing SI at NPPs.

High

2.3.6 Need for Soil Constitutive model

Need for accurate soil constitutive model to evaluate performance of seismic isolation systems in nuclear facility structures (more accurate/ better models).

Importance to Industry

NLSSI seismic analysis is needed to quantify the benefit of seismic isolation. NLSSI is also needed to determine if SI is needed. Accurate soil constitutive models are needed to produce reasonable NLSSI results.

Current State of Knowledge

Medium

Current Research and Development

Boris Jeremic at UC Davis has been developing accurate nonlinear soil constitutive models that can accurately capture the cyclic behavior of soil during seismic events [Jeremic e.t. 2013].

INL is currently involved in an activity to develop a NLSSI methodology. As part of this process INL is comparing linear analysis with non-linear analysis at increasing levels of ground motion to demonstrate importance of including nonlinear effects.

Medium

Need

Medium

2.3.7 Need for time domain methodology that can handle nonlinear behavior such as seismic isolation

Need for time domain approach that can handle nonlinear behavior such as seismic isolation.

Importance to Industry

Nonlinear soil-structure interaction seismic analysis is needed to quantify the benefit of seismic isolation. NLSSI is also needed to determine if SI is needed.

Current State of Knowledge

Medium

Current Research and Development

UB, INL, and UC Davis are currently working on numerical tools and methods for performing NLSSI

Medium

Need

Medium

2.3.8 Implementation of SI in Nuclear Facility Safety

The forthcoming version of ASCE 4 provides standardized language of implementation of SI for the entire nuclear facility. However, currently in the U.S. there is not an application of SI related to nuclear facilities. TEPCO, after the Kashiwazaki earthquake in 2007, installed seismically isolated emergency response buildings at all their NPP sites including (Hijikata 2012) Fukushima Daichii. These facilities provided valuable emergency response equipment to deal with the nuclear reactor issues and allowed for continued on site response.

Figure 2.3.10: Seismically isolated emergency response building placed at the Fukushima Daiichi site

Importance to Industry

Implementation of SI at nuclear facilities has potential to reduce seismic risk and manage costs associated with seismic concerns.

Current State of Knowledge

Currently in the US there is not an application of SI in facilities that support nuclear safety.

Limited

Current Research and Development

Limited

Need

There was general consensus at the gap working meeting that SI has potential to manage seismic risk at NPP sites. One important comment from the meeting is there may be some reluctance in the nuclear community that first application of SI be the nuclear island. To ease seismic isolation into supporting nuclear facility safety some possible facilities other than the nuclear island, but still important to nuclear safety are: Consolidated storage facilities and industry FLEX facilities. This would allow for application of SI at facilities that support nuclear safety outside of the nuclear island and demonstrate implementation of the technology in nuclear safety applications.

High

2.4 Systems and Components

2.4.1 Cost Benefit (Economic Viability) for SI of systems and components

Same as presented in Section 2.3.5 in this report.

2.4.2 SI Solutions for Nuclear Systems and Components

Seismic isolation solutions for LWRs (documented in ASCE 4) may not be appropriate for isolation of systems and/or components because the mass of many systems and/or components is relatively small, and their geometry is very different. Can SI solutions presented in ASCE 4 be scaled for implementation with systems and components or is it necessary to develop new SI solutions?

Importance to Industry

It is unlikely that deeply embedded NPPs will implement SI for the entire plant as standardized in ASCE 4. However, they may be interested in SI solutions for systems and/or components.

Current State of Knowledge

Limited

Current Research and Development

Limited

Need

High

Deeply embedded NPP venders are likely to seek SI solutions (if needed) for systems and components. ASCE 4 currently does not address SI of systems and components. Therefore development of SI solutions for systems and components is necessary. Implementation of these solutions on consensus codes is necessary.

2.4.3 SI for Individual Components, leading to differential displacement Issues

Differential displacement between the isolated and unisolated interface is a known issue that has to be addressed in the design. It is also important to quantify the risk associated with this differential displacement.

Importance to Industry

Using SI to only isolate systems and/or components in NPPs may create differential displacement issues which need to be addressed.

Current State of Knowledge

Medium

Current Research and Development

Need adequate modeling and simulation methods and tools to accurately capture this behavior. These methods and tools are currently under development but have not been used to quantify risk associated with differential displacement issues at NPPs.

Medium

Need

Medium

2.4.4 Model Validation and Uncertainty Quantification

SI numerical models must be verified and validated to provide confidence in predicted structural response. Nonlinear structural dynamics models are needed to accurately predict the behavior of seismic isolation systems. Uncertainty quantification is very essential to access the range of validity for the model (based on assumptions) and experiments (based on operating conditions).

Importance to Industry

It is necessary to have confidence in SI numerical models to make decisions in the design process of whether or not SI is needed.

Current State of Knowledge

Limited

Current Research and Development

University at Buffalo has developed verified and validated numerical models for SI design that will be used to isolate the entire plant. However limited effort to date has focused on what seismic isolation solutions are needed for systems and components and developing V&V numerical models for these.

Limited

Need

Medium

2.4.5 Rocking Effect on Seismic Isolation of a Component (very essential to understand for Integral SMR designs)

SI of certain NPP systems and components may create rocking loads that current isolation technologies, standardized in ASCE 4, were not designed to handle.

Importance to Industry

SI solutions for deeply embedded structures will likely only be used for systems and components. Therefore it is necessary to develop SI tools, methods, and solutions similar to what is currently in ASCE 4 for SI of the entire NPP.

Current State of Knowledge

Limited

Current Research and Development

Limited

Need

Depending on SI designs for systems and components this may be important

Medium

3. Additional SI Implementation Considerations

Some advanced reactor designs, particularly liquid metal reactors (LMRs), may employ a pool design rather that a loop-based design. Thus, (1) there's the "sloshing" considerations, does the fundamental mode of sloshing align that of the SI system, comparable to what was discussed for spent fuel pools and (2) not as many issues associated with the umbilical concerns as for loop designs.

Most advanced reactor designs employ passive safety features. Some may use natural circulation for decay heat removal that at some point involve moving air through structures to create a chimney effect and dissipate the heat above ground to the air.

Jose Pires of NRC noted ITAAC (Inspection, Testing, Analysis, and Acceptance Criteria) as a longer-term consideration for SI issues. However, for new plants in the future that may employ SI, the vendor/applicant and SI designer will need to consider how they will demonstrate via an ITAAC approach that an SI system was constructed/installed as designed and will operate as designed. They will need to recognize early on what the basis of their ITAAC is to meet the acceptance criteria once installed.

An incremental step forward in implementing SI in the nuclear arena, prior to actually isolating some portion of a nuclear plant, could be; application for consolidated used fuel facilities, or the two FLEX locations in Memphis and Phoenix. These are the two U.S. "storage" locations for spare diesel generators, pumps, etc., selected by industry in response to Fukushima.

4. Results and Conclusions (Path Forward for R&D)

The seismic isolation working meeting, held on August 19th highlighted gaps associated with implementation of SI in the nuclear industry. The gaps that are identified as most important are:

- SI Solutions for Nuclear Systems and Components
- Quantification of Cost Benefit (Economic Viability) for SI
- Understanding margins in Seismic Analysis
- Implementation of SI in Nuclear Facility Safety Remove Hard Stop Requirements

Research and development activities performed by a collaborative team that includes DOE, industry, nation laboratories, and universities, would help close these gaps.

5. References

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6. NTTF, “Recommendations for Enhancing Reactor Safety in the 21st Century,” NRC, July 2011.

Appendix A
Meeting Attendance List and Agenda

Meeting Attendance List

Name	Organization	Email	Telephone
Justin Coleman	INL	justin.coleman@inl.gov	208-526-4741
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Idaho National Laboratory

SEISMIC ISOLATION WORKSHOP

Tuesday, August 19th, 2014

Objective: To discuss the current state of seismic isolation (SI) at nuclear facilities and determine what gaps existing between current application of SI to systems and/or components. Presentations will be provided in the morning to discuss the current state of SI and a round table discussion will be held in the afternoon to talk about current issues and proposed applications of seismic isolation.

Attire: Business Casual

DOE
Brent Gutierrez
Chris Chaves
Rich Reister
Steve Mcduffie
Subir Sen
Mark Blackburn
Sharon Jasim-Hanif

DOE/NNSA
Jeff Roberson

EPRI
John Richards

INL
Justin Coleman
Piyush Sabharwall

LANL
Mike Salmon

NRC
Jim Xu
John Burke
Jose Pirez
Mohamd Shams
Bhagwat Jian

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Andrew Whittaker - Buffalo

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Frank Vereb

Host(s): Justin Colemam, (208) 526-4741

Meeting Coordinator: Jamie Smith, (208) 526-1937

Revision 2

7/18/2014

SEISMIC ISOLATION WORKSHOP

Tuesday, August 19th, 2014

INL Washington DC Office, 955 L'Enfant Plaza SW, North Building Suite 600A

8:00 Introductions .... All

8:10 Seismic Isolation Task Overview .... Justin Coleman
Idaho National Laboratory

8:30 ASCE-4 Implementation Process ....Michael Salmon
Los Alamos National Laboratory

8:50 Technical Consideration for Seismic Isolation (ASCE-4 & NUREG)......Andrew Whittaker
University of Buffalo

9:35 NRC Research in Seismic Isolation.. Jose Pires
Nuclear Regulatory Commission

10:05 Break ....

10:20 EPRI Research in Seismic Isolation ....Bob Kassawara
Electric Power Research Institute

11:00 Safety System for Nuclear Reactors...Piyush Sabharwall
Idaho National Laboratory

11:30 Working Lunch Topic: uncertainty's associated with external seismic hazards, best estimate risk evaluation, and INL's development of advanced tools and methods for using in design and risk assessment. .... Justin Coleman
Idaho National Laboratory

Lunch invitees: See attached list

SEISMIC ISOLATION WORKSHOP

Tuesday, August 19th, 2014

1:00 Group Discussion ....

- What systems and components benefit form seismic isolation
- Potential performance characteristics of seismic isolation

2:15 Break ....

2:30 Group Discussion Continued ....

3:30 Adjourn ....

Appendix B
Meeting Notes

1. For a successful nuclear future seismic isolation measures should be integrated with SMRs and Advanced Reactors.
2. A thorough analysis still needs to be done to show the effectiveness of seismic isolation for the critical components, such that safety and integrity is maintained
3. Seismic analysis needs to be carried out for specific sites/location as one needs to take into account different soil effect (Hard soil, soft soil)
4. Seismic systems for the critical components of the plant will enable the plant to maintain safe plant operations despite emerging or unanticipated scenario's. Current reactor designs offer minimal flexibility in responding to natural occurring disasters. With seismic isolation systems, the severe accidents scenario could be handled better and the reactor and its critical components could maintain better integrity.
5. Advanced capabilities in modeling could reduce uncertainties and advance our understanding of seismic performance of nuclear power systems
6. What activities in parallel might be and should be done to realize the full potential of advanced seismic simulation methods and its significance to the nuclear community/utilities
7. Need to carry out and show the importance of structural models for embedded systems:
8. taking into account the interaction between structure and soil.
9. Need to account for soil deformation overtime
10. Soil non-linearities (soft/hard soil type, homogeneous soil/layered soil structure)
11. need to understand the behavior of embedded systems for both predicted (design-basis) and beyond design basis earthquakes in order to determine the threshold or critical level/point beyond which the integrity of the critical component is compromised
12. To promote/encourage utilities and various vendors to look into seismic isolation techniques, is only possible when:
13. These systems are well understood, such that could be integrated into design codes itself (Blink and Budnitz, NEAMS, 2012)
14. Could be taken as added safety measures from nuclear safety regulatory process perspective and ultimately helps in licensing.
15. Reduction in structure response to a horizontal ground motion could be achieved with seismic isolation and thus could enhance safety for NPP with respect to seismic hazards.

1. Hard stops are designed in order to prevent any further displacement than the SI is designed for.
2. Seismic hazard is a moving target and usually increases.
3. For NPP (such as SMRs) SI could provide following benefits:
    a. Reduction in downtime, will be a great cost benefit
    b. SI system could be considered as an added defense in depth for loosing critical components
4. Seismic analysis for PRA (SPRA) is more complicated than seismic analysis for plant design because SPRA needs more or less determined/evaluated values to the best possible accuracy along with uncertainty info, whereas for seismic analysis for plant design some values could be best estimate or best-predicted values, thus more effort is involved with SPRA
5. Using high fidelity codes (when needed) to predict/model SI accurately with high confidence level
6. Time domain analysis can assist with looking at effect of concrete cracks, inclined wave effects, non-linear effect of soil, effect of embedment
7. Before using SI for nuclear structures/components, in order to gain confidence we should look into smaller systems or building (emergency response building) and consolidated storage facilities→ will help gain nuclear community and general public confidence

8. Aircraft Impact to the Main Containment building with SI: since the relative size/mass of the containment is much greater than aircraft, hardly any movement will be noticed
   - effect for embedded system (should not be much of an issue but analysis not done yet), could also depend on depth of embedment
   - size of the structure (could be an issue for smaller structures, like SMR containment, because of aircraft impact will be more like an impulse (here the issue is of momentum transfer)

Appendix C
Noted Gaps

1. SI of entire nuclear facility is standardized in forthcoming version of ASCE-4. These are horizontal isolation systems. Vertical seismic response is an issue at some sites and thus there may be a need for vertical isolation. Currently there is relatively little knowledge in the U.S. on designing robust vertical isolation. Need to understand what the need is for vertical isolation and develop methods and solutions for vertical isolation.
2. 3D isolation may be feasible for individual components but robust methods and solutions have yet to be proven.
3. Margins in Seismic Analysis is something, which is not clearly understood and not demonstrated. Three recent earthquakes in the last seven years have exceeded their design basis earthquake values (so damage to SSC's should have occurred). These seismic events were recorded at North Anna (August 2011), Fukushima Daichii and Daini (March 2011), and Kaswazaki-Kariwa (2007). However, seismic walk downs at some of these plants indicate that very little damage occurred to safety class systems and components due to the seismic motion. Therefore it is necessary to gather the applicable data to quantify the margins in current seismic analysis technics (linear analysis) at nuclear power plants.
4. Cost benefit (economical viability) for SI for components and structures and the whole plant is still not completely understood.
5. Can seismic isolation minimize the qualification requirements for certain components and thus reduce the cost of certain NPP systems and components.
6. SI for individual components is also lacking proper understanding, such that Isolating one component and not the other, could lead to displacement issues
    a. Needs to look from a systems perspective how a given component interfaces/interacts with other SSCs. One of the major considerations in examining failure modes for a given component or system is how does it interact with other SSCs resulting in cascading failures
7. Validation need for models
8. Need for accurate soil constitutive model to evaluate performance of seismic isolation system in nuclear facility structures (more accurate/ better models)
9. Need for time domain approach that can handle nonlinear behavior such as seismic isolation
10. Impact of rocking effect on seismic isolation component would be very essential to understand for Integral SMR designs
11. Need to look into other possible damping material alternatives, such as gurb springs (vertical isolation)
12. Application of SI technology (Industry and DOE perspective)
    a. Entire nuclear island?
        i. Passive engineered fill? Dissipate energy? Engineered backfill
        ii. Differential settlement due to soil…does this disrupt the performance of the seismic isolation system?
    b. Systems and components, if so which systems and components?
        i. Hard stop issues also apply to SI solutions for systems and components…how do we deal with this?

ii. Differential displacement between isolated and non-isolated systems and components?
iii. Design of the isolation system can be shaped to displacement requirements for equipment?
iv. Isolating a piece of vibrating equipment…criteria?
v. Independent equipment, water storage tank?
    1. Sloshing concerns?
    2. Can't drive nonlinear system to resonance
vi. Independent equipment might demonstrate SI solutions for "non-safety class" systems
vii. Are there scaling issues…going from heavy mass to light mass
viii. Rules in ASCE-4 are written for only 3 types of SI's…are there other isolation concepts that should be included?
    1. Pendulum isolators
    2. Recommendation on damping materials?? Passive
    3. Damping devices??
ix. Family of isolators developed for components…numerical methods…testing…implementation in standards

13. Seismic isolation gaps exist in
    c. Acceptable numerical methodologies?
    d. Seismic isolation technologies for systems and components?
        i. Rocking effects?
        ii. Weight is less so may need other SI solutions…need demonstration…standardized process…
        iii. Thermal issues…differential thermal expansion…load case to consider?
    e. Cliff edge affects?
        i. Fail safe?
        ii. Technology solution for a soft stop?
    f. Hard stop…eliminating the hard stop? Standard? Guidance?
    g. Issues associated with piping and lines that cross the isolated non-isolated interface?...What's available in the market (ITER is using some technologies)
    h. Gather existing data
    i. Isolation of structure, systems, and components from large vertical in-structure demands?
14. For SI system is an Aircraft impact to the structure an important issue. Can we set criteria or depth of embedment or quantify significance of mass of structure

15. Can standardized design be used for SI, different ground motions for different sites create different performance criteria for the isolators? Lower frequency ground motions? This could be a great benefit by focusing design changes across different sites only to the isolation system (instead of design changes to whole plant)

16. NRC concerns of seismic isolation? Vertical isolation (or lack of) mitigation…umbilical lines , interface issues between isolation and non-isolated interface…computation capability using SSI analysis of SI (including seismic isolators in this analysis), path to V&V of analysis tool…NRC staff encourages innovative solutions…need NLSSI approach that can handle issues such as SI…

17. There is a need for validation…of site response…SI for systems and components…new types of isolators and systems…

18. Comfort level with existing seismic isolation concepts…might need a small application of SI so people become more comfortable with SI solutions…need a demonstration…

19. Proper understanding on the required R&D activities that could fill the gaps

20. Cost/Economic benefit of the SI concept

Appendix D

Meeting Presentations

Seismic Isolation Working Meeting

Justin Coleman, P.E.
Nuclear Science and Technology
Idaho National Laboratory

August 19th, 2014

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Idaho National Laboratory

Seismic Isolation R&D Task Vision

- Reduce horizontal earthquake demands and increase the safety of nuclear structures, systems, and components (SSCs) by managing the risk associated with uncertainty in the seismic hazard.
- Our working meeting will identify what gaps exist with implementation of seismic isolation at nuclear facilities
- A document will be produced that identifies current gaps associated with implementing seismic isolation at nuclear facilities
- These gaps will guide future research and development (R&D) activities

Purpose of SI Working Meeting

- Discuss current state of practice for seismic isolation of nuclear facilities (Morning presentations)
  - ASCE-4 and 43 implementation process and NRC acceptance (Michael Salmon, LANL)
  - Technical considerations for seismic isolation (Andrew Whittaker, UB)
  - NRC research in seismic isolation (Jose Pires, NRC)
  - EPRI research in seismic isolation (John Richards, EPRI)
  - Safety systems for nuclear reactors (Piyush Sabharwall, INL)
- Determine what seismic isolation gaps exist and what research and development (R&D) activities could fill those gaps (Afternoon discussions):
  - Numerical methodologies
  - Seismic isolation technologies for systems and components
  - Cliff edge affects
  - Issues associated with piping and lines that cross the isolated non-isolated interface

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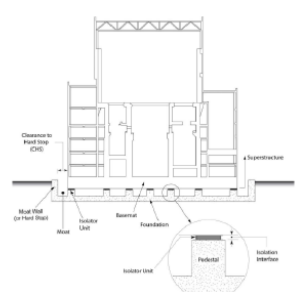
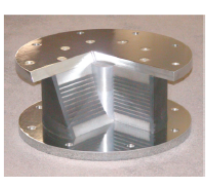
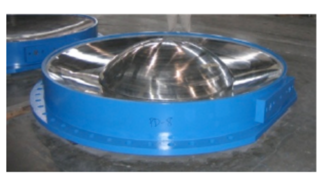
Seismic Isolation Overview

- SI systems have been proposed by the nuclear community for entire nuclear facility using commercially available technology.
- General application will be standardized in the forthcoming American Society of Civil Engineers (ASCE) 4 "Seismic Analysis of Safety-Related Nuclear Structures and Commentary," to be released in late 2014.
- This SI solution proposes to isolate the entire Nuclear Power Plant (NPP).







What is the Need?

	KK 2007	Fukushima 2011	North Anna 2011
Design Value (g)	0.20	0.26 (Original) 0.45 (Update)	0.18
Recorded Value (g)	0.32	0.56	0.26

All Exceeded Design Basis Earthquake

- The estimated hazard has been exceeded at nuclear facilities
- Uncertainty associated with seismic hazard
- Seismic Isolation is a potential technology to manage seismic hazard uncertainty and mitigate seismic risk

Managing Uncertainties is a desirable goal

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What is the NEED?

- From NTTF Recommendation # 2:***"reevaluate and upgrade as necessary the design-basis seismic and flooding protection of SSC's for each operating reactor"***

- Current State of Seismic Analysis at NPP
  - NRC endorses EPRI-1025287, "Seismic Evaluation Guidance"
    - NPPs develop new site specific hazard curves based on CEUS
    - Utilize screening process to eliminate certain plants from further review
    - Perform SPRA or SMA for NPPs
    - Submit proposed actions to evaluate seismic risk contributions

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What is the NEED?

- Existing nuclear facilities may need seismic isolation technologies to mitigate increased seismic demands associated with implementation of NTTF recommendation #2
  – SI could mitigate the effects of increased hazard for systems and components
- New nuclear facility designs may want to include SI to reduce seismic demands and manage seismic hazard uncertainty

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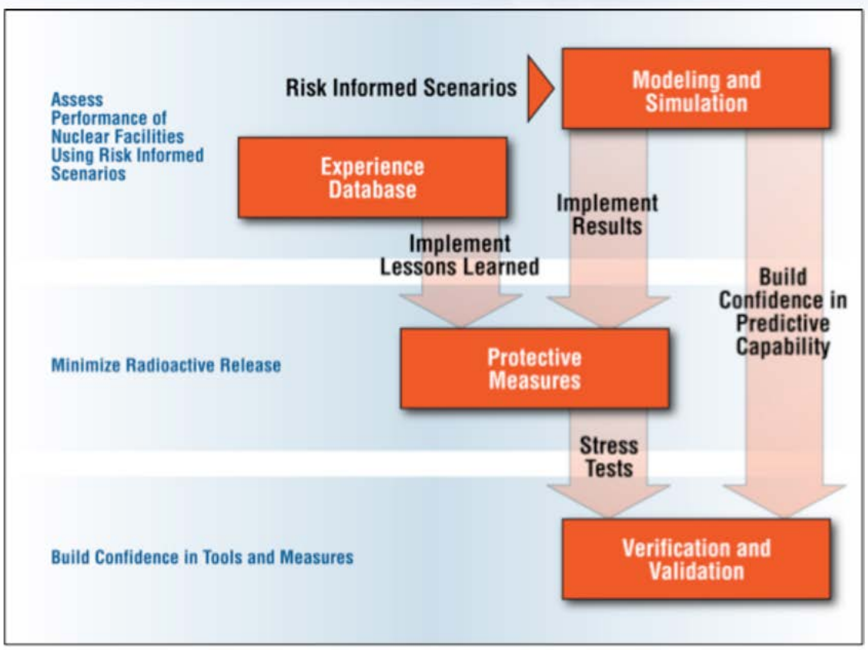
Seismic Evaluation Process



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Seismic Evaluation Process

- Seismic hazards at some nuclear facilities are increasing
- Larger earthquakes produce increased geometric and material nonlinearities
- Need numerical tools to evaluate seismic demands
- Need appropriate protective measures (such as seismic isolation) to manage seismic hazard uncertainty

Seismic Isolation Application

Seismic Isolated Building

- *"Seismic Isolated Building" installed in 2010 for emergency response based on lessons learned from the Kashiwazaki's earthquake in 2007.*
- *Building with gas turbine electric generator, ventilation equipment with high performance filter, video conference system, etc.*
- *Without this building, it would have been impossible to continue the activity against the accident.*

TOKYO ELECTRIC POWER COMPANY

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Seismic Isolation (Protective Measure)/Non-Isolated Commercial Buildings

- 1995 Kobe earthquake impact on fixed base commercial buildings, Magnitude 6.8

Map showing the epicenter of the earthquake

Damage from the Great Hanshin Earthquake is kept intact at the Earthquake Memorial Park near the port of Kobe. The elevated Hanshin Expressway, in the background, was partially toppled by the earthquake.

Date	January 17, 1995
Magnitude	Mw 6.8 (USGS) Mj 7.3 (adjusted from 7.2; JMA scale)
Depth	16 km (9.94 mi)
Epicenter	Awaji Island, Japan
Countries or regions	Japan
Peak acceleration	0.8 *g*
Casualties	6,434 killed,[1] around 300,000 left homeless

SI deployment depends on robust nonlinear analysis capability

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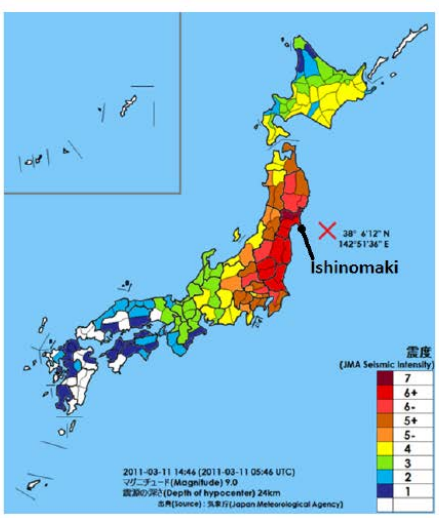
Seismic Isolation (Protective Measure)/ Isolated Hospital in Ishinomaki

- 2011 Great East Japan Earthquake (Tohoku), Magnitude 9.0
- Ishinomaki one of the closest cities to the epicenter of earthquake
- http://www.youtube.com/watch?v=Pc1ZO7YwcWc



Peak tsunami wave height summits, color-coded with red representing most severe

Date	11 March 2011
Origin time	14:46:23 JST (UTC+09:00)
Duration	6 minutes[1]
Magnitude	9.0 (M_w)[2][3]
Depth	32 km (20 mi)
Epicenter	38.322°N 142.369°E
Type	Megathrust earthquake
Countries or regions	Japan (primary) Pacific Rim (tsunami, secondary)
Total damage	Tsunami wave, flooding, landslides, fires, building and infrastructure damage, nuclear incidents including radiation releases
Max. intensity	IX
Peak acceleration	2.99 *g*
Tsunami	Up to 40.5 m (133 ft) in Miyako, Iwate, Tōhoku

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Questions for Discussion

- Existing nuclear facilities and NPPs?
  - Economics
  - Mission Critical
  - Recovery from event
  - New DOE facilities would benefit from SI technology as outlined in ASCE-4
    - Gaps associated with this? Vertical Ground motion is a big issue…How do you deal with this?
      - The equipment in the facility is the big concern…a cookbook of standardized isolation systems
      - Hybrid system, isolating entire structure, also isolate internal components
    - Non-nuclear facilities…DOE standard that looks at nuclear and non-nuclear facilities
- Need an ongoing long term effort to demonstrate seismic isolation solutions that would provide information to program managers and regulators.
- New concepts?
  - SMRs
  - Advanced Reactors
- Education on SI solutions

13

Questions for Discussion

- Where would industry like to apply seismic isolation technology
  - Entire nuclear island?
  - Systems and components, if so which systems and components?
  - Or Both?
- What seismic isolation gaps exist in
  - Acceptable numerical methodologies?
  - Seismic isolation technologies for systems and components?
    - Rocking effects?
    - Weight is less so may need other SI solutions…need demonstration…standardized process…
  - Cliff edge affects?
  - Hard stop…eliminating the hard stop? Standard? Guidance?
- What R&D activities could fill those gaps?

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Idaho National Laboratory
The National Nuclear Laboratory
15

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ASCE-4 Implementation Process

Michael Salmon

Chair – DANS Working Group

8/19/2014

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ASCE Codes and Standards

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- ASCE is an ANSI Accredited Standards Developing Organization
- Develop and Maintain Standards according to ASCE Rules for Standards Committees
- Accreditation Process and Rules Establish Procedure for Consensus Standards Development

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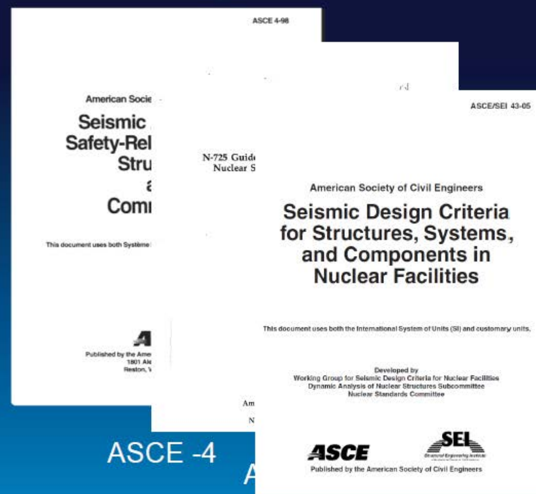
DANS

- Working Group
- Reports to Balanced Nuclear Standards Committee
- Responsible for Nuclear Standards



ASCE -4

ASCE-43

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Revision Process

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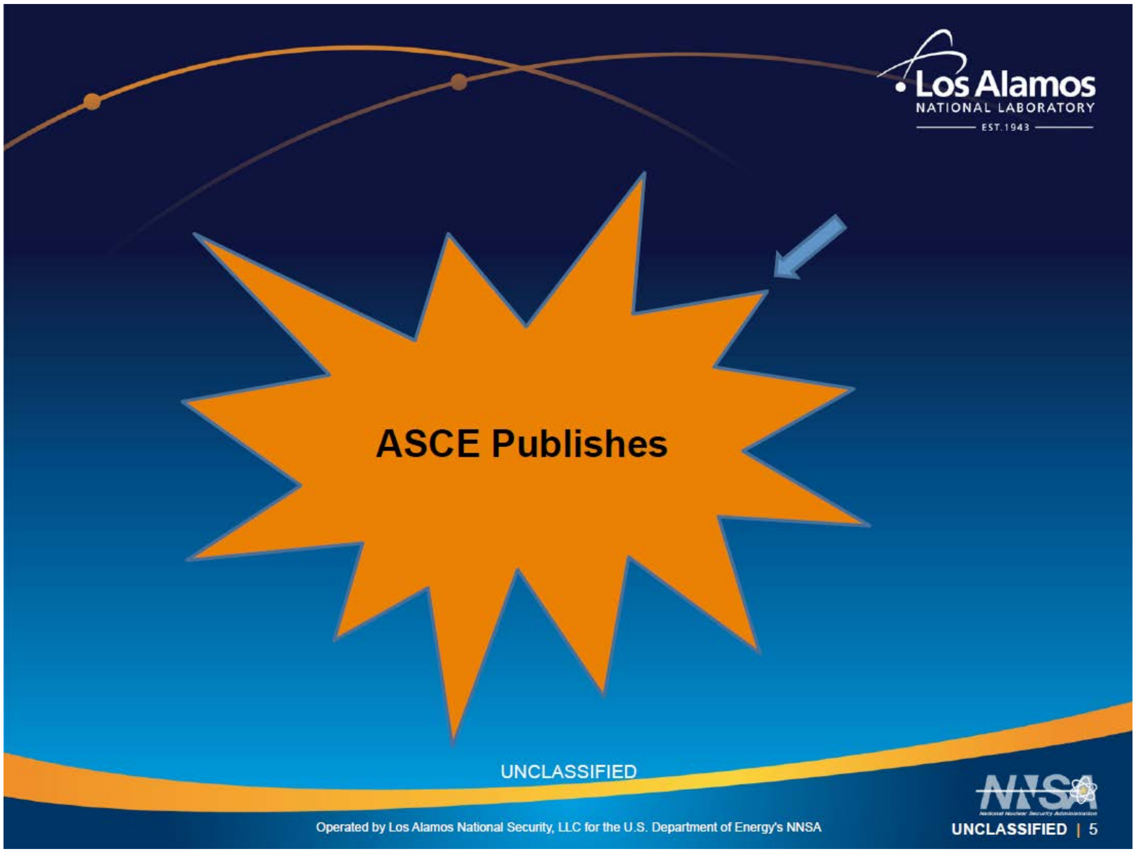
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Where ASCE 4-XX Stands
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DANS Committee has approved
NSC has balloted and approved
In editing at ASCE, in process for approval at SEI/EXCOM
After publication/public comment period will seek formal endorsement from NRC
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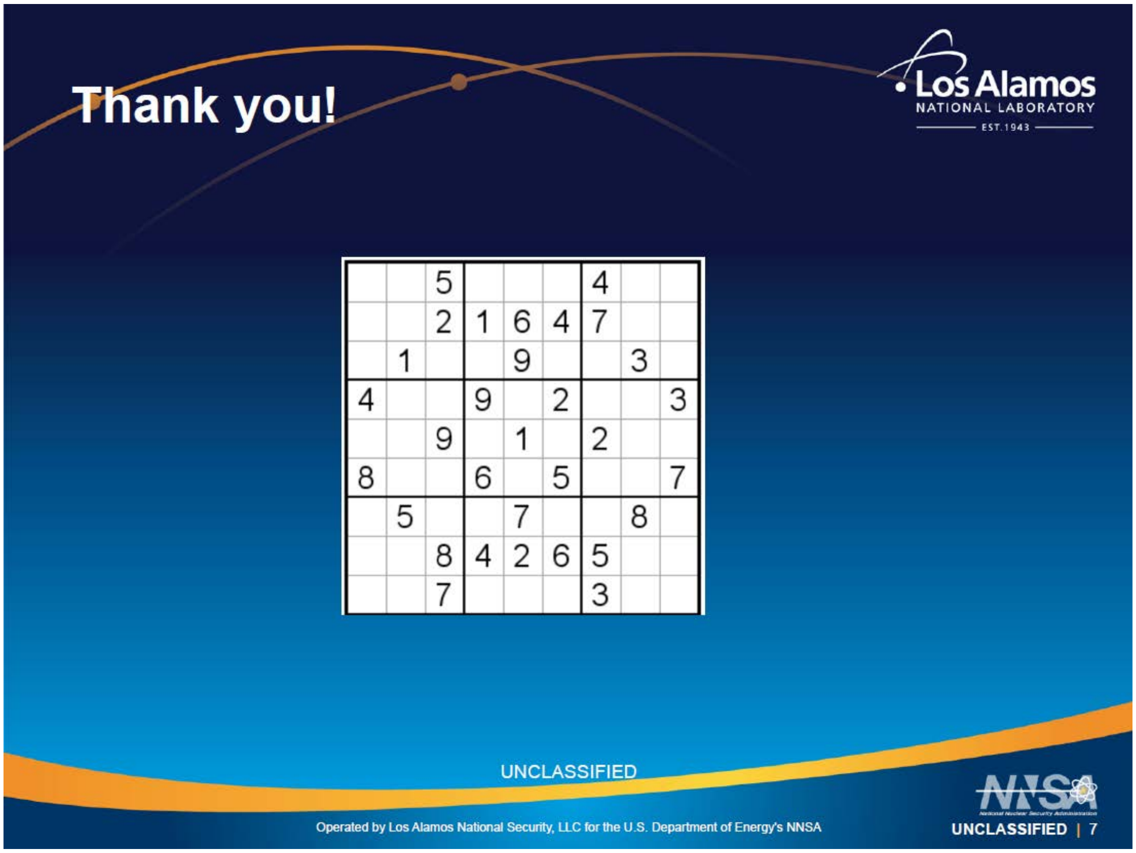

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Risk-informed seismic isolation design in DOE and NRC space

Andrew Whittaker, Ph.D., S.E.
Professor and Chair
Director, MCEER
Department of Civil, Structural and Environmental Engineering
University at Buffalo

Outline

- DOE and NRC commonalities
- US seismic isolation hardware
- Isolator modeling
- Regulatory guidance in the United States
- On-going studies
- Isolation of components

DOE and NRC commonalities

- Horizontal isolation of surface-mounted nuclear facilities
- Applicable in principle to
  - Components and systems
  - Deeply embedded facilities
  - Small modular reactors
  - Three-dimensional isolation systems
- Augmented procedures and isolators needed for alternate systems

DOE and NRC commonalities

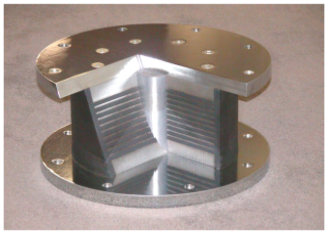
- First Onset of Significant Inelastic Deformation
  - Applied at the component level
  - Developed for conventional nuclear structures
  - Adopted in principle for isolation NUREG
- Risk-oriented framework of ASCE 43
  - FOSID at MAFE = E-5
    - How applied to nonlinear isolation systems?
  - DBE = DF * UHS at E-4 = GMRS
  - 1% NEP for 100% DBE shaking
  - 10% NEP for 150% DBE (EDB GMRS) shaking
- Plant level HCLPF for USNRC-regulated NPPs
  - 1% NEP for 167% GMRS shaking

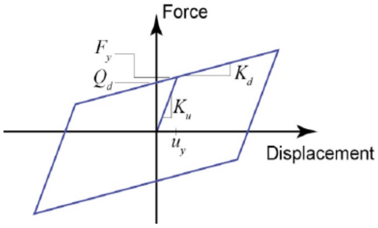
Isolators and isolation systems

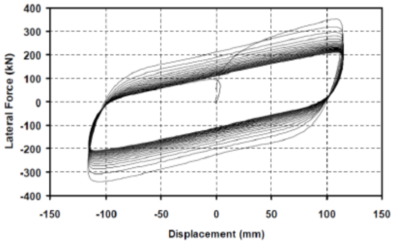
- Addressed for US practice
  - Low damping natural rubber
  - Lead-rubber
  - Spherical sliding (FP) bearing
- Others acknowledged in the NUREG/ASCE 4-14
  - Elastomeric
    - High-damping rubber
    - Synthetic rubber (neoprene)
  - Sliding
    - EradiQuake
  - 3D isolation system

Isolators and isolation systems

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







Isolators and isolation systems

- High-damping rubber
  - Compound + cure
  - Grant et al. (2004)
    - Phenomenological model
    - Bidirectional horizontal response
    - Calibrated to measured responses
      - Elastic force by 5th order polynomial
      - Nonlinear damping function
      - Scragging and Mullins effects
    - No rate dependence
  - Path forward for a HDR isolator
    - One compound, complete cure
      - Documented process by isolator geometry
      - Thermo-chemical-mechanical analysis
    - USNRC 6-step process
    - Develop V&V models without calibration

Journal of Earthquake Engineering,
Vol. 8, Special Issue 1 (2004) 161–185
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BIDIRECTIONAL MODELLING OF
HIGH-DAMPING RUBBER BEARINGS

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High-damping rubber (HDR) bearings are used in seismic isolation applications for buildings and bridges, although no models are currently available for the accurate description of the shear force-deformation response under bidirectional loading. A strain rate-independent, phenomenological model is presented which effectively represents the stiffness, damping, and degradation response of HDR bearings. The model decomposes the resisting force vector as the sum of an elastic component in the direction of the displacement vector and a hysteretic force component parallel to the velocity vector. The elastic component is obtained from a generalised Mooney–Rivlin strain energy function, and the hysteretic component is described by an approach similar to bounding surface plasticity. Degradation is decomposed into long term ("scragging") and short term ("Mullins' effect") components. Calibration is carried out over a series of bidirectional test data, and the model is shown to provide a good match of slow strain-rate experimental data using a unique set of material parameters for all tests. A testing protocol and calibration of the model for use in design of structures with HDR bearings are discussed.

Keywords: High-damping rubber bearings; seismic isolation; mathematical model.

1. Introduction

Seismic isolation is widely used in buildings and bridges to protect them from the effects of strong ground motion. Flexible isolation bearings are placed between the primary mass of a structure and the support motion, effectively using inertia and increased flexibility to limit structural deformation in critical components. In this manner, buildings are isolated from their foundations, and the superstructures of bridges are isolated from the piers.

High-damping rubber (HDR) bearings are a type of seismic isolator used in bridge and building construction and retrofit. As with other elastomeric isolation devices, HDR bearings are composed of layers of an elastomeric compound, reinforced

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EARTHQUAKE ENGINEERING TO EXTREME EVENTS

Isolators and isolation systems

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

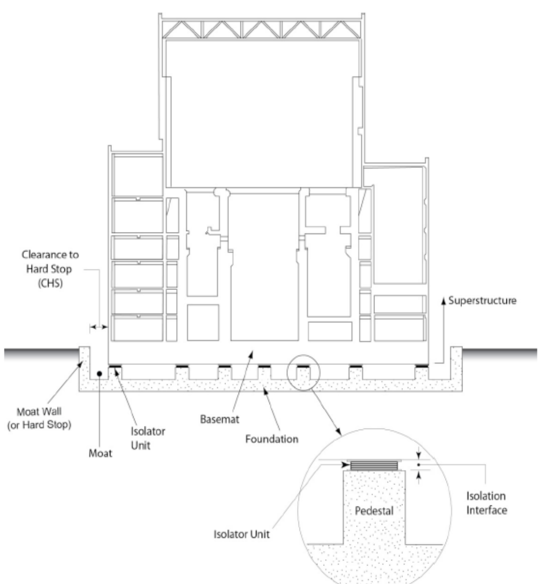
EARTHQUAKE ENGINEERING TO EXTREME EVENTS

Isolator modeling

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

August 19, 2014 DOE Seismic Isolation Workshop, Washington, DC

Regulatory guidance for isolation



August 19, 2014 DOE Seismic Isolation Workshop, Washington, DC

Regulatory guidance for isolation

- ASCE 4-14 Section 7.7 (Seismic isolation NUREG)
- Performance expectations of ASCE 43
  - FOSID at MAFE = E-5
  - DBE = DF * UHS at E-4 = GMRS
  - 1% NEP for 100% DBE shaking
  - 10% NEP for 150% DBE shaking
- Analyzable for beyond design basis loadings
  - Definitions differ for DOE and NRC applications
- Reliable numerical models of isolators
  - Validated by full-scale dynamic testing
- Modeling and analysis of isolated structures
- Prototype and production testing

Regulatory guidance for isolation

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

Regulatory guidance for isolation

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

		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 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.

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

Ground motion levels	Isolation system: Isolation unit and system design and performance criteria	Isolation system: Approach to demonstrating acceptable performance of isolator unit	Superstructure design and performance	Umbilical line design and performance	Moat or hard stop design and performance
GMRS+[2] The envelope of the RG1.208 GMRS and the minimum foundation input motion[3] for each spectral frequency	No long-term change in mechanical properties. 100% confidence of the isolation system surviving without damage when subjected to the mean displacement of the isolator system under the GMRS+ loading.	Production testing must be performed on each isolator for the mean system displacement under the GMRS+ loading level and corresponding axial force.	The superstructure design and performance must conform to NUREG-0800 under GMRS+ loading.	Umbilical line design and performance must conform to NUREG-0800 under GMRS+ loading.	The moat is sized such that there is less than 1% probability of the superstructure contacting the moat or hard stop under GMRS+ loading.
EDB[4] GMRS The envelope of the ground motion amplitude with a mean annual frequency of exceedance of $1x10^{-5}$ and 167% of the GMRS+ spectral amplitude	90% confidence of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under EDB loading.	Prototype testing must be performed on a sufficient number of isolators at the CHS[5] displacement and the corresponding axial force to demonstrate acceptable performance with 90% confidence. Limited isolator unit damage is acceptable but load-carrying capacity must be maintained.	There should be less than a 10% probability of the superstructure contacting the moat or hard stop under EDB loading.	Greater than 90% confidence that each type of safety-related umbilical line, together with its connections, remains functional for the CHS displacement. Performance can be demonstrated by testing, analysis or a combination of both.[6]	CHS displacement must be equal to or greater than the 90th percentile isolation system displacement under EDB loading. Moat or hard stop designed to survive impact forces associated with 95th percentile EDB isolation system displacement.[7] Limited damage to the moat or hard stop is acceptable but the moat or hard stop must perform its intended function.

1. Analysis and design of safety-related components and systems should conform to NUREG-0800, as in a conventional nuclear structure.
2. 10CFR50 Appendix S requires the use of an appropriate free-field spectrum with a peak ground acceleration of no less than 0.10g at the foundation level. RG1.60 spectral shape anchored at 0.10g is often used for this purpose.
3. The analysis can be performed using a single composite spectrum or separately for the GMRS and the minimum spectrum.
4. The analysis can be performed using a single composite spectrum or separately for the 10^{-5} MAFE response spectrum and 167% GMRS.
5. CHS=Clearance to the Hard Stop
6. Seismic Category 2 SSCs whose failure could impact the functionality of umbilical lines should also remain functional for the CHS displacement.
7. Impact velocity calculated at the displacement equal to the CHS assuming cyclic response of the isolation system for motions associated with the 95th percentile (or greater) EDB displacement.

Design considerations

- Basemat and foundation
  - Loss of isolator
  - Capacity design of pedestal and connections
- External events
  - Flooding
  - Aircraft impact, IED detonation
- Fire suppression system
- Operating temperature
- Isolator QA/QC
- Prototype and production testing

MCEER EARTHQUAKE ENGINEERING TO EXTREME EVENTS

Prototype and production testing

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

On-going isolation-related studies

- PRA methodologies to address isolation
  - Huang et al. 2009
- Target spectra for distributions of response
- Design factors for GMRS
- Design procedures for hard stop
- Procedures to eliminate hard stop
- Required complexity of isolator models

Isolation of components

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Isolation of components

- Deeply embedded SMRs
  - Not feasible to isolate the entire structure
    - Engineered fill?
  - Component isolation feasible
- Components on a common mat
  - RPV and steam generators
  - LDR, LR and FP isolators
  - Treatment of umbilical lines
  - Fully coupled time domain analysis
    - Propagate motions from depth through soil and structure
  - Risk-based analysis and design per ASCE 4/43

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Isolation of components

- Component isolation
  - 3D isolation possible
  - Component geometry and fragility
    - Different from LLWR
    - Isolator design for non-seismic fragility
  - Alternate isolator(s)
    - Family of component isolators
    - Extend Section 7.7 of ASCE 43
    - Expand seismic isolation NUREG
  - Fully coupled time domain analysis
    - Seismic input filtered by structure

Acknowledgments

- US Nuclear Regulatory Commission
- US Department of Energy
- Yin-Nan Huang, NTU
- Michael Salmon, LANL
- Justin Coleman, INL
- Robert Budnitz, LBNL
- Jim Johnson, JJJ
- Robert Kennedy, RPK Structural Mechanics
- Michael Constantinou, UB
- Manish Kumar[2], UB
- Boris Jeremic, UC Davis

NRC Base Isolation Research

By
Jose A. Pires
Office of Nuclear Regulatory Research, Division of Engineering
US Nuclear Regulatory Commission

Base Isolation Workshop
(Organized by Idaho National Laboratory)
Washington, DC
August 19, 2014

Acknowledgements / Disclaimer

Acknowledgements:

- Annie Kammerer (formerly NRC)
- Bret Tegeler (formerly NRC)
- Richard Rivera-Lugo (NRC)
- Scott Stovall (NRC)
- Mohamed Shams (NRC)

Disclaimer

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Purpose / Agenda

- Purpose
  - Present summary of on-going NRC research
  - Address views and expectations for reviews
- Agenda
  - NRC research on base isolation
  - Reviews: views/expectations
  - Summary

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NRC Research on Base Isolation

- Effort Initiated in 2008
- Technical experts at SUNY-Buffalo, LBNL, UC-Davis
  - Isolation user elements (UELs) developed for OpenSees and Abaqus
  - Technical bases for understanding the performance of base isolation systems when subjected to earthquake ground motions
  - Technical bases for formulation of a set of regulatory criteria and guidance
  - NRC's ESSI simulator work ongoing

NRC Research on Base Isolation

- Research addresses key items
  - Vertical and beyond-design-basis loading
    - Showed that 3D modeling is necessary
  - Development of isolator component UELs (Will be publically available)
  - Support formulation of performance-based criteria for regulation of NPPs using seismic isolation systems (NUREG ch. 8 & 9)
  - Modeling of low damping rubber bearings (UELs)
  - Modeling of sliding bearings accounting for variation in time of axial pressure, sliding velocity and temperature (UELs)
  - Response history analysis of nuclear power plants
  - Selection and scaling of ground motions
  - Impact on surrounding wall (moat)

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NRC Research on Base Isolation

- Additional research (University of Nevada, Reno)
  - Testing of isolator systems to confirm analysis tools, models, and assumptions (testing performed on e-Defense – contractor report under review)
  - Sensitivity study on isolator mechanical properties completed – Showed that modeling the isolator properties during loading require time domain modeling
- Interaction with IAEA-ISSC Working Area 2
  - Insights gained also inform IAEA-ISSC collaborative research on base isolation

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NRC Research on Base Isolation

- Technical basis for formulation of a set of regulatory criteria and guidance
  - Draft NUREG report
  - Collect and summarize existing technical information
  - Develop preliminary recommendations addressing design, construction, and operational needs
  - Summarize Japanese regulatory guidance
- Status:
  - Draft is currently in internal NRC review
  - Publication anticipated in 2014
  - Guidance development, e.g., SRP update, depending on level of industry interest

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Reviews: Views and Expectations

- Staff encourages innovative designs, such as base isolated structures
- New designs for innovative structures must satisfy regulations
- Staff expects design to be based on sound engineering principles and validated methods

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Reviews: Views and Expectations

Regulations

- Existing Nuclear Power Plant fleet designed in compliance with the regulations:
  - GDC 1: Quality standards and records – Structures, systems, and components important to safety shall be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed.
  - GDC2: Design bases for Protection against natural phenomena – Structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornados, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions.
- New designs for innovative structures must satisfy the above regulations
- Lack of applicable codes and standards will result in more effort to demonstrate compliance with the regulations

Review Guidance
Standard Review Plan framework is applicable to innovative structures

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Reviews: Views and Expectations

- Potential Design Challenges
  - Lack of detailed design information at the Design Certification stage
  - Lack of code applicability
  - Lack of detailed site information
  - Performance criteria
  - Consideration of uncertainties, defense-in-depth, and seismic margin early in the design process
  - Consideration of environmental effects, such as material aging, creep, operating temperature, and exposure to moisture early in the design process

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Reviews: Views and Expectations

- Potential Analysis Challenges
  - Nonlinear behavior of isolation system
  - Understanding applicability and limitations of methods
  - Validation of methods through testing/benchmarking
  - Evaluation and interpretation of analysis results for their adequacy
  - Ground motion selection and scaling
  - Earthquake soil-structure interaction

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Reviews: Views and Expectations

- Identification of significant design information (Design Certification)
  - Critical Section Description
  - Tier 2* Information
  - ITAAC

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Summary

- New and innovative design is encouraged
- New designs for innovative structures making use of base isolation must satisfy regulations
- Base isolated designs should be based on sound engineering principles and validated methods
- Consideration of uncertainties, defense-in-depth, and seismic margin should be considered early in the design certification process
- Environmental effects, such as material aging, creep, operating temperature, and exposure to moisture, should also be considered early in the design.

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Acronyms

3D	Three-dimensional
GDC	General Design Criterion
IAEA	International Atomic Energy Commission
ISSC	International Seismic Safety Center
ITAAC	Inspections, Tests, Analyses, and Acceptance Criteria
LBNL	Lawrence Berkeley National Laboratory
NRC	Nuclear Regulatory Commission
SRP	Standard Review Plan
SUNY	State University of New York
UC	University of California

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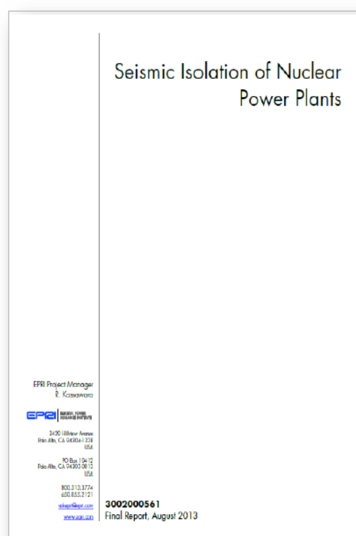
EPRI Research in Seismic Isolation

John Richards / Bob Kassawara
EPRI Risk and Safety Management

Seismic Isolation Working Meeting
August 19, 2014

Most Recent Report, EPRI 3002000561

- Goals were to identify
  - Benefits and challenges in using seismic isolation for nuclear facilities
  - Issues related to experiences with existing seismically isolated NPPs and infrastructure facilities
  - Key aspects of work needed to develop guidelines for isolation for NPP facilities



Seismic Isolation of Nuclear Power Plants

EPRI Project Manager
R. Kassawara

3002000561
Final Report, August 2013

 2

Research Approach

- Principal Investigator, Steve Mahin, PEER
- Extensive literature review
  - Research and development of technologies
  - Application to major civil works and to NPPs and related nuclear facilities
- Interview engineers with expertise in
  - Seismic design of NPPs
  - Seismic isolation
  - Manufacturing of seismic isolation bearing and supplemental damping devices
  - Inspection and maintenance of seismically isolated NPPs

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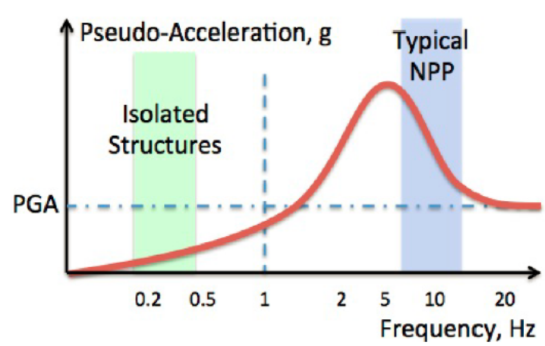
Key Conclusions

- Seismic isolation is a relatively mature technology with wide spread applications
- Isolated structures have performed well, as expected, in recent earthquakes
- There seem to be no major technical impediments to the implementation of seismic isolation to NPPs
- Education and training needed for regulators, plant owners / operators, and structural and mechanical engineers



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Key Conclusions

- Increasing focus on risk-informed, performance-based assessment raises many regulatory and technical uncertainties
- Many issues similar to fixed base structures
  - RIPB framework and performance criteria
  - Seismic hazard & appropriate selection, scaling and modification ground motions
  - SSI and nonlinear modeling and analysis of systems, structures and components
  - Fragilities of structures, systems and components
- Trade improved certainty of demand above the isolators for greater uncertainty in isolator displacement characterization

Research Needs

- Effect of SSI on effectiveness of isolation system
- Response in beyond design basis events
  - Required seismic gap size (can it be reduced)
  - Bearing and umbilical behavior under extreme events
  - Restrain ultimate displacement of isolation plane with least consequence
- Vertical ground excitations & response
- Analysis methods and models
  - High fidelity and validated models needed for isolators, dampers, soils, structures, components, etc.
  - Guidelines and best practices for conducting nonlinear dynamic time history analyses

Research Needs (continued)

- Tests and integrated validation analyses
  - Performance-based component tests (isolators, etc.)
  - Shaking table tests to validate concepts and analytical models
  - Equipment tests to insure that fragility data is adequate for low frequency range of response
- Seismic instrumentation and condition assessment tools
  - Rapid assessment of performance
  - Decision support to help guide walk downs and restart power generation

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Next Steps?

- Regulatory uncertainty
  - Plant owners are unsure how a seismically isolated plant (or portions of a plant) would be reviewed
  - That uncertainty contributes to limited serious consideration for owners and designers
- NPP cost savings are unclear
  - Would plant costs be cheaper?
  - Do seismic loads govern design?
- Perhaps an economic study would be valuable

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Together…Shaping the Future of Electricity

Safety System for Nuclear Reactors

- Post-Fukushima (Seismic Isolation Gaining Importance)
- Advanced Reactors
- Small Modular Reactors

Piyush Sabharwall

Idaho National Laboratory

August 19th 2014

www.inl.gov

INL Idaho National Laboratory

Seismic Isolation Workshop, August 19th 2014, Washington DC, INL Office

INL Idaho National Laboratory

Contents

- *Objective*
- *Evolution of Nuclear Power*
- *PWR and Advanced Reactors*
- *AHTR Reactor Building System*
- *ASME Safety Classification*
- *SMRs*
- *Critical Components*
- *Seismic Analysis – Component Specific Qualification Tests*
- *Seismic Isolation Need*
- *Where are we headed (My Perspective)*
- *Key Take Away..(Summary)*

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Objective

Under Seismic events we need to ensure the following:

- No radioactive release to the public
- Keeping the core cool (preventing core meltdown)
- Integrity of the plant (to our best ability)

To meet the above mentioned objective Seismic Isolation of key components is very very essential.

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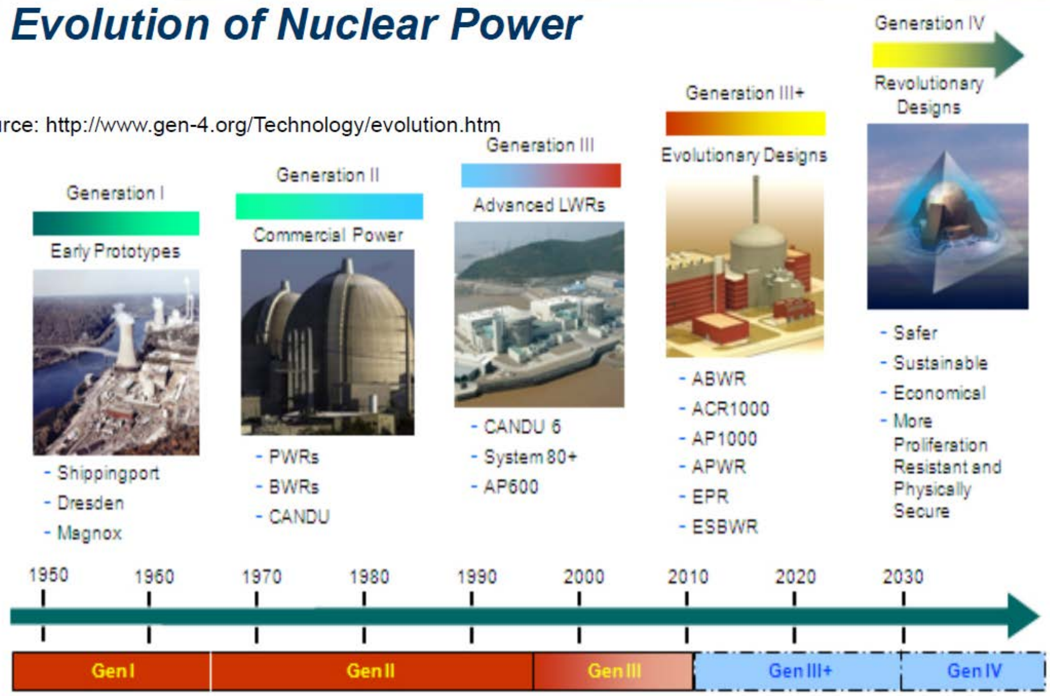
Evolution of Nuclear Power

Source: http://www.gen-4.org/Technology/evolution.htm



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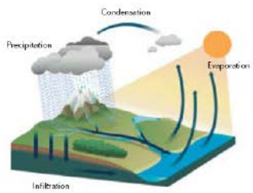
Energy Security: A Balance of Priorities



Clean

Low greenhouse gas emissions
Reduced water withdrawals
Reduced land impacts

Secure

Domestic source
Physical & cyber protection

Affordable

Reasonable TOTAL costs
Predictable, stable price
Marketable in free-economy

Reliable

Available on demand
Continuous quality
Easily maintainable

Resilient

Adapts to resource characteristics
Adjusts to market demands
Capable of meeting new regulations

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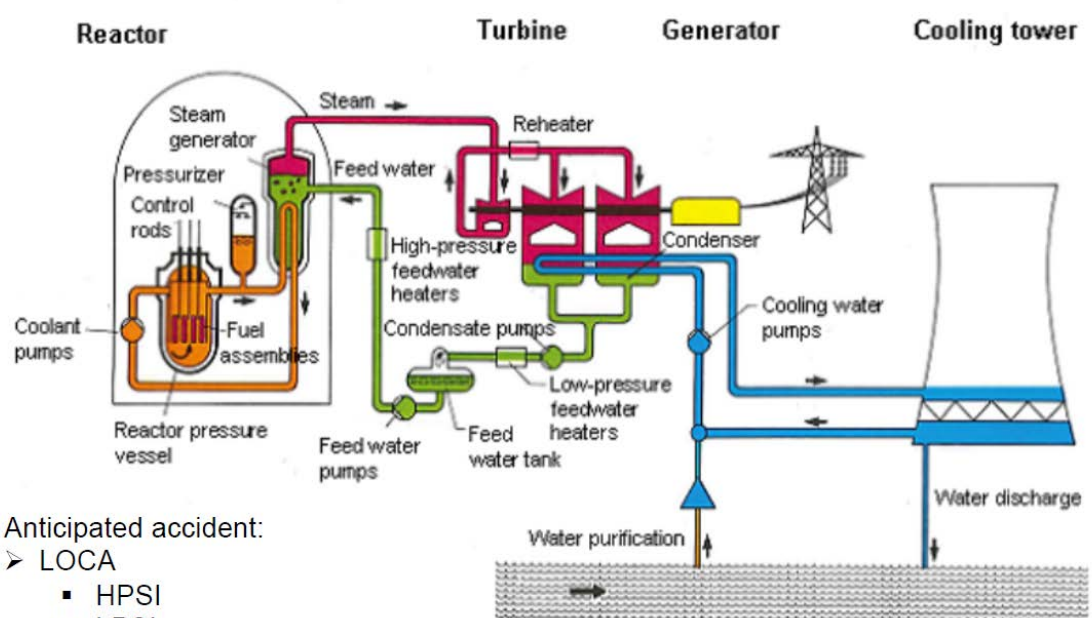
PWR



Anticipated accident:
- LOCA
  - HPSI
  - LPSI
  - Steam accumulators

Source: http://de.areva.com/EN/areva-germany-2049/reactor-types.html

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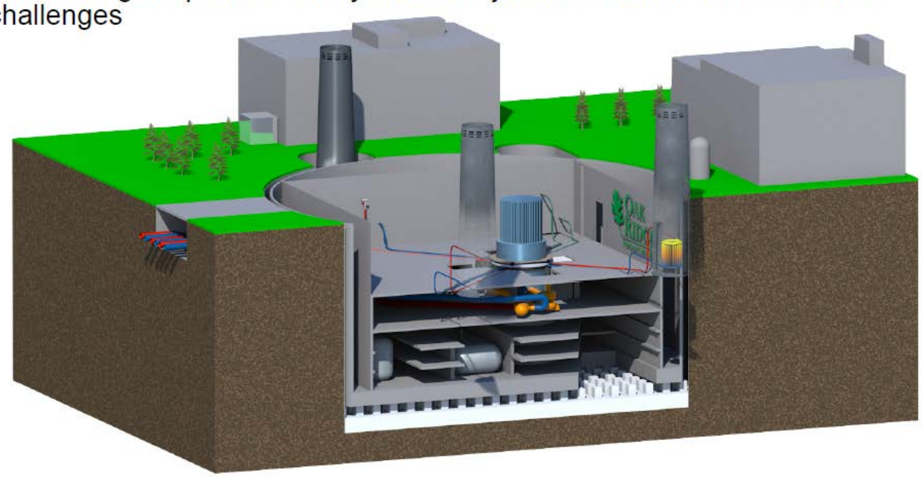
Integrated Design of the AHTR Reactor Building Systems and Structures is Underway

- Focus is on integrating necessary systems, structures, and components
- A design focus is on maximizing the system economic performance
  - Employing modular, open-top construction to minimize cost
  - Maintaining full passive safety when subjected to severe environmental challenges



Holcomb. et.al. AHTR Talk. ANS 2012 **Seismic Isolation Workshop, August 19th 2014, Washington DC, INL Office**

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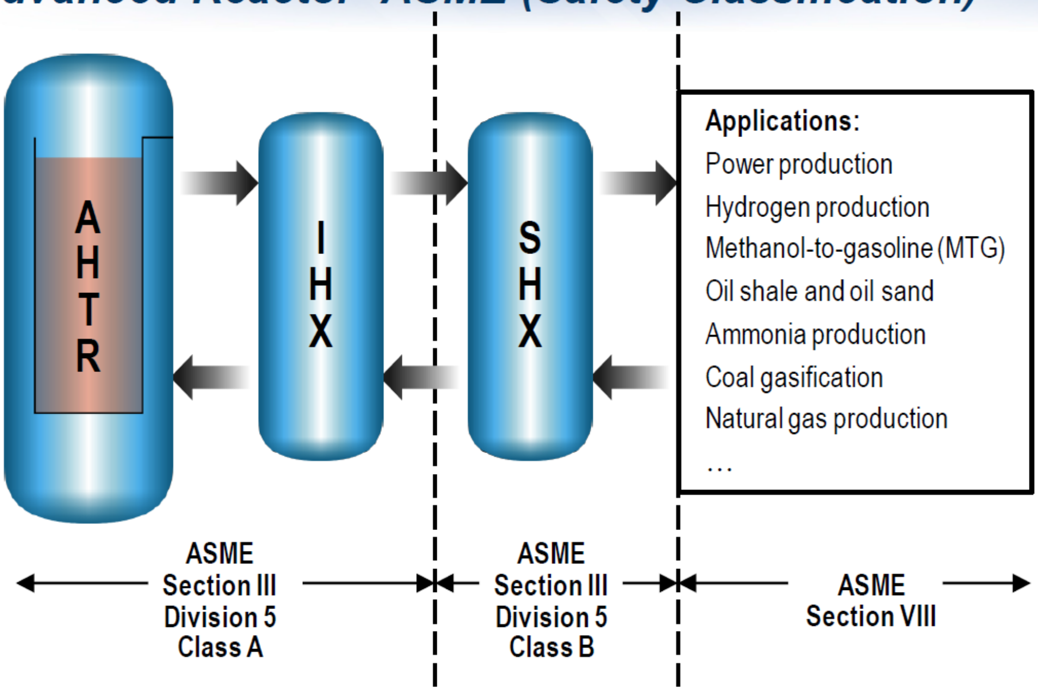
Advanced Reactor- ASME (Safety Classification)



Sabharwall et.al. INL/EXT-12-26219 **Seismic Isolation Workshop, August 19th 2014, Washington DC, INL Office**

Small Modular Reactors (SMRs)

- IAEA definitions:
  - ➢"Small" < 300 MWe
  - ➢"Medium" 300 – 700 MWe
  - ➢"Large" > 700 MWe

*Most new plants are >1000 MWe

- DOE definition of "small":
  - ➢ <300 MWe
  - ➢Factory fabrication, rail/road transportable to site
  - ➢Operated as multi-module plant

Gen-III+ and Gen-IV concepts

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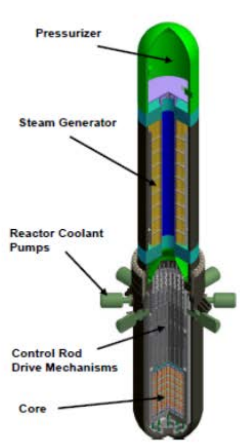
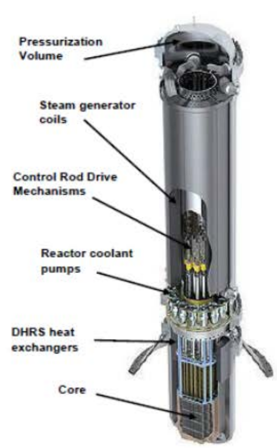
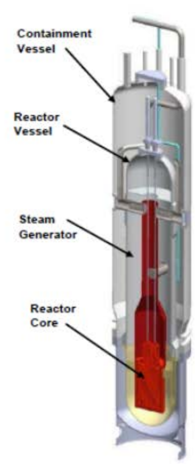
Integrated LWR SMR Designs







Westinghouse SMR 200 MWe | **mPower, Babcock & Wilcox 125 MWe** | **NuScale 45 MWe**

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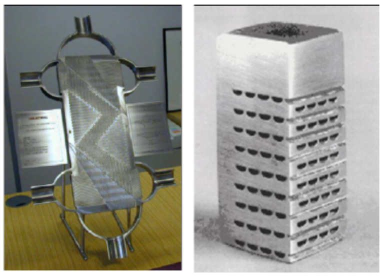
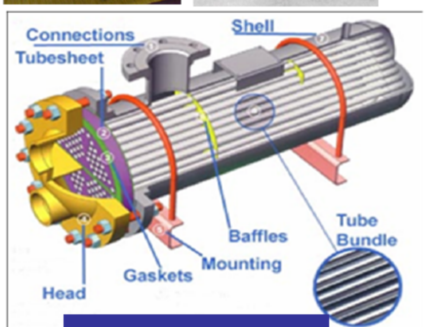
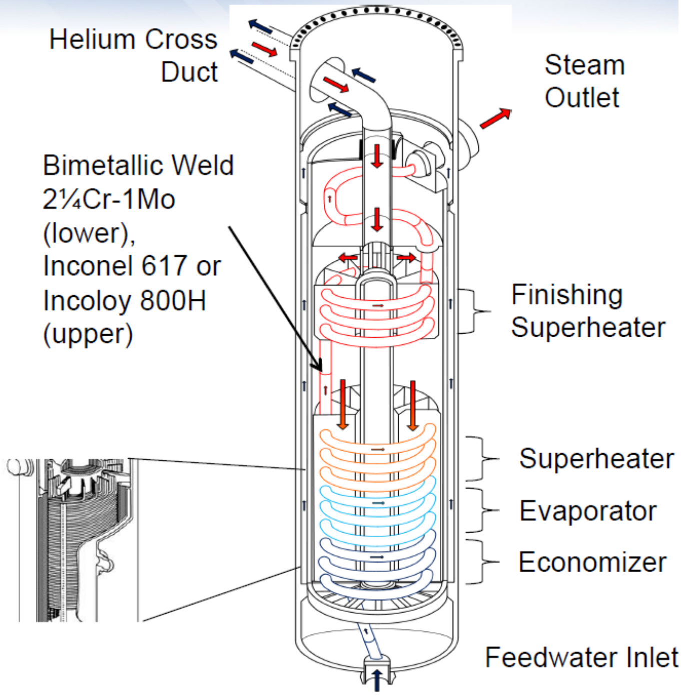
Critical Components

Compact (PCHE)





Shell and Tube



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Seismic Analysis (Component Specific Qualification Tests)

- Very essential to understand and identify governing failure modes
- Need to understand the seismic response of the structures including the effect of the soil (location/site based analysis and need to capture time varying effect of soil system nonlinearities)
- Need to perform
  - sensitivity studies
  - 1g static analysis, review displacements and force distributions
- Need to address uncertainty
  - Reducible with more data, better data, and better models
  - All parameters in the model have uncertainty

Post Fukushima incident and lessons learned will serve as the foundation for control and safety criteria for advanced reactors (reactors that are being presently designed) and signifies the importance of seismic analysis for each specific critical component

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Seismic Isolation Need

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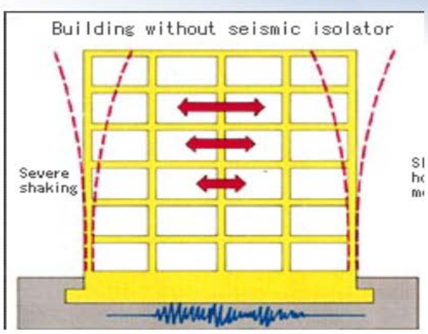
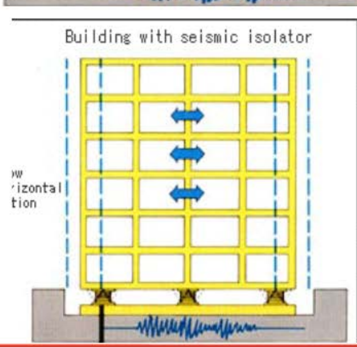
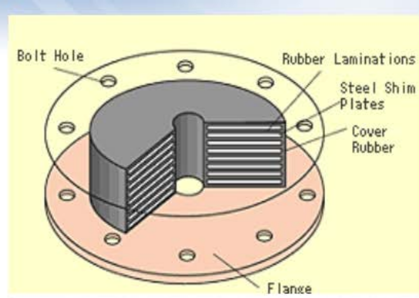
Seismic isolation at a Glance







Dominguez, J., and Oteiza, J., Assessing Seismic Isolation of an ADS Reactor Building

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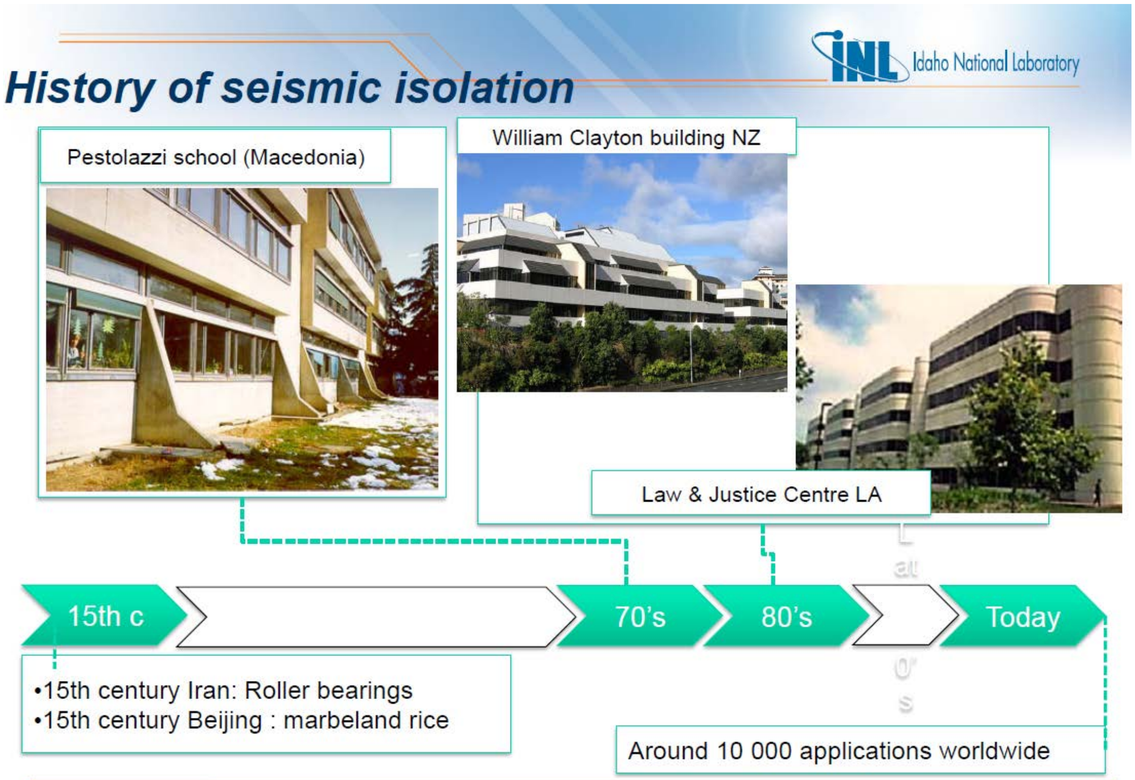

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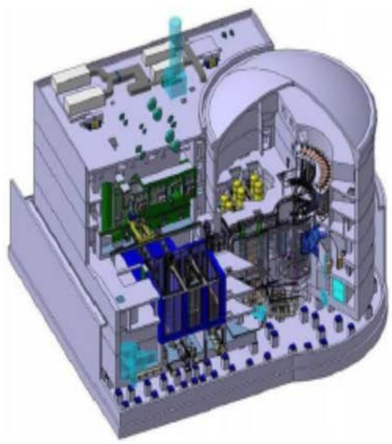
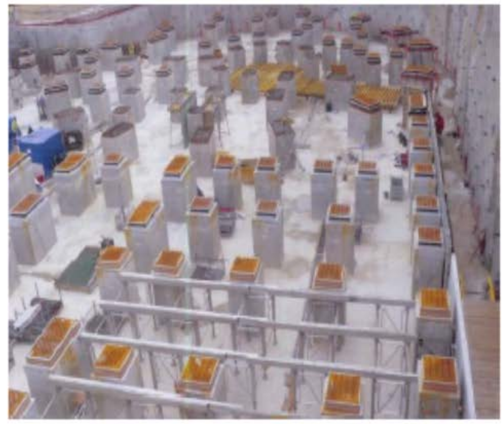
JHR (France)





Sketch of the Jules Horowitz reactor and view of the isolation system during installation at the Cadarache centre (France)

Source: http://editors.enea.it/it/internazionali/eventi-internazionali/enea-in-japan-2011/earthquake-engineering/forni.pdf

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Where are we headed..?

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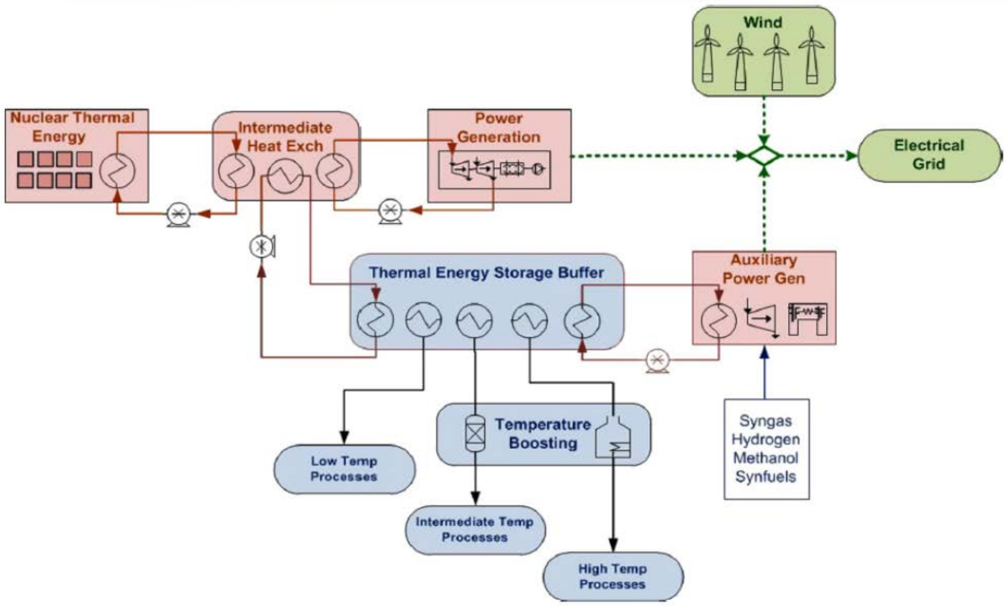
Nuclear Hybrid Energy Systems (NHES)



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Key Take Away..

- For a successful nuclear future seismic isolation measures should be integrated with SMRs and Advanced Reactors.
- A thorough analysis still needs to be done to show the effectiveness of seismic isolation for the critical components, such that safety and integrity is maintained
- Seismic analysis needs to be carried out for specific sites/location as one needs to take into account different soil effect (Hard soil, soft soil)
- Seismic systems for the critical components of the plant will enable the plant to maintain safe plant operations despite emerging or unanticipated scenario's. Current reactor designs offer minimal flexibility in responding to natural occurring disasters. With seismic isolation systems, the severe accidents scenario could be handled better and the reactor and its critical components could maintain better integrity.
- Advanced capabilities in modeling could reduce uncertainties and advance our understanding of seismic performance of nuclear power systems

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Discussion..

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- What activities in parallel might be and should be done to realize the full potential of advanced seismic simulation methods and its significance to the nuclear community/utilities
- Need to carry out and show the importance of structural models for embedded systems:
  - taking into account the interaction between structure and soil.
    - Need to account for soil deformation overtime
    - Soil non-linearities (soft/hard soil type, homogeneous soil/ layered soil structure)
  - need to understand the behavior of embedded systems for both predicted (design-basis) and beyond design basis earthquakes in order to determine the threshold or critical level/point beyond which the integrity of the critical component is compromised
- To promote/encourage utilities and various vendors to look into seismic isolation techniques, is only possible when:
  - These systems are well understood, such that could be integrated into design codes itself (Blink and Budnitz, NEAMS, 2012)
  - Could be taken as added safety measures from nuclear safety regulatory process perspective and ultimately helps in licensing..

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