INL Seismic Initiative

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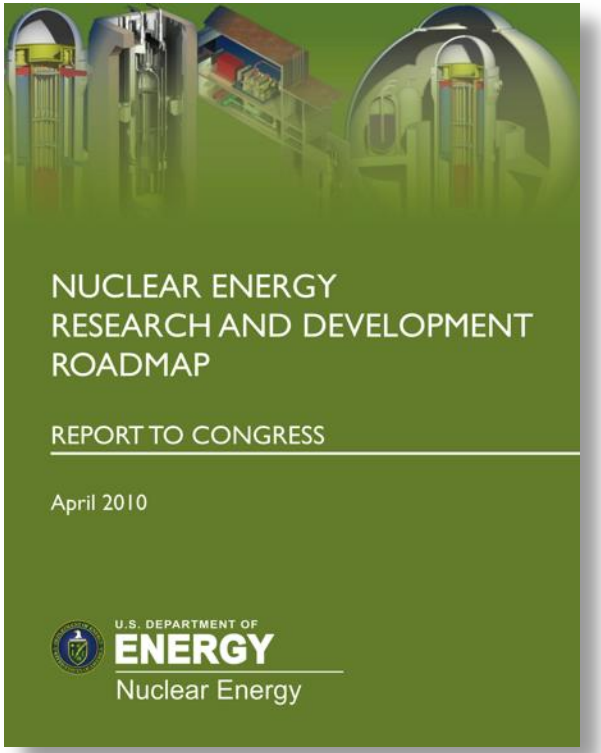
U.S. DEPARTMENT OF ENERGY | Nuclear Energy

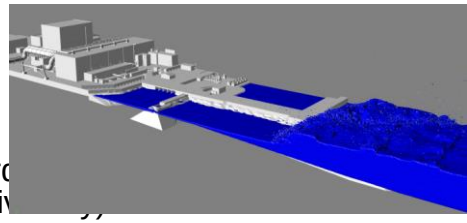
Light Water Sustainability Program Goals and Scope

- Goals
  - Develop the fundamental scientific basis to understand, predict, and measure changes in materials and systems, structures and components (SSCs) as they age in environments
  - Apply this knowledge to develop and demonstrate methods and technologies that support safe and economical long-term operation of existing reactors
  - Research new technologies that enhance plant performance, economics, and safety
- Scope
  - Materials Aging and Degradation
  - **Risk-Informed Safety Margin Characterization**
  - Advanced Instrumentation, Information, and Control Systems Technologies

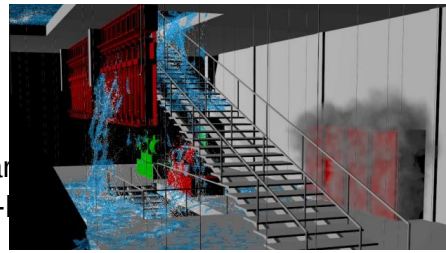


RISMC External Events – Building Advanced Capabilities through Methods, Tools, and Data

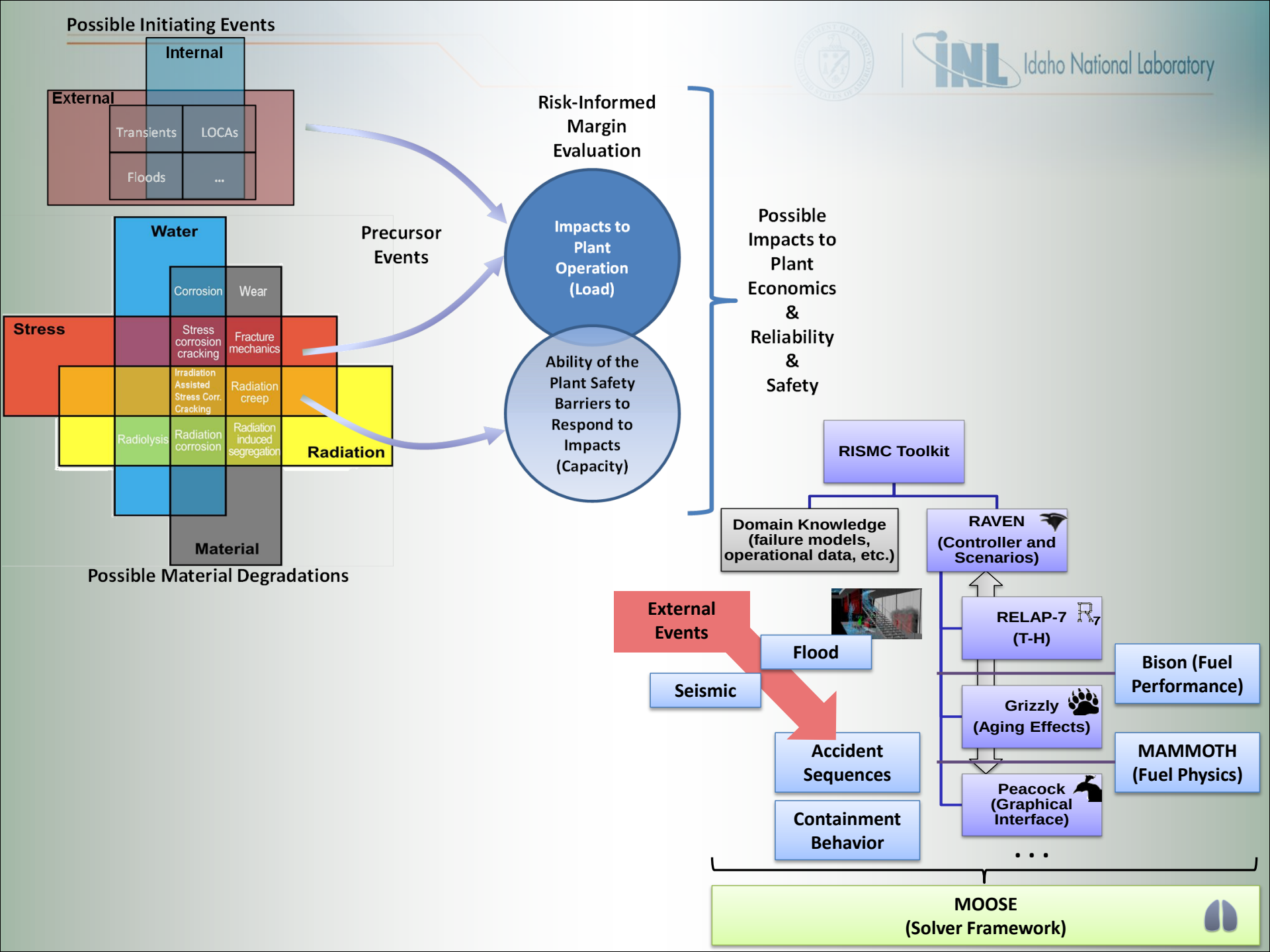
- Safety margin characterization requires understanding of plant risks
- RISMC is evaluating external events since they are important to safety of the current nuclear power fleet
  - Advanced modeling and simulation of seismic and flooding
- Seismic activities are in their second year, building on the RISMC approach and Toolkit
  - Seismic modeling & simulation to support validation of enhanced approaches (including comparison against traditional models)
    - Making progress on gathering data including, seismic hazard data, seismic motions, tsunami data, design basis values, plant dimensions, system and component information
  - Developed plan for performing advanced PRAs (INL/EXT-14-33302)
  - Engaging domain experts, NRC, DOE, and universities
    - Working closely with EPRI
    - Looking to engage the Japanese on potential collaboration (e.g., data exchange)
  - Have had open calls for collaborations and research ideas (e.g., 2013 NEUP call, awarc RISMC for Nuclear Facility Seismic Analysis, led by Professor Sezen of Ohio State Univ



- Flooding activities are in their second year, building on the RISMC approach and Toolkit
  - Altering traditional PRA techniques → combine them with advanced 3D physics simulations + high performance computing (HPC) to give us detailed analysis insights
  - NPP site analysis for flooding (e.g., tsunamis of various heights)
    - Coupled to Bayesian frequency of the tsunami
  - Simulation of component failure due to building flood analysis
  - Using advanced 3D modeling and particle-based fluid solvers
  - Coupling the models & physics in order to perform risk-informed margins management
    - Working with experts, universities (e.g., Ohio State NEUP, Oregon State Tsunami Resear
  - Current progress and technical plans described in reports (e.g., INL-EXT-14-32906, INL-



- Using these RISMC external events methods, tools, and data for industry application activities


Possible Initiating Events
Internal
External
Transients
LOCAs
Floods
...
Water
Corrosion
Wear
Stress
Stress corrosion cracking
Fracture mechanics
Irradiation Assisted Stress Corr. Cracking
Radiation creep
Radiolysis
Radiation corrosion
Radiation induced segregation
Radiation
Material
Possible Material Degradations
Precursor Events
Risk-Informed Margin Evaluation
Impacts to Plant Operation (Load)
Ability of the Plant Safety Barriers to Respond to Impacts (Capacity)
Possible Impacts to Plant Economics & Reliability & Safety
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RISMC Toolkit
Domain Knowledge (failure models, operational data, etc.)
RAVEN (Controller and Scenarios)
External Events
Flood
Seismic
RELAP-7 (T-H)
Bison (Fuel Performance)
Grizzly (Aging Effects)
MAMMOTH (Fuel Physics)
Accident Sequences
Containment Behavior
Peacock (Graphical Interface)
. . .
MOOSE (Solver Framework)

INL Seismic R&D Mission and Vision

- Provide DOE and industry with verified and validated advanced methods and tools that provide a better understanding of nuclear facility response during and after external hazard events
  - The goal is to manage seismic risk at nuclear facilities through cost effective analytical approaches and technologies
  - This reduces uncertainty and quantifies the safety margins at existing and new nuclear facilities.

VISION

Advanced external hazard analysis tools and methods are implemented in a comprehensive, risk-informed framework that provides realistic best estimate nuclear facility response and ensures plant safety during and after beyond design basis events.

Short to Medium Term Goal (1-5 years)

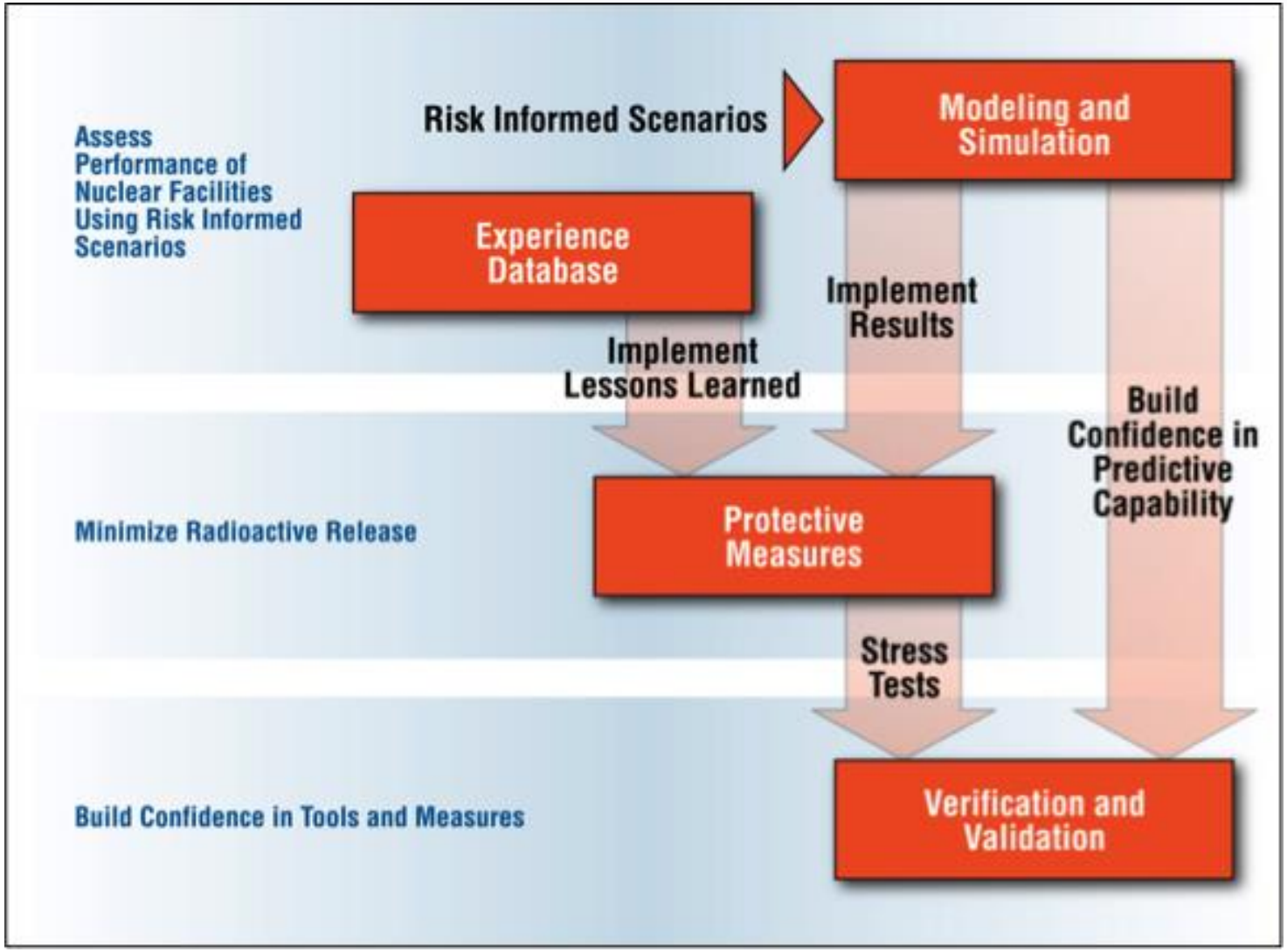
- Integrate RD&D efforts and expertise to leverage current efforts to create a unified methodology
- Minimize seismic risk at nuclear facilities through cost-effective, verified and validated analytical methods and tools
- Develop and deploy seismic risk management technologies, such as seismic isolation (SI)

Long Term Goal

- Evaluate the performance of virtual nuclear power plants and nuclear facilities to a wide range of external hazards including multiple event scenarios.
- This allows nuclear facility owners to virtually test external hazards before the actual facilities are tested with actual hazards.
- Owners can then anticipate potential issues and resolve them

Risk Informed Process

- Manages external hazard uncertainty
- V&V is needed
- Protective measures such as seismic isolation in higher seismic areas can manage seismic risk
- Need to implement lessons learned from previous events



Seismic R&D Activities

METHODS (Methods include acceptable numerical approaches and risk-informed evaluation approaches.)

- Nonlinear Soil Structure Interaction (NLSSI) Methodology Development (DOE NNSA and TerraPower)
- Method for Seismic Isolation of suspended components (DOE NNSA and TerraPower)
- Application of NLSSI into Seismic PRA's (DOE-NE, LWRS)
- Identifying regulatory gaps associated with implementation of seismic isolation for advanced reactors (DOE-NE, Advanced Reactors)

TOOLS (Tools development includes using and integrating existing numerical software and developing new software when necessary to support the methods.)**(Numerical Software)**

- Time integration calculation for solving structural dynamic problems (DOE-NE, LWRS)
- Tools for solving NLSSI problems (DOE-NE, LWRS)
- Tools for linking NLSSI with other external hazards (DOE-NE, LWRS)
- Stochastic 3D dynamic soil response during earthquake ground motions (LDRD)

DATA (Data will be gathered and experimental tests run to validate the methods and tools. Data will be gathered from existing seismic and external hazard events at nuclear power plants. Experimental tests will be performed to provide validation data.)

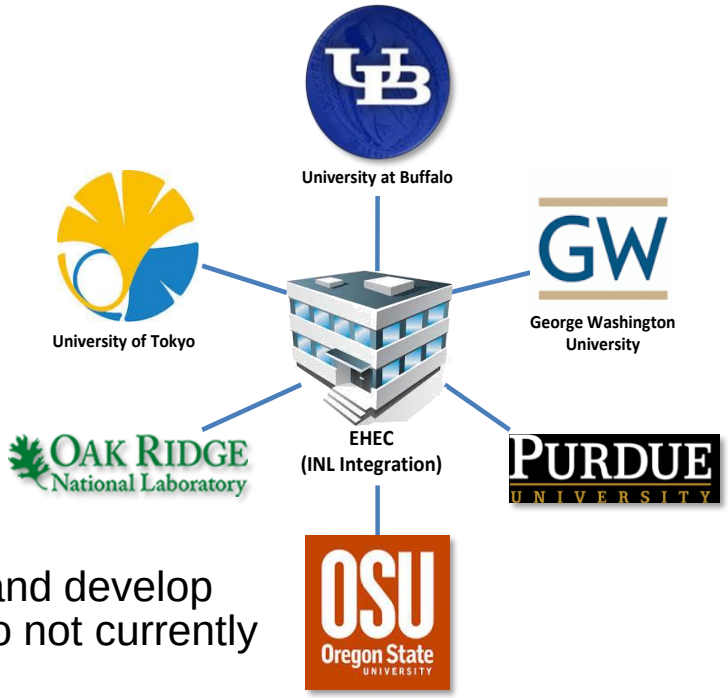
- Methods and tools under development will be verified and validated using existing data and using the proposed External Hazards Experimental Center (EHEC). (PROPOSED)
- Large scale testing used to validate numerical models used in Seismic Isolation of suspended components (DOE NNSA and TerraPower)
- Validate of seismic wave propagation in soils. 1D Geotechnical laminar box testing at University at Buffalo (DOE-NNSA)
- Seismic event followed by accident thermal condition and then aftershocks…central topic with new designs…NRC asking tough questions…Currently no data…This is controlling new designs (PROPOSED)

Applications (Real world Nuclear Facilities and Power Plants used to test verified and validated methods and tools)

- Seismic and Flooding Multievent scenario at NPP with industry partners (DOE-NE, LWRS)
- Seismic event followed by accident thermal condition and then aftershocks…central topic with new designs…NRC asking tough questions…Currently no data…This is controlling new designs (PROPOSED)
- Economics Study of seismic isolation of generic NPP

EHEC

- The methods and tools under development will be verified and validated using existing data and using the proposed External Hazards Experimental Center (EHEC).
- EHEC will be a partnership between INL, other national laboratories, and universities to perform necessary external hazard experiments.
- The external hazard experiments will be used to validate physics-based external hazards numerical methods and tools.



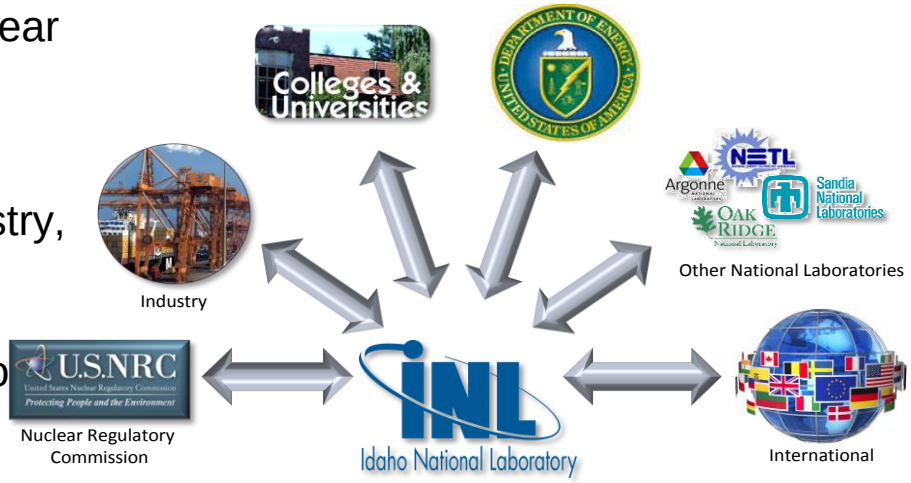
- The partnership will leverage existing capabilities and develop new experimental capabilities where capabilities do not currently exist.

Short to Medium Term R&D

- Focus on developing non-linear soil-structure interaction (NLSSI) methodologies
  - This method could be implemented using a wide range of tools (Currently using ABAQUS and LS-DYNA)
  - Method outlines an approach for implementing time domain SSI analysis
- Develop advanced SPRA methodology
  - Task focused on removing conservatism from traditional SPRAs
  - Currently focused on implementing a geometric nonlinearity into the FEA seismic demand calculation (removes the assumption the structural response scales linearly with ground motion)
- Close gaps associated with implementation of seismic isolation for nuclear facilities
- Advanced SPRA Fukushima case study
- V&V

Integrator of Seismic R&D

- Integrates efforts within existing programs (within DOE-NE and DOE-National Nuclear Security Administration (NNSA), NRC, Universities, other national laboratories)
- Actively promotes technical RD&D collaboration between universities, industry, government agencies and national laboratories.
- Collaboration and integration is critical to success of this program.



- Building a strong team to guide the activities and perform the necessary tasks, the outcome will be successful

Acknowledgements

- DOE
- TerraPower
- INL Team
  - Chandu Bolisetti
  - Bob Spears
- UC Davis (Professor Boris Jeremić)
- University at Buffalo (Professor Andrew Whittaker)
- Simpson Gumpertz and Heger (SGH)
  - Performing traditional SPRA for demonstration project
- Advisory Panel
  - Bob Kennedy (Consultant and industry expert)
  - Bob Budnitz (LBL and SPRA expert)
  - Nilesh Choskshi (Retired from NRC where he lead response to NTTF 2.1)
- Steering Committee Members
  - Bob Kennedy, Chairman
  - Farhang Ostadan
  - Greg Mertz
  - Mike Salmon
  - Andrew Whittaker
- EPRI

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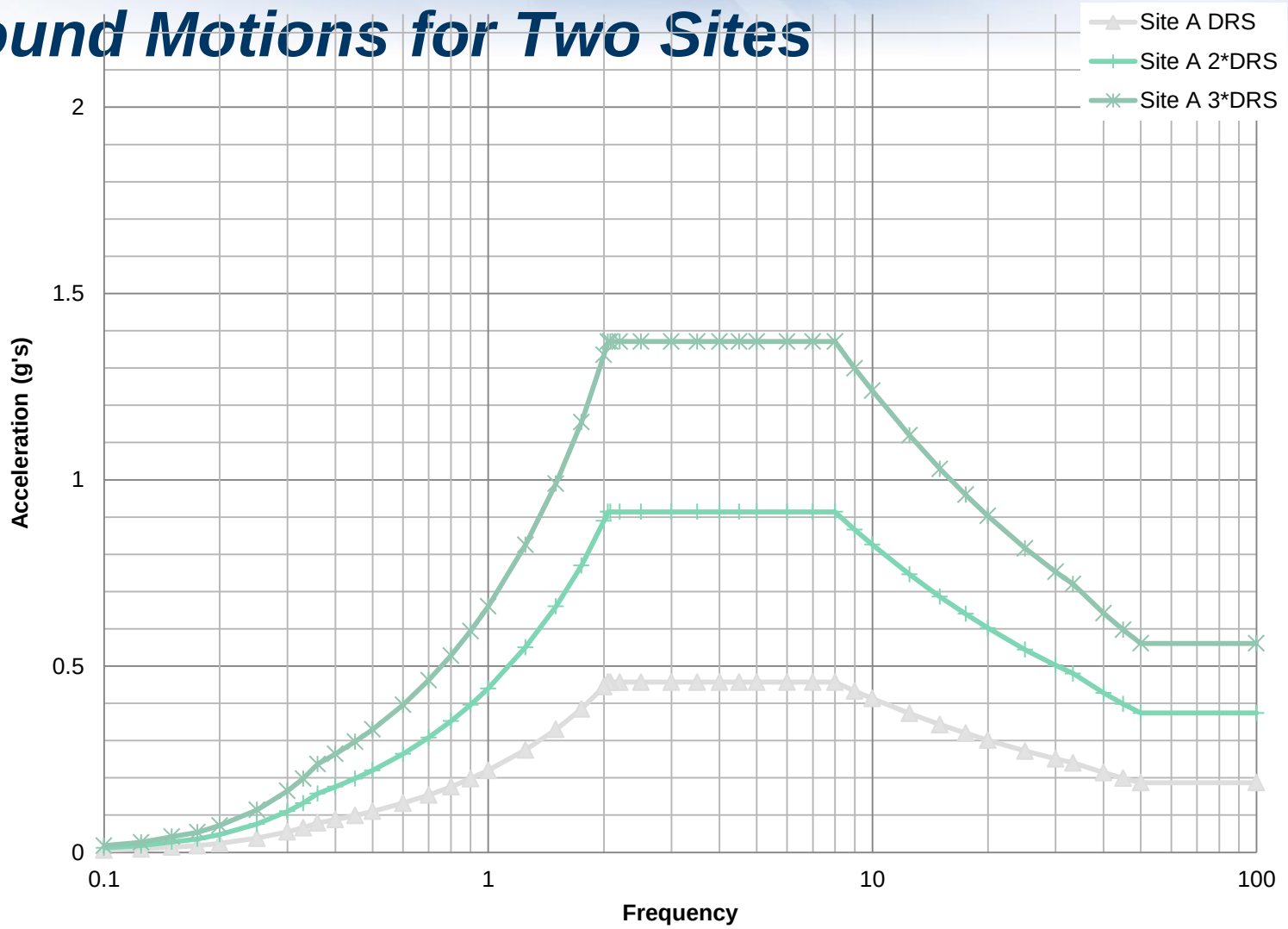
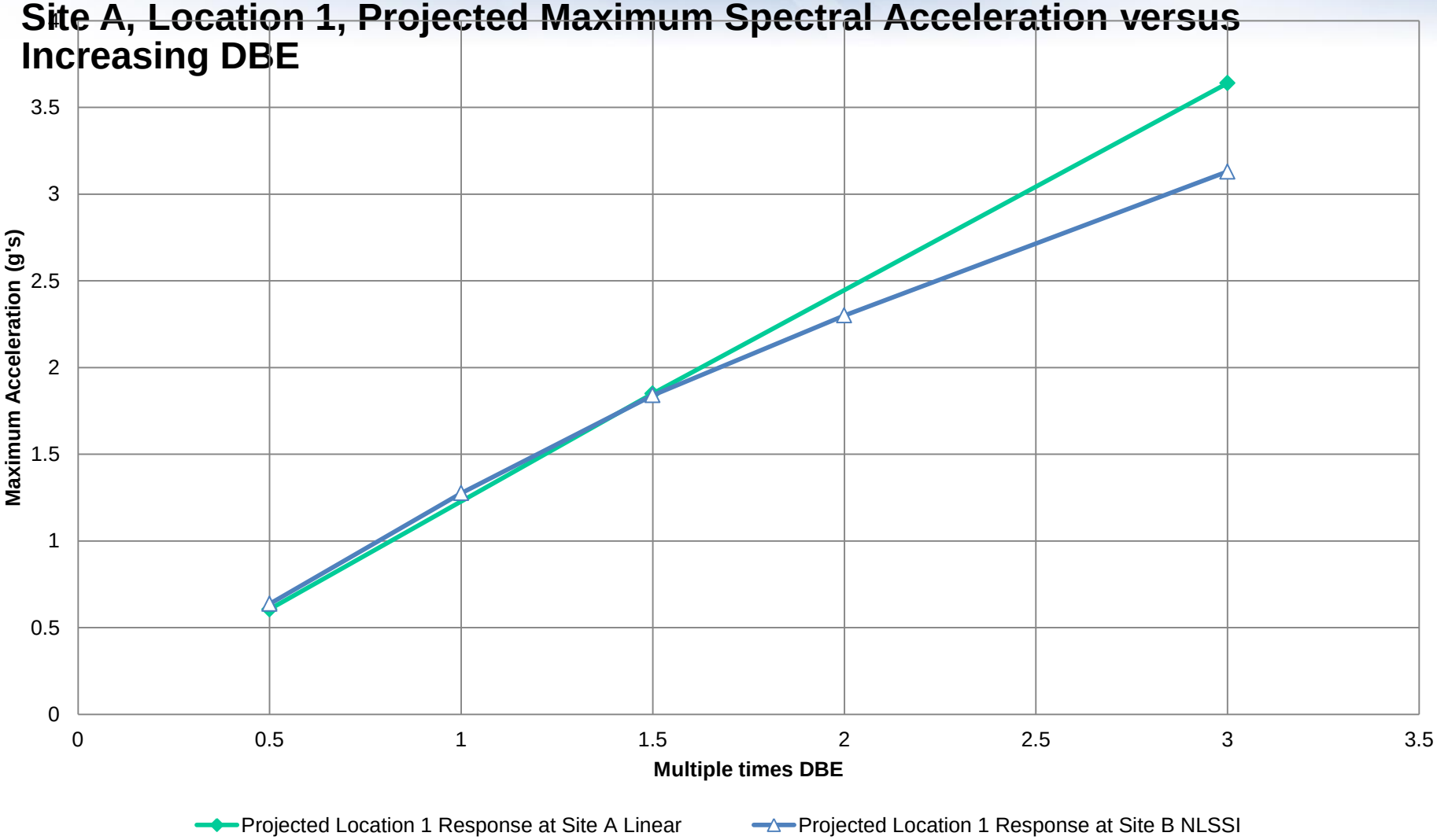
Nonlinear Soil-Structure Interaction Animation

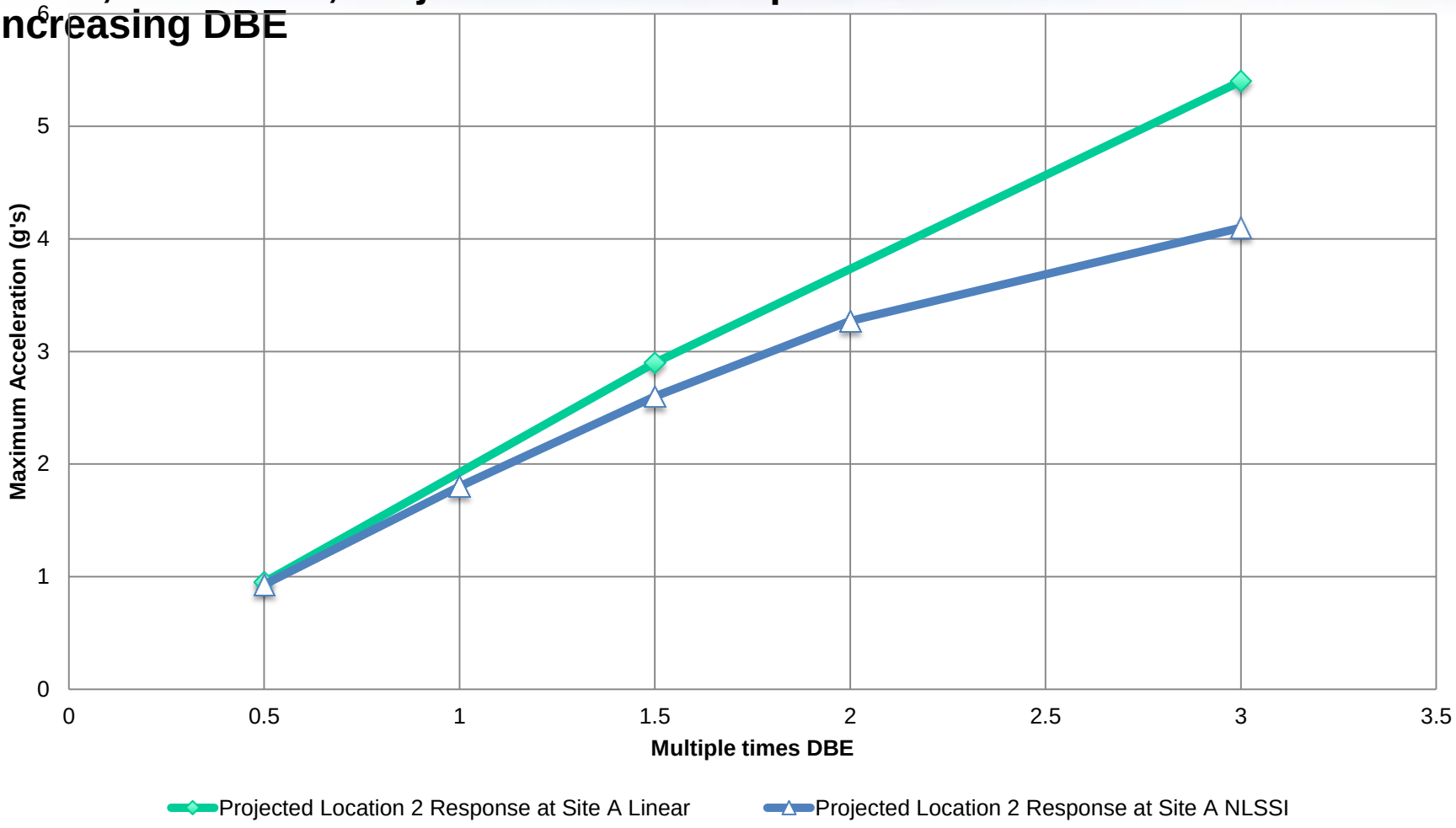
Ground Motions for Two Sites



Site A, Location 1, Projected Maximum Spectral Acceleration versus Increasing DBE



Site A, Location 2, Projected Maximum Spectral Acceleration versus Increasing DBE



Journal Articles, Papers, INL Publications

- **Journal and Conference Papers**
- B. Spears, J. Coleman, “Calibrating Nonlinear Soil Material Properties for Seismic Analysis Using Soil Material Properties Intended for Linear Analysis,” Accepted SMiRT 23, August 2015
- B. Spears, J. Coleman, “Generation of High Frequency Response in a Dynamically Loaded, Nonlinear Soil Column,” Accepted SMiRT 23, August 2015
- J. Coleman, B. Spears, and C. Bolisetti, “Development of a Nonlinear Time Domain Methodology (Part I),” Accepted SMiRT 23, August 2015
- J. Coleman, B. Spears, and C. Bolisetti, “Development of a Nonlinear Time Domain Methodology (Part II),” Accepted SMiRT 23, August 2015
- J. Coleman, Boris Jeremic, and Andrew Whittaker, “Nonlinear Time Domain Seismic Soil Structure Interaction (SSI) Analysis for Nuclear Facilities and Draft Appendix B of ASCE 4,” Nuclear Engineering and Design Special SMiRT 22 Edition, DRAFT
- J. Coleman, and P. Sabharwall, “Seismic Risk Management Solution for Nuclear Power Plants “ Federation of American Scientists, November 2014.
- J. Coleman, Mohamed Talaat, Philip Hashimoto, and Curtis Smith, “Advanced Seismic Probabilistic Risk Assessment using Nonlinear Soil-Structure Interaction Analysis,” PSA, April 2015.
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- **Internal INL Publications**
- Coleman, Justin, Chandu Bolisetti, “Seismic Data Gathering and Validation,” February 2015.
- Coleman, Justin, Spears, Bob, “Nonlinear Time Domain Seismic Soil-Structure Interaction (SSI) Methodology Development,” September 2014.
- Coleman, Justin, “Demonstration of NonLinear Seismic Soil Structure Interaction and Applicability to New System Fragility Seismic Curves,” September 2014.
- Coleman, Justin, Piyush Sabharwall, “Seismic Isolation Working Meeting Gap Analysis Report,” September 2014

Coleman, Justin, Chandu Bolisetti, "Seismic Data Gathering and Validation," February 2015.

EXECUTIVE SUMMARY

Three recent earthquakes in the last seven years have exceeded their design basis earthquake values (so it is implied that damage to SSC's may have occurred). These seismic events were recorded at North Anna (August 2011, detailed information provided in [*Virginia Electric and Power Company Memo*]), Fukushima Daichii and Daini (March 2011 [TEPCO 1]), and Kaswazaki-Kariwa (2007, [TEPCO 2]). However, seismic walk downs following the earthquake at some of these plants indicate that very little damage occurred to safety class systems and components due to the seismic motion. This report presents seismic data gathered for two of the three events mentioned above and recommends a path for using that data for two purposes. One purpose is to determine what margins exist in current industry standard seismic soil-structure interaction (SSI) tools. The second purpose is the use the data to benchmark and validate seismic site response tools and SSI tools.

The gathered data represents free field soil and in-structure acceleration time histories. Gathered data also includes elastic and dynamic soil properties and structural drawings.

Gathering data and comparing with existing models has the potential to identify areas of uncertainty that may be removed from current seismic analysis and SPRA approaches. Removing uncertainty (to the extent possible) from SPRA's will allow NPP owners to make decisions on where to reduce risk. Once a realistic understanding of seismic response is established for a nuclear power plant (NPP), then decisions on needed protective measures, such as seismic isolation, can be made.

Coleman, Justin, Spears, Bob, "Nonlinear Time Domain Seismic Soil-Structure Interaction (SSI) Methodology Development," September 2014.

- **INTRODUCTION**
- The Department of Energy (DOE) and the nuclear industry currently perform seismic soil-structure interaction (SSI) analysis of existing and new nuclear facilities using equivalent-linear numerical analysis tools. These tools approximate the nonlinear response of the soil and the structure, and involve modeling of the soil-foundation interface using rudimentary procedures. Equivalent-linear tools are expected to produce reasonable estimates of in-structure response for lower levels of earthquake ground motion intensities that result in low strains and almost linear soil and structural response. For higher levels of ground motion intensities for which, the soil strains are high and gapping and sliding at the soil-foundation interface is likely, these tools are likely inaccurate.
- Seismic hazard at nuclear facilities has generally continued to increase as more information is gathered on seismic sources and events, and additional research is performed to update attenuation relationships and characterize local site effects. As the seismic hazard increases, more intense input ground motions are used to numerically evaluate nuclear facility response. This results in higher soil strains, increased potential for gapping and sliding and larger in-structure responses. Therefore, as the intensity of ground motions increases, the importance of capturing nonlinear effects in numerical SSI models increases.
- Nonlinear SSI analysis in the time-domain is needed to explicitly capture material nonlinearities in the soil and geometric nonlinearities such as gapping and sliding. Because nonlinear time-domain analysis is not routinely performed in the nuclear industry, a methodology is needed to enable its widespread implementation. This methodology is herein termed Nonlinear Soil-Structure Interaction (NLSSI); this report provides the first DOE-funded building block upon which a NLSSI methodology can be based.
- **GENERAL CONCLUSIONS**
- This report documents a methodology for NLSSI analysis of safety-related nuclear structures. The NLSSI methodology includes the important step of benchmarking nonlinear analysis against equivalent-linear analysis for low-intensity ground motions applied to competent sites. Predictions of spectral accelerations at two locations inside a generic NPP are presented for the different analysis methods. Considerable differences in the spectral accelerations calculated using the equivalent-linear and nonlinear methods are observed at significant levels of ground motion shaking, which represent beyond design basis shaking at DOE sites such as INL, and design basis shaking (or less) at other sites in the complex such as LANL. For the generic NPP analyzed here, these differences are attributed to gapping and sliding, which cannot be explicitly captured using an equivalent-linear analysis. Figure E-8 illustrates the gapping phenomena captured in the NLSSI analysis.
- The differences in the in-structure response spectra reported here may not be considered significant for new nuclear facility construction, but they could determine whether expensive facility upgrades (or decommissioning) are needed in many of the existing buildings in the DOE complex. More importantly, given that the seismic risk often increases in a nuclear facility for shaking more intense than design basis, it is important to calculate best estimates of conditional risk for beyond design basis shaking. The analysis results reported here indicate that the traditional equivalent-linear methods will overestimate seismic demands for beyond design basis shaking, overestimating the mean annual frequency of unacceptable performance, and might trigger unnecessary facility upgrades.
- The studies reported here also highlight the importance of verification and validation of numerical methods and models. The analysis of identical linear models produced significant differences in peak and spectral accelerations, demonstrating that a careful and thoughtful evaluation of the numerical methods and models is needed for both the linear and nonlinear approaches.

J. Coleman, and P. Sabharwall, "Seismic Risk Management Solution for Nuclear Power Plants " Federation of American Scientists, November 2014.

- **Abstract**
- Nuclear power plants should safely operate during normal operations and maintain core-cooling capabilities during off-normal events, including external hazards (such as flooding and earthquakes). Management of external hazards to expectable levels of risk is critical to maintaining nuclear facility and nuclear power plant safety. Seismic risk is determined by convolving the seismic hazard with seismic fragilities (capacity of systems, structures, and components). Seismic isolation (SI) is one protective measure showing promise to minimize seismic risk.
- Current 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 American Society of Civil Engineer Standard 4, ASCE-4, to be released in the winter of 2014, for light water reactors facilities using commercially available technology. The intent of ASCE-4 is to provide criteria for seismic analysis of safety related nuclear structures such that the responses to design basis seismic events, computed in accordance with this standard, will have a small likelihood of being exceeded.
- The U.S. nuclear industry has not implemented SI to date; a seismic isolation gap analysis meeting was convened on August 19, 2014, to determine progress on implementing SI in the U.S. nuclear industry. The meeting focused on the systems and components that could benefit from SI. This article highlights the gaps identified at this meeting.

J. Coleman, Mohamed Talaat, Philip Hashimoto, and Curtis Smith, "Advanced Seismic Probabilistic Risk Assessment using Nonlinear Soil-Structure Interaction Analysis," PSA, April 2015.

- **EXECUTIVE SUMMARY**
- Risk calculations should focus on providing best estimate results, and associated insights, for evaluation and decision-making. Specifically, seismic probabilistic risk assessments (SPRAs) are intended to provide best estimates of the various combinations of structural and equipment failures that can lead to a seismic induced core damage event. However, in some instances the current SPRA approach has large uncertainties, and potentially masks other important events (for instance, it was not the seismic motions that caused the Fukushima core melt events, but the tsunami ingress into the facility).
- Figure 1: Seismic Risk Quantification Process
- SPRA's are performed by convolving the seismic hazard (the frequency of certain magnitude events) with the seismic fragility (the conditional probability of failure of a structure, system, or component given the occurrence of earthquake ground motion). In this calculation, there are three main pieces to seismic risk quantification, 1) seismic hazard and nuclear power plants (NPPs) response to the hazard, fragility or capacity of structures, systems and components (SSC), and systems analysis. Figure 1 provides a high level overview of the risk quantification process.
- The focus of this research is on realistic modeling and simulation with the focus on removing uncertainties (when possible) in the quantification of seismic risk at NPPs.
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- Risk analysts performing traditional SPRA calculations for nuclear power plants make assumptions that may create uncertainties. This research will provide methods, tools, and data that can be used to remove or minimize these uncertainties. Some assumptions that simplify the problem and create uncertainty in the calculation are:
- **NPP response scales linearly with ground motion**. This assumption effects the "Plant SSC Response to Initiator" box in Figure 1 where we see that as the earthquake intensity increases, the NPP response increases in a non-linear fashion
  - R&D solution: Determine the degree of reasonableness of this assumption by evaluating the response of a generic NPP to increasing levels of ground motion and tracking NPP response. The results documented in Section 5 indicate that even at the INL, which is a low to moderate seismic site, the assumption is likely conservative. (FY 2014)
  - R&D solution: Calculate the seismic core damage frequency (SCDF) using a traditional SPRA approach that uses linear seismic analysis with an advanced SPRA approach that uses NLSSI. This is the focus of the FY 2014 task that will be complete in December 2014. (FY 2014 & 2015)
- **Uniform Hazard Spectrum (UHS) is used to define ground motions for determining NPP in-structure response**. The UHS is conservative since it is an envelope of all ground motions (This is the "characterize seismic hazard" box in Figure 1).
  - R&D Solution: Evaluate the change in SCDF when using ground motions that a produced from a conditional mean spectrums (CMS), which is more representative of actual earthquakes (not an envelope of all earthquakes for a given site). (FY 2015 & 2016)
- **The use of parameters to define SSC fragility curves that are weakly correlated to the damage of that SSC**. For instance peak ground acceleration (PGA) is typically used to define failure of an SSC when this parameter is weakly correlated to damage of SSC's (This is the "SSC Failures" box in Figure 1).
  - R&D Solution: Study the impact on system and component probability of failure when using current practice with fragility curves that base probability of failure on PGA versus fragility curves that have a strong correlation to failure of that system or component such as differential displacement between components in the facility. (FY 2015 & FY 2016)