U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST)

Clean. Reliable. Nuclear.

PNNL-SA-162410

Modeling the Seismic Response of Spent Nuclear Fuel in Dry Storage

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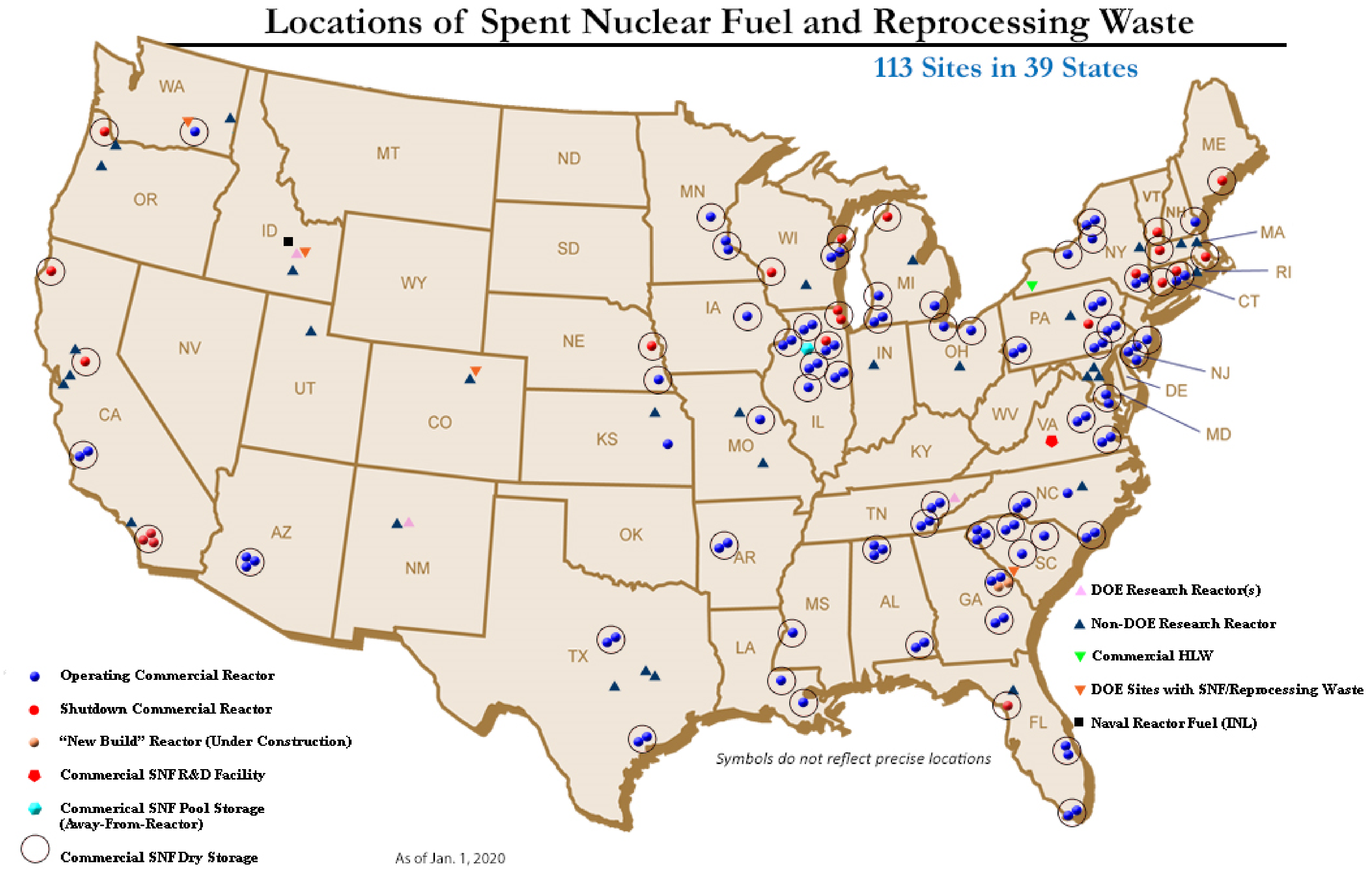
May 17, 2021
PEER workshop
(Zoom virtual meeting)

This work was sponsored by the US Dept. of Energy, Office of Nuclear Energy.

US History of Commercial Power Reactors



131 Commercial Reactors

- 9 Early Prototypes
  - No fuel on site
- 1 Never Operated at Full Power
- 1 Disabled
  - Fuel moved to DOE
- 1 Demonstration High Temperature Gas Reactor
- 23 Ceased Operations
  - Fuel on site
  - 3 reactors on sites with ongoing nuclear operations
  - 20 reactors on 17 sites all reactors shutdown
- 96 Operating Reactors
- 2 New Units Under Active Construction

Key Term: ISFSI (Independent Spent Fuel Storage Installation)

Multimodal Transportation Test: Measuring Realistic Mechanical Loads on SNF

DOE Spent Fuel & Waste Science and Technology Program (SFWST)

YouTube Video of MMTT

(Note: Use link for video on Youtube - https://www.youtube.com/watch?v=wGKtgrozrGM&feature=youtu.be)

30 cm Cask Drop (1/3 Scale)

- Cask drop testing at BAM in Germany.
- Cask dynamics data used to inform a full scale drop of a SNF assembly at Sandia National Laboratories.
- PNNL modelers are using the data to validate fuel assembly models and perform a parametric study on the potential SNF loads in the general cask drop scenario.

Full Scale SNF Cask Shake Test

- Test Goal: Record the mechanical loading on SNF in storage cask systems during simulated hypothetical earthquakes in the US.
  - Consider earthquakes up to the design basis of SNF dry storage sites in the US.
  - Consider earthquakes up to 300 years of dry storage.
  - Cask system integrity is assured by the regulations – not a concern of this test.
- DOE SFWST Program Goal: Close the Stress Profiles Knowledge Gap
  - Materials testing of SNF needs realistic range of loading.
  - Finite element models need validation data.
  - Test data and analysis will close the knowledge gap.
- International Collaboration and Test Team
  - US, Spain, South Korea, Germany

UC San Diego Large High-Performance Outdoor Shake Table (LHPOST)

Van Den Einde L, Conte JP, Restrepo JI, Bustamante R, Halvorson M, Hutchinson TC, Lai C-T, Lotfizadeh K, Luco JE, Morrison ML, Mosqueda G, Nemeth M, Ozcelik O, Restrepo S, Rodriguez A, Shing PB, Thoen B and Tsampras G (2021) NHERI@UC San Diego 6-DOF Large High-Performance Outdoor Shake Table Facility. Front. Built Environ. 6:580333.doi: 10.3389/fbuil.2020.580333

DOE SFWST Shake Test Team

Key Organizations and Staff

US National Laboratories

Sandia National Laboratories
Elena Kalinina (Lead)
Doug Ammerman

Pacific Northwest National Laboratory
Nick Klymyshyn
Steve Ross

Industry and Contractors

SC Solutions
Norm Abrahamson
Derrick Watkins
Julio Garcia
Payman Tehrani

Gordon Bjorkman

Academia

UCSD
Joel Conte
Jose Restrepo
Koorosh Lotfizadeh

Spain

ENSA
ENRESA

South Korea

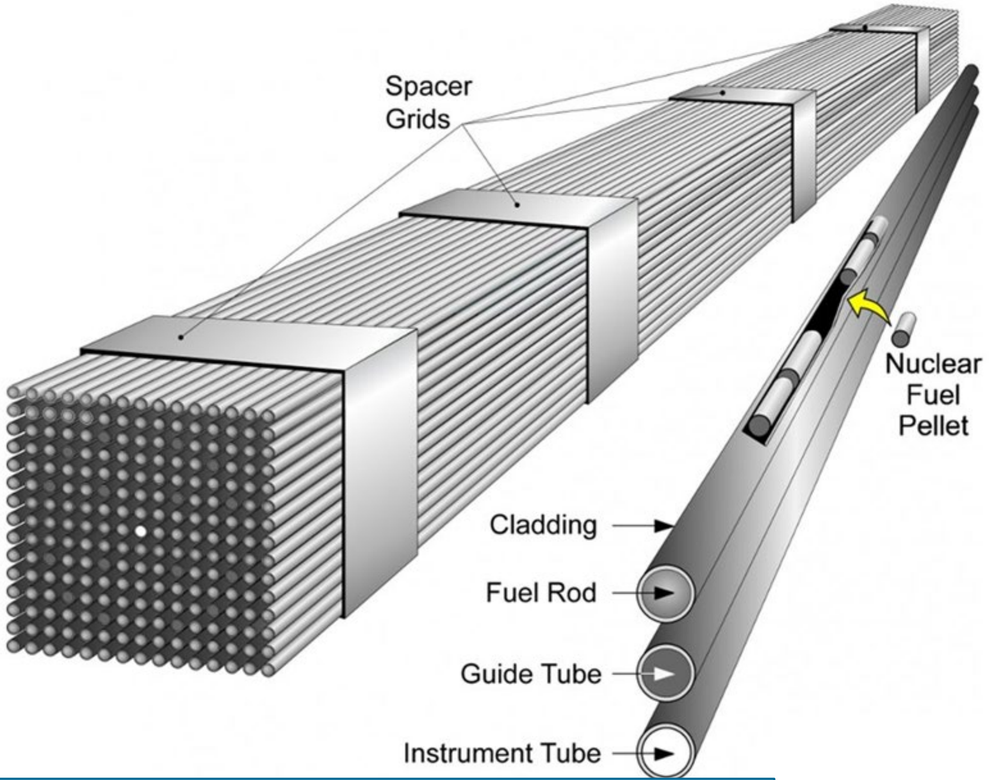
KEPCO NF
KAERI

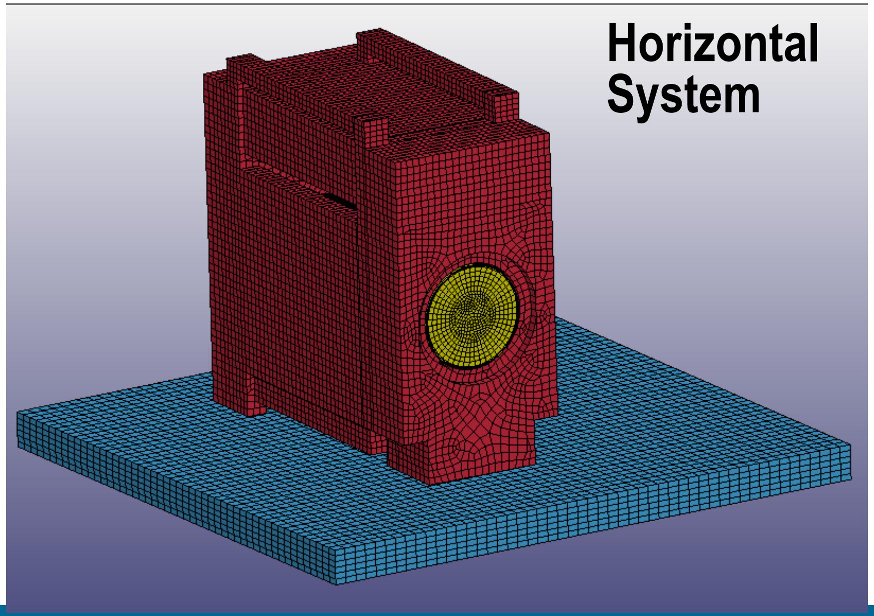
Germany (Potential)

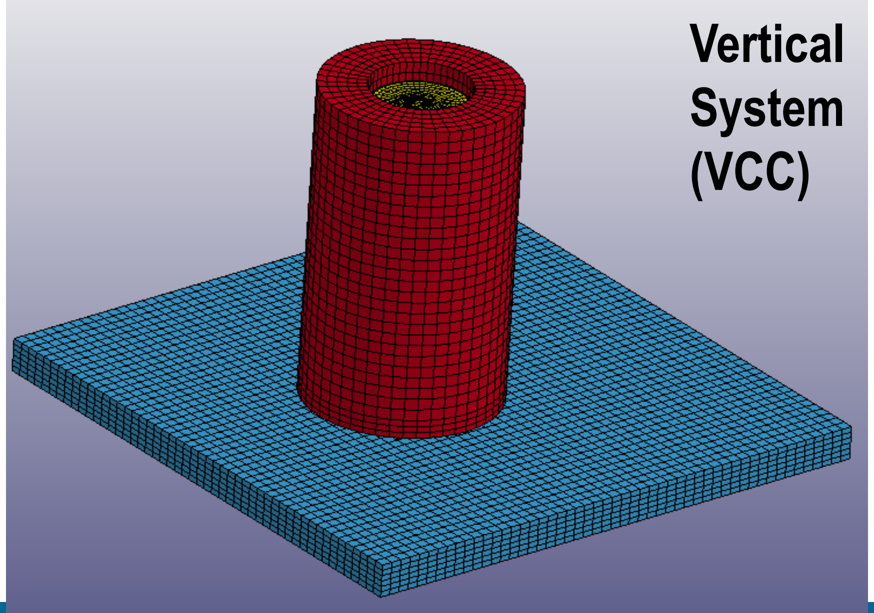
GNS

Test Plan Overview

- Test 50 to 100 ground motions
  - Covers the US (lower 48) up to ISFSI design basis
- Two full scale cask systems (Instrumented assemblies)
  - Horizontal System
  - Vertical Concrete Cask (VCC) system (Fabricated Mockup)
- Potential reduced scale system (contains dummy assemblies)
  - 1/3 scale dual purpose metal cask (ENSA ENUN 32P)
  - 1/3 scale vertical canister system (Fabricated Mockup)



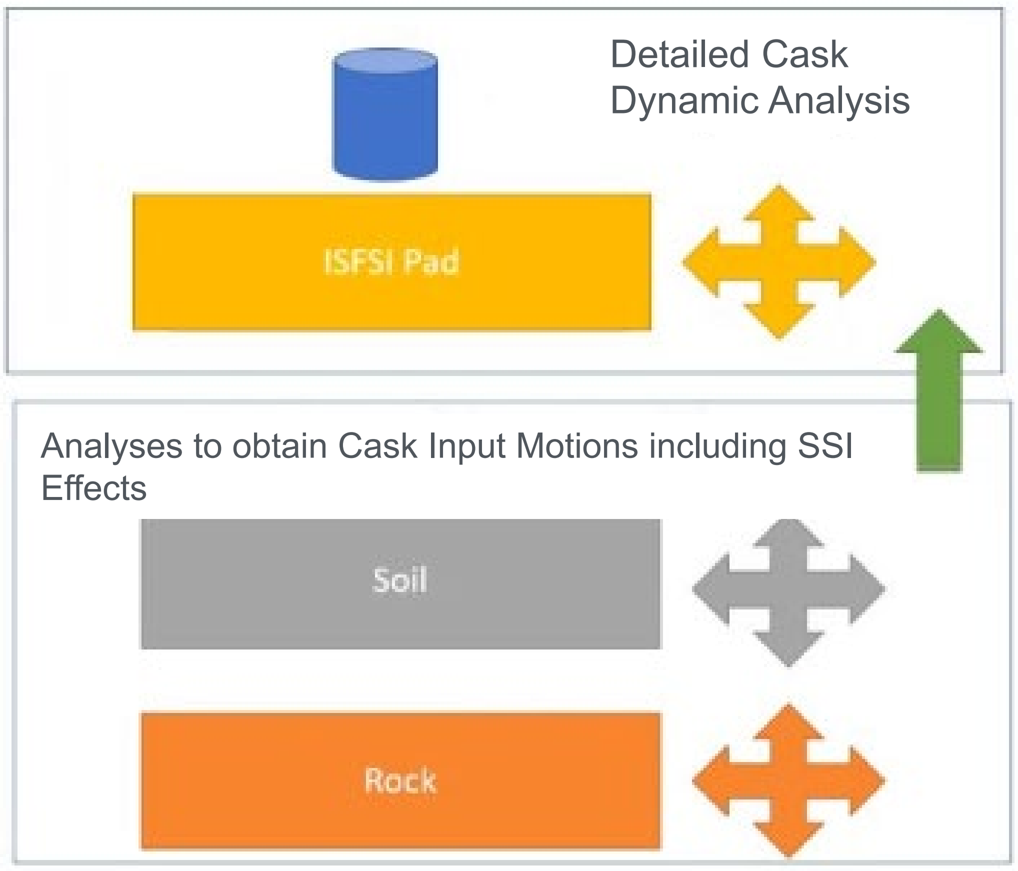




1/3 Scale Cask Model TBD

Input Motions to Shake Table

Modeling Strategy



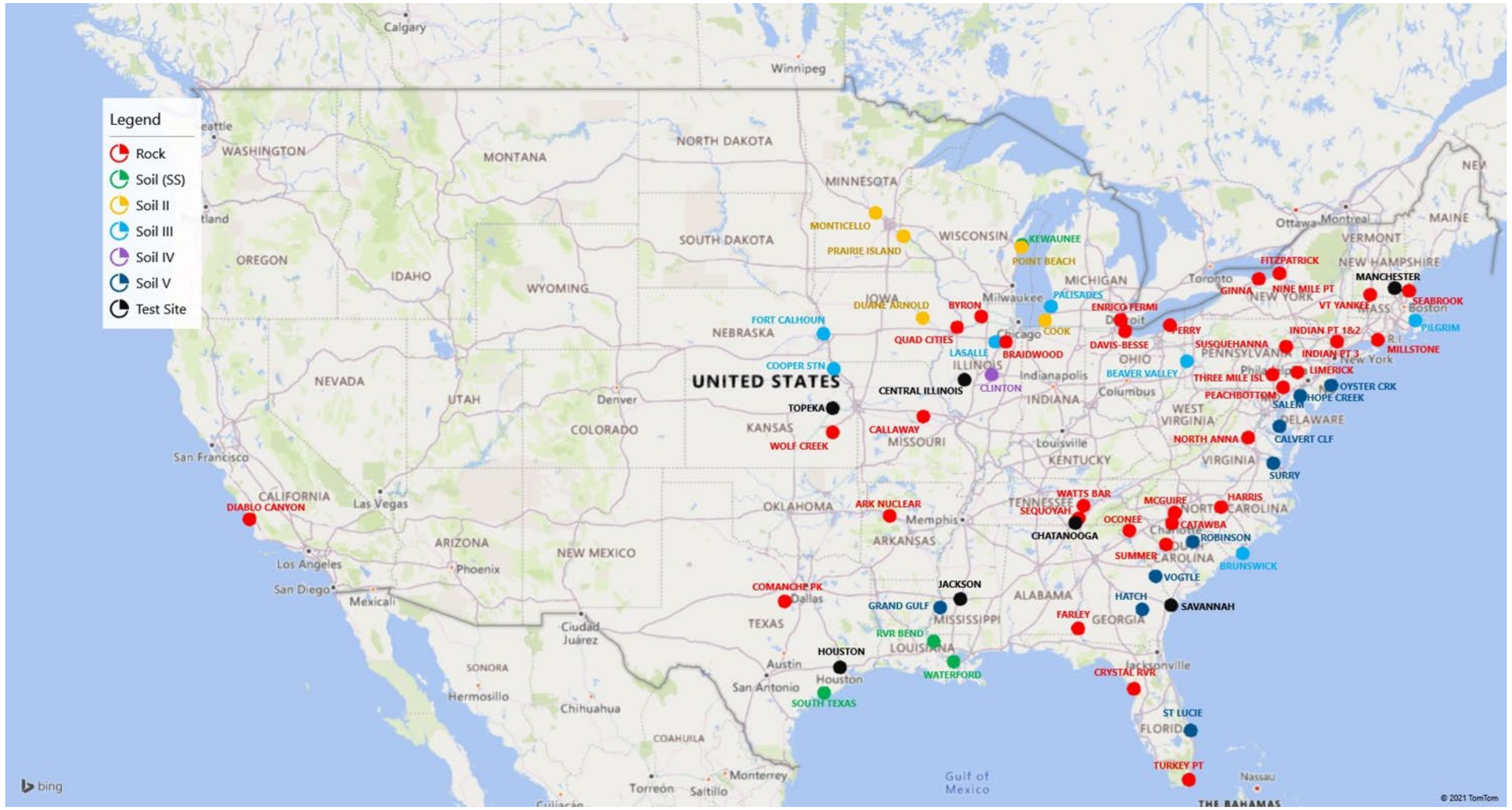
Soil Structure Interaction (SSI) Effects
(Soil + ISFSI Pad
+ Neighbor Casks)

Ground Motions
(Site + Rock + Soil)

Ground Motions + **SSI Effects** = **Input Motion to Shake Table**

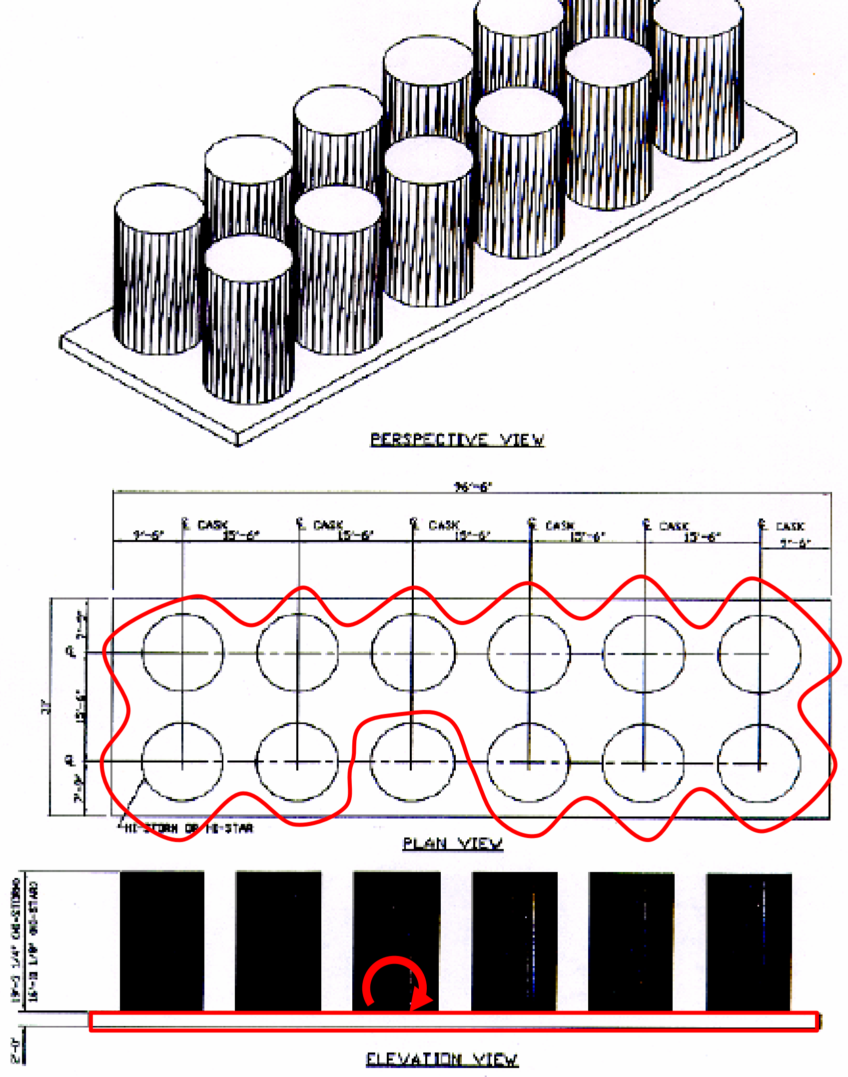
Ground Motions for United States

- Geographic Coverage with Representative Sites: seven sites in CEUS; four sites in WUS
- Wide Range of Site Conditions: Hard Rock, Soft Rock and Soil
- Generic Controlling Earthquake Scenarios (Magnitude and Distance pairs)
- Intensity Amplitudes Covering Hazard from 1E-3 to 1E-5 Annual Frequencies of Exceedance



Soil-Structure Interaction (SSI) Effects

Hypothetical ISFSI

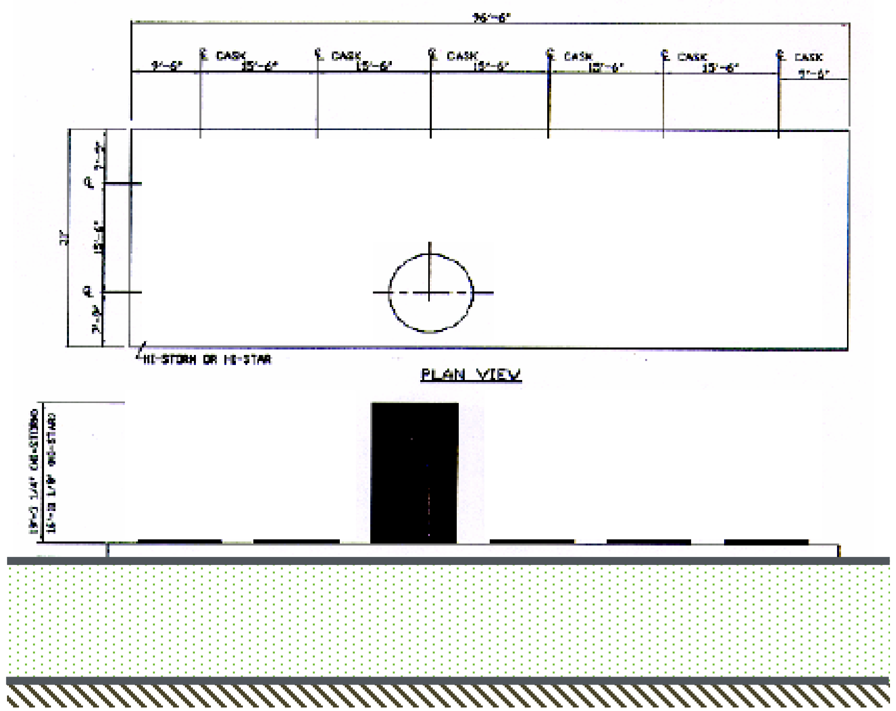


Numerical Simulations to be Combined with Free Field Motion to Account for:

- Underlaying Radiation Soil Damping
- Underlaying ISFSI Pad Flexibility
- Effects of nearby Casks
- Potential Rotational Motions (Shake table can reproduce up to 2 deg of rotational input)

Soil-Structure Interaction (SSI) Effects

- Test set-up will simulate SSI effects through Input Motions to Shake Table
- Supporting Test Plan: Verification and Replication of SSI Effects on a potentially Rigid Shake Table Set-up prior to Experimental Tests



PNNL Modeling Overview

- 2021
  - Supporting Test Plan
  - Shake Table Model Development
    - Report on modeling 2021
- 2022
  - Pre-Test Predictions (Shake Table Scenario)
    - Supporting Test Safety!
    - Report on pretest predictions modeling 2022
  - Test in July
  - Data Collection and Distribution
- 2023
  - Model Validation and Refinement Using Test Data
    - Report on validation and refinement 2023
    - Shake table configuration
  - SNL analysis of data and report
  - Potential NEUP (Nuclear Energy University Program)
- 2024
  - Model Application to Realistic Systems
    - How would real, complete systems respond to test conditions?
    - ISFSI configuration
    - Final Report in 2024

Assessment:

- Do we have a complete technical story?
- Do we need soil box testing to close the knowledge gap?

Accurate model predictions require understanding the key physics.

Key Questions:

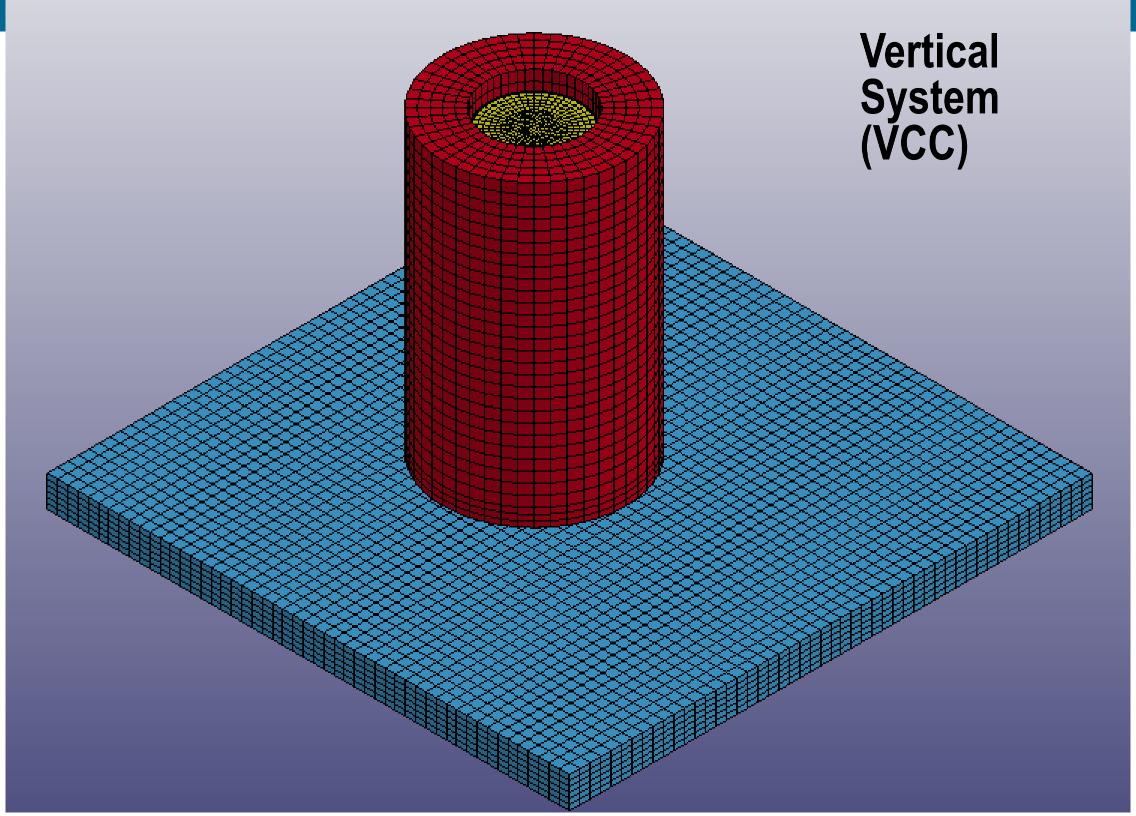
- What are the mechanical loads on the SNF? (Quantify them.)
- Will a cask tip over?
- Will a cask impact another cask on the pad?
- Will a cask walk (slide/roll) off the edge of a pad and tip over?

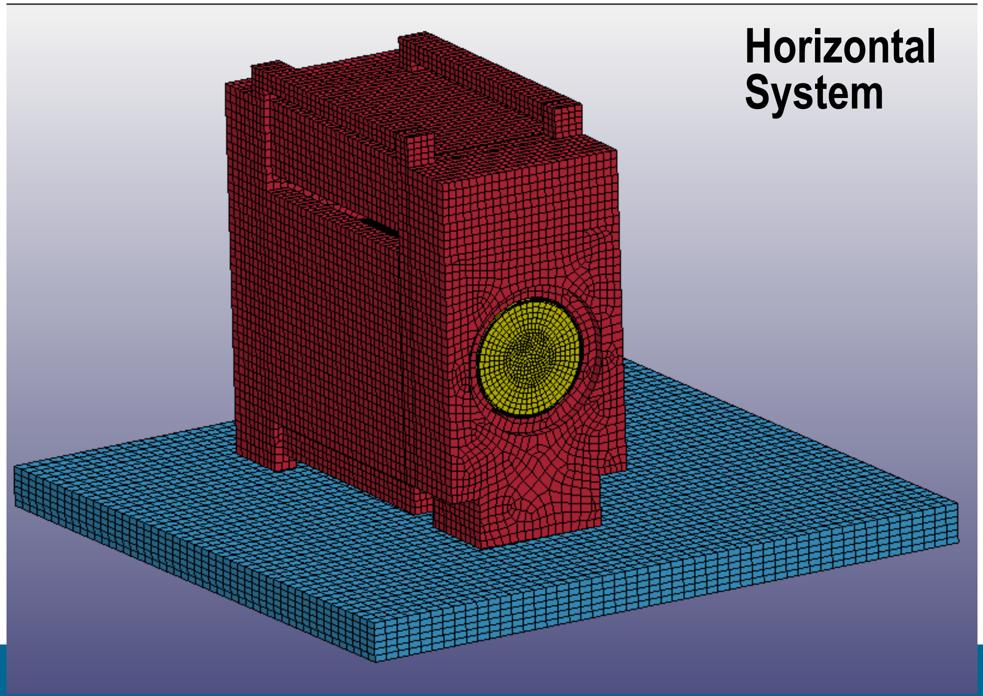
We Expect the Answers Depend On:

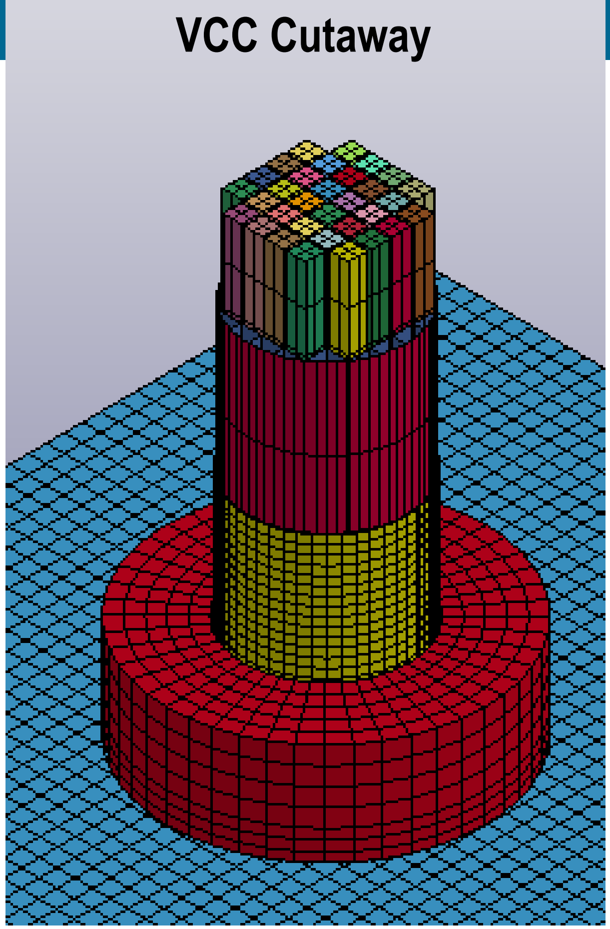
- Pad Motion
- Friction
- Damping
- Contact
- Gross Pad Deflection
- Local Pad Deflection
- Soil Structure Interaction

The test data will inform us about most of these phenomena. Which ones are most important?

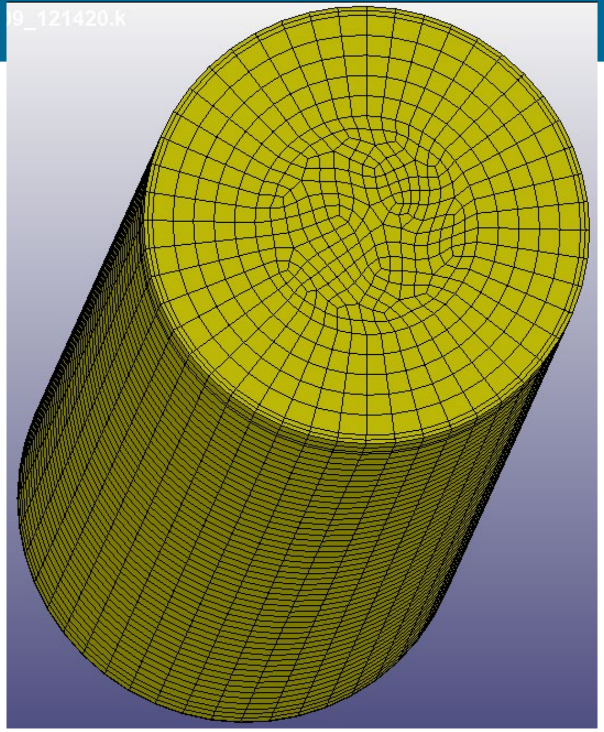
Preliminary Models


Vertical System (VCC)

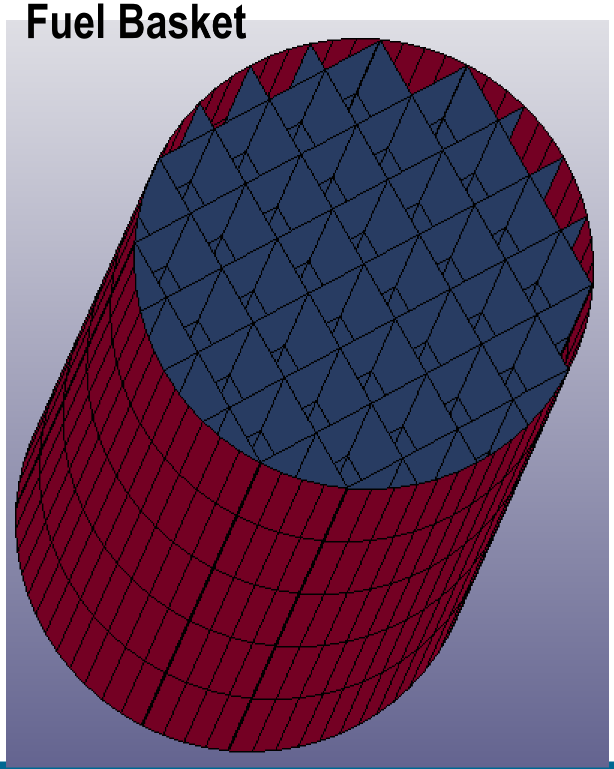

Horizontal System


VCC Cutaway

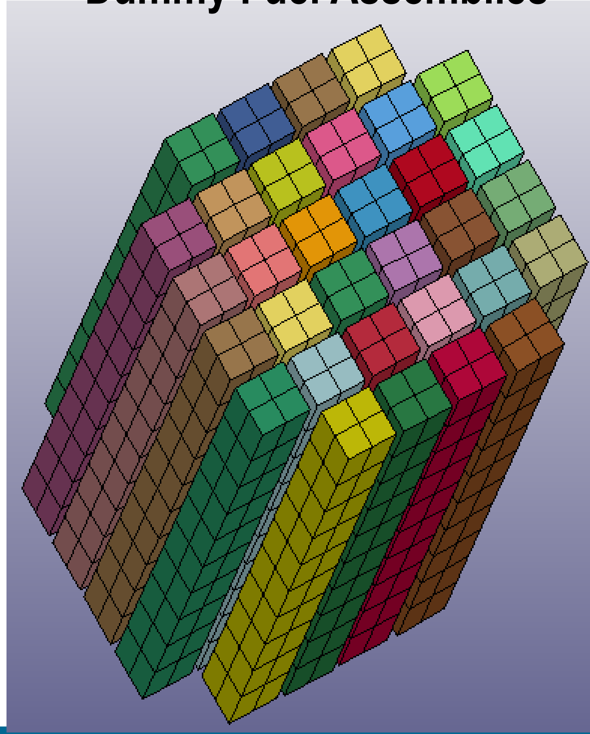
Canister
(Used in both models.)



Fuel Basket

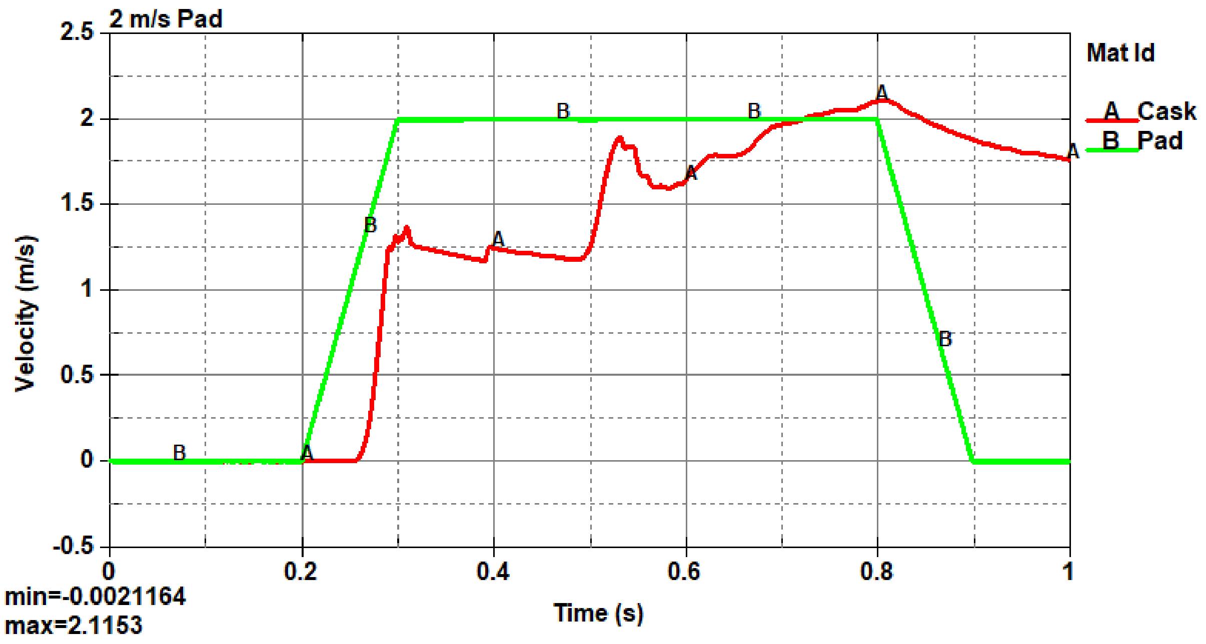


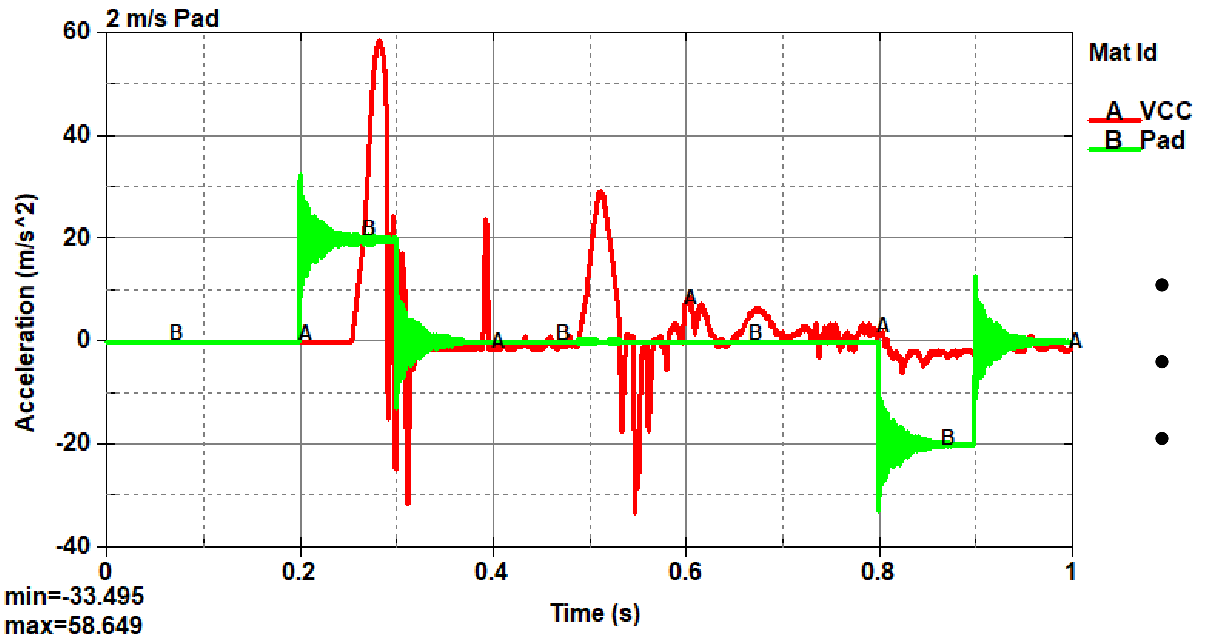
Dummy Fuel Assemblies



Preliminary VCC Model: 1D Horizontal Motion

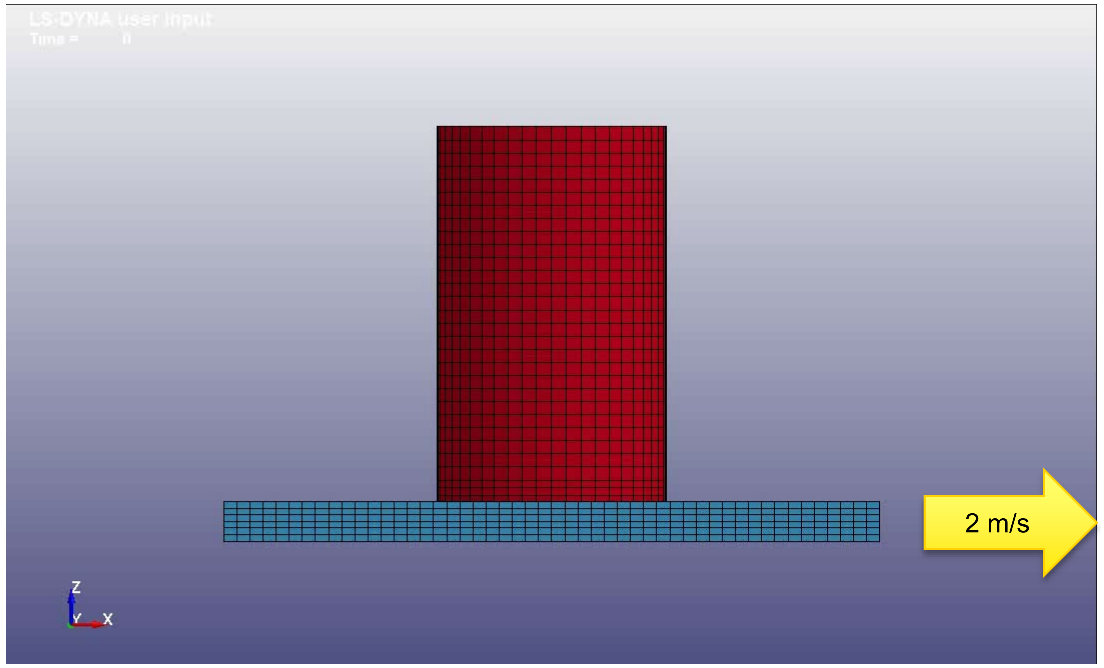
Green = Applied Pad Velocity
Red = Resulting Cask Velocity





- No Tip Over
- Rocking/Rolling
- Chaotic/Unstable Response
- NUREG/CR-6865

Model: Full Scale Cask, 1D Horizontal Sliding



- 2 m/s Applied Velocity
- ~2 g Step Acceleration
- Friction Coefficient: ~0.01

- 268 mm Max Lift-up
- 3500 mm VCC Diameter
- 4.3° Lift-up Angle

NUREG/CR-6865 – Cask Rocking and Rolling

As the cask rocks back and forth, energy is absorbed every time the cask impacts the pad. This can be a significant energy dissipation mechanism, and the type of soil underlying the pad can have a noticeable effect on the amount of energy dissipated. This mechanism is believed to be the most important soil-structure interaction effect after the cask begins to tip. It is important to note that the cylindrical cask can assume either a rocking motion or a rolling motion. Significant energy is dissipated if the cask is rocking back and forth, but very little energy is dissipated in the rolling motion.

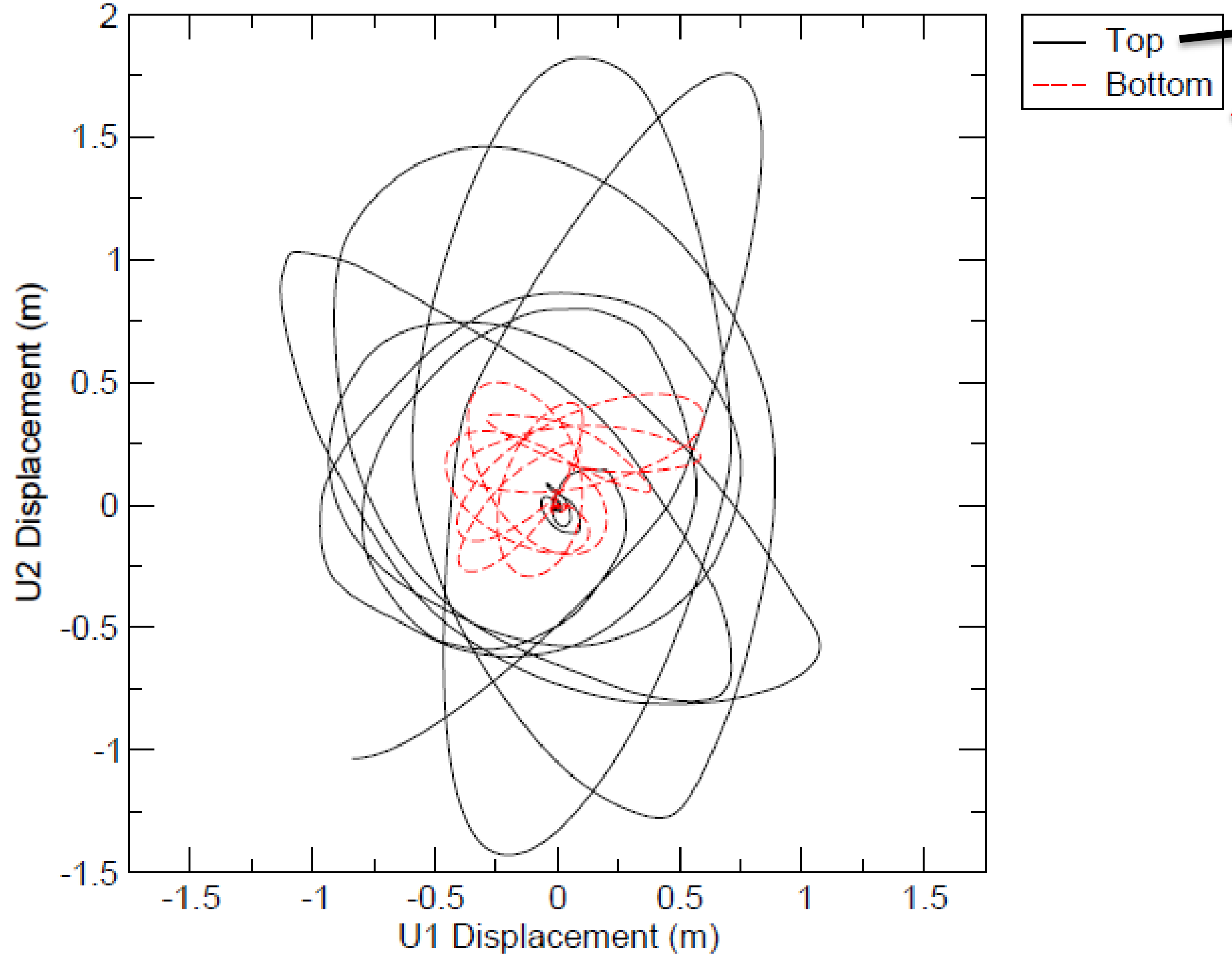


Figure 5.9: Lateral Displacement Trajectories for Cylindrical Cask Top and Bottom, Iran Tabas Earthquake, NUREG/CR-0098 Spectral Shape, PGA=1.0 g, Stiff Soil Profile, Cask/Pad μ=0.55

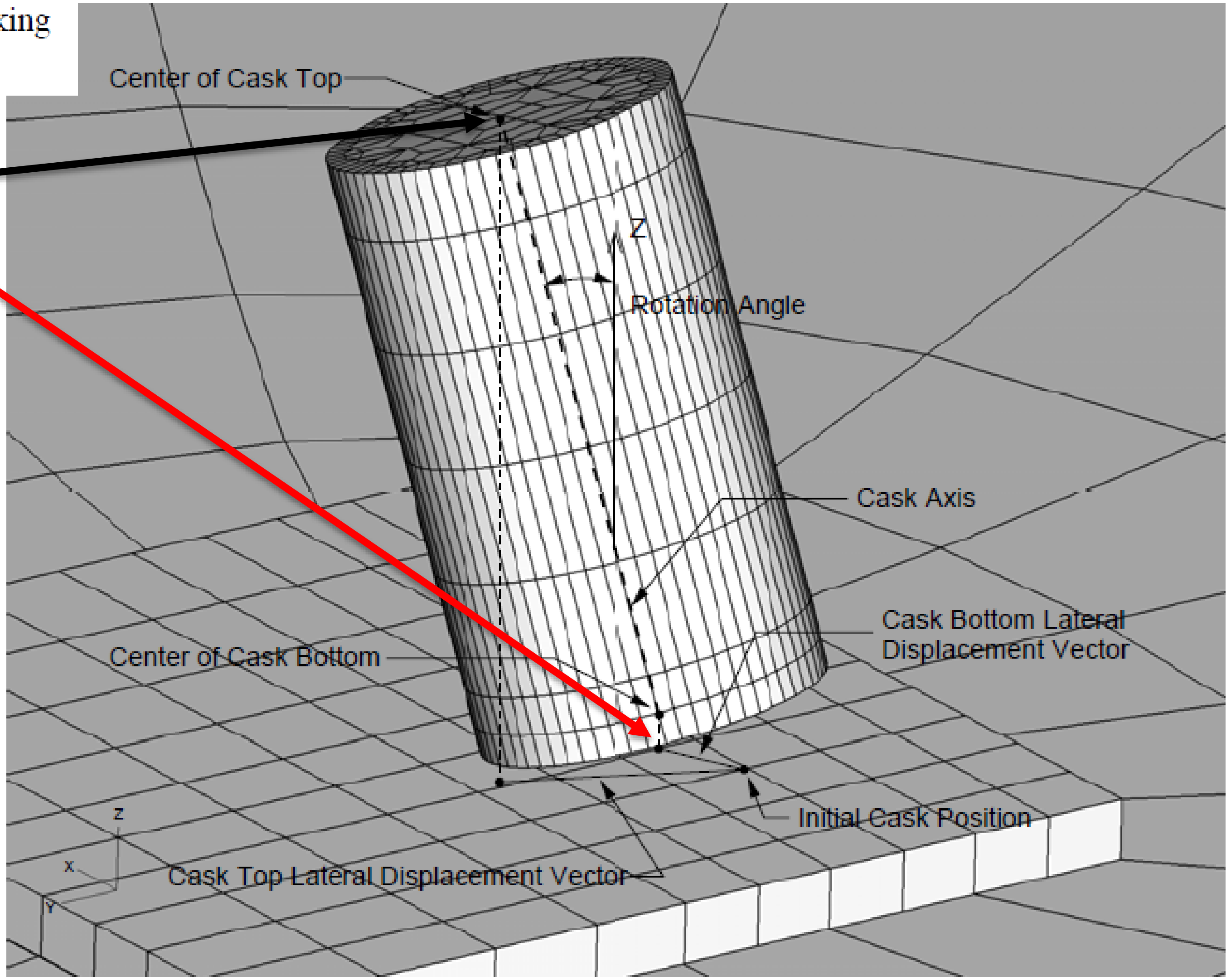


Figure 5.8: Explanation of Key Response Quantities

Note: NUREG/CR model predicts cask tip over in cases as low as 0.6g PGA.

Seismic Hazard Range of Interest for SNF Cask Shake Test

Annual Frequency of Exceedance
(AFOE or AFE)

Years (t)	Probability of Exceedance (PE) 0.98	0.84	0.5	0.16	0.02	0.003
50	7.8E-02	3.7E-02	1.4E-02	3.5E-03	4.0E-04	6.0E-05
100	3.9E-02	1.8E-02	6.9E-03	1.7E-03	2.0E-04	3.0E-05
150	2.6E-02	1.2E-02	4.6E-03	1.2E-03	1.3E-04	2.0E-05
200	2.0E-02	9.2E-03	3.5E-03	8.7E-04	1.0E-04	1.5E-05
250	1.6E-02	7.3E-03	2.8E-03	7.0E-04	8.1E-05	1.2E-05
300	1.3E-02	6.1E-03	2.3E-03	5.8E-04	6.7E-05	**1.0E-05**
400	9.8E-03	4.6E-03	1.7E-03	4.4E-04	5.1E-05	
500	7.8E-03	3.7E-03	1.4E-03	3.5E-04	4.0E-05	
600	6.5E-03	3.1E-03	1.2E-03	2.9E-04	3.4E-05	
700	5.6E-03	2.6E-03	9.9E-04	2.5E-04	2.9E-05	
800	4.9E-03	2.3E-03	8.7E-04	2.2E-04	2.5E-05	
900	4.3E-03	2.0E-03	7.7E-04	1.9E-04	2.2E-05	
1,000	3.9E-03	1.8E-03	6.9E-04	1.7E-04	2.0E-05	
2,000	2.0E-03	9.2E-04	3.5E-04	8.7E-05	**1.0E-05**	
10,000	3.9E-04	1.8E-04	6.9E-05	1.7E-05	2.0E-06	
20,000	2.0E-04	9.2E-05	3.5E-05	8.7E-06	1.0E-06	
30,000	1.3E-04	6.1E-05	2.3E-05	5.8E-06	6.7E-07	

Practically Certain

Coin Flip

Very Unlikely

Low Probability: 3/1000

AFE Color Code

∞	1.00E-02
9.99E-03	1.00E-03
9.99E-04	1.00E-04
9.99E-05	1.00E-05
9.99E-06	1/∞

100,000-year earthquake

Columbia Generating Station, SNF Shake Test Range

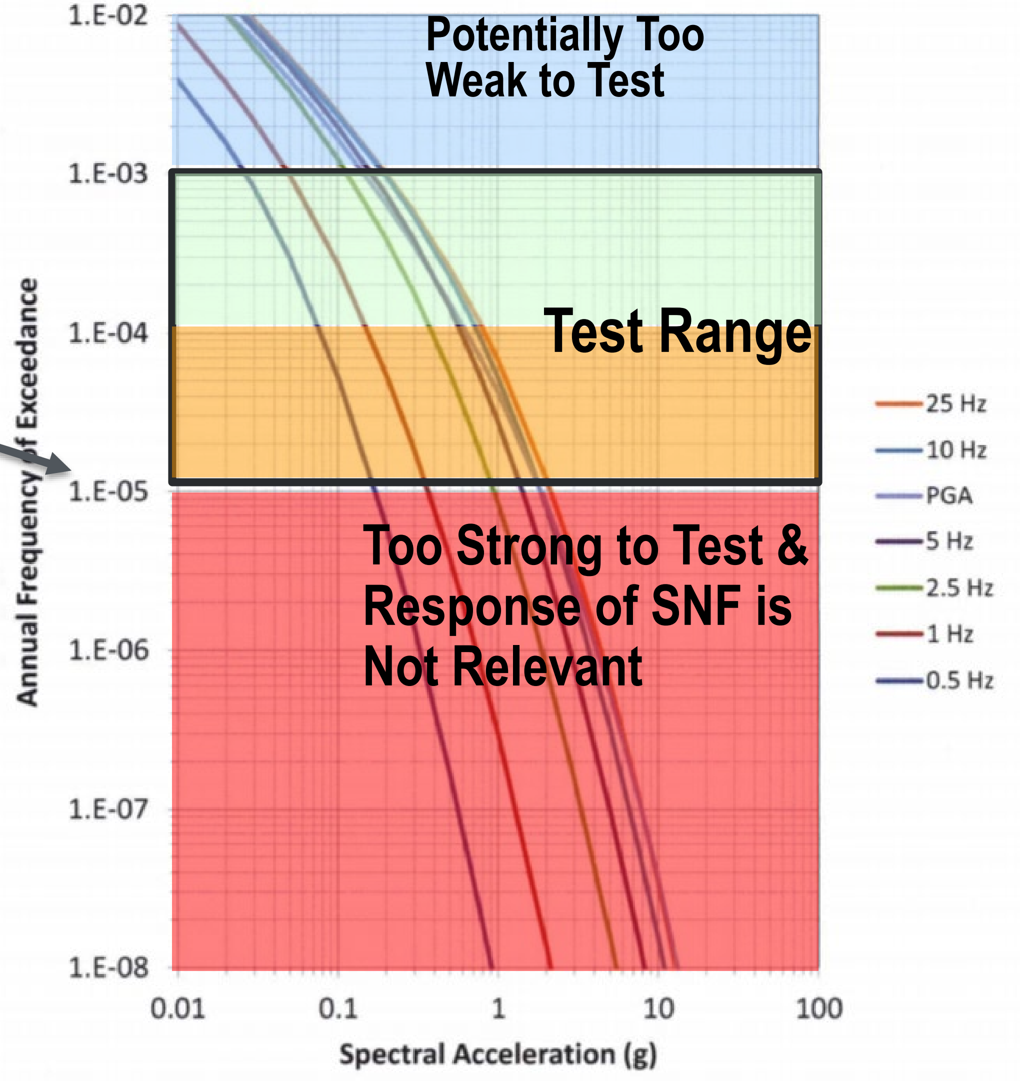


Figure 2.2.2-1: Mean Base Rock Hazard Curves for Oscillator Frequencies of 0.5, 1, 2.5, 5, 10, 25 and 100 Hz at Columbia Generating Station (PNNL, 2014) at 5% Spectral Damping

Model Development Case: Columbia Generating Station

RESPONSE TO NRC REQUEST FOR INFORMATION PURSUANT TO TITLE 10 OF THE CODE OF FEDERAL REGULATIONS 50.54(F) REGARDING RECOMMENDATION 2.1 OF THE NEAR-TERM TASK FORCE RECOMMENDATION 2.1: SEISMIC FOR SEISMIC HAZARD REEVALUATION AND SCREENING FOR RISK EVALUATION
Enclosure

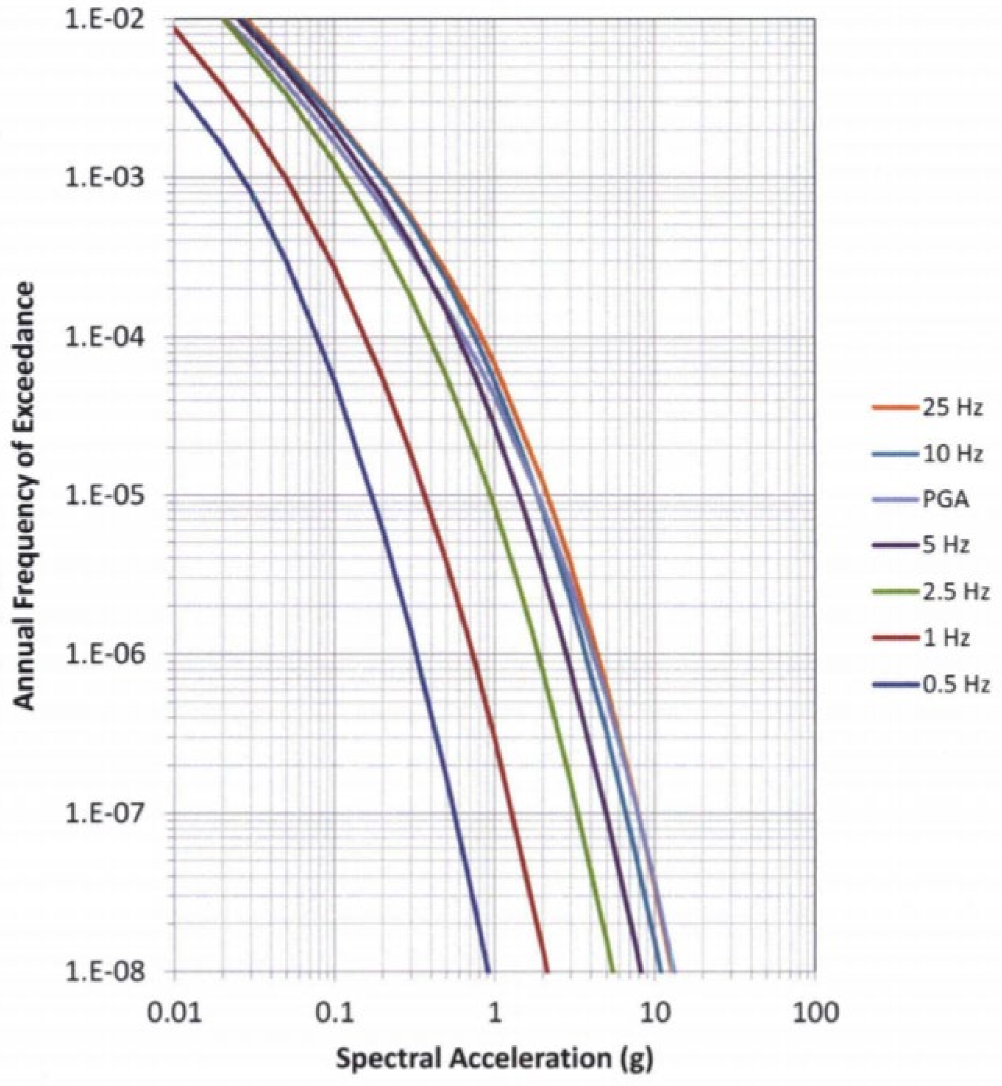


Figure 2.2.2-1: Mean Base Rock Hazard Curves for Oscillator Frequencies of 0.5, 1, 2.5, 5, 10, 25 and 100 Hz at Columbia Generating Station (PNNL, 2014) at 5% Spectral Damping

Hazard Curves define the earthquake spectra for a location over a broad range of probability.

Annual Frequency of Exceedance (AFE, AFOE) relates spectra to a yearly probability of occurrence.

Spectra define the characteristics of earthquakes: amplitude, frequency content, etc.

Ground Motion Time Histories are created (or selected) to match the spectrum at a particular AFE.

SNF Shake Test Range

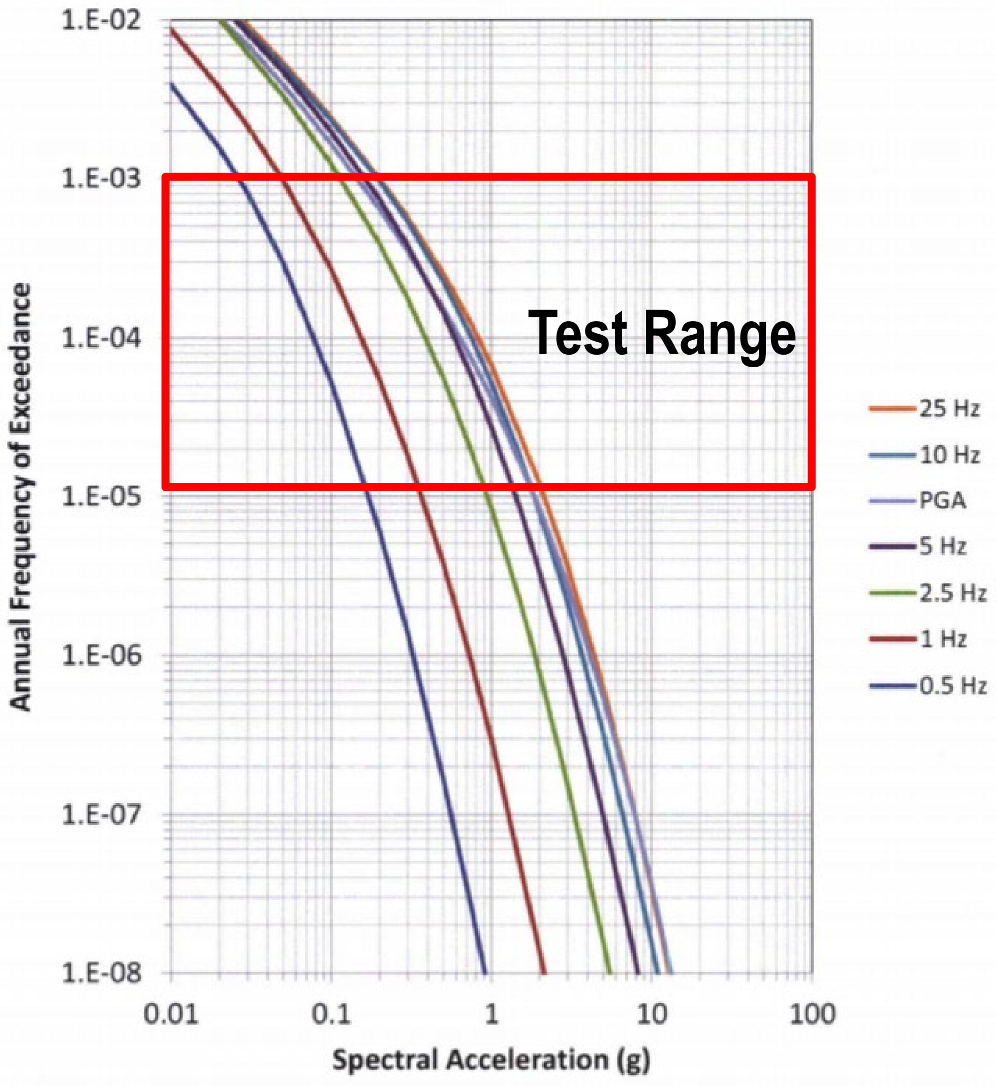
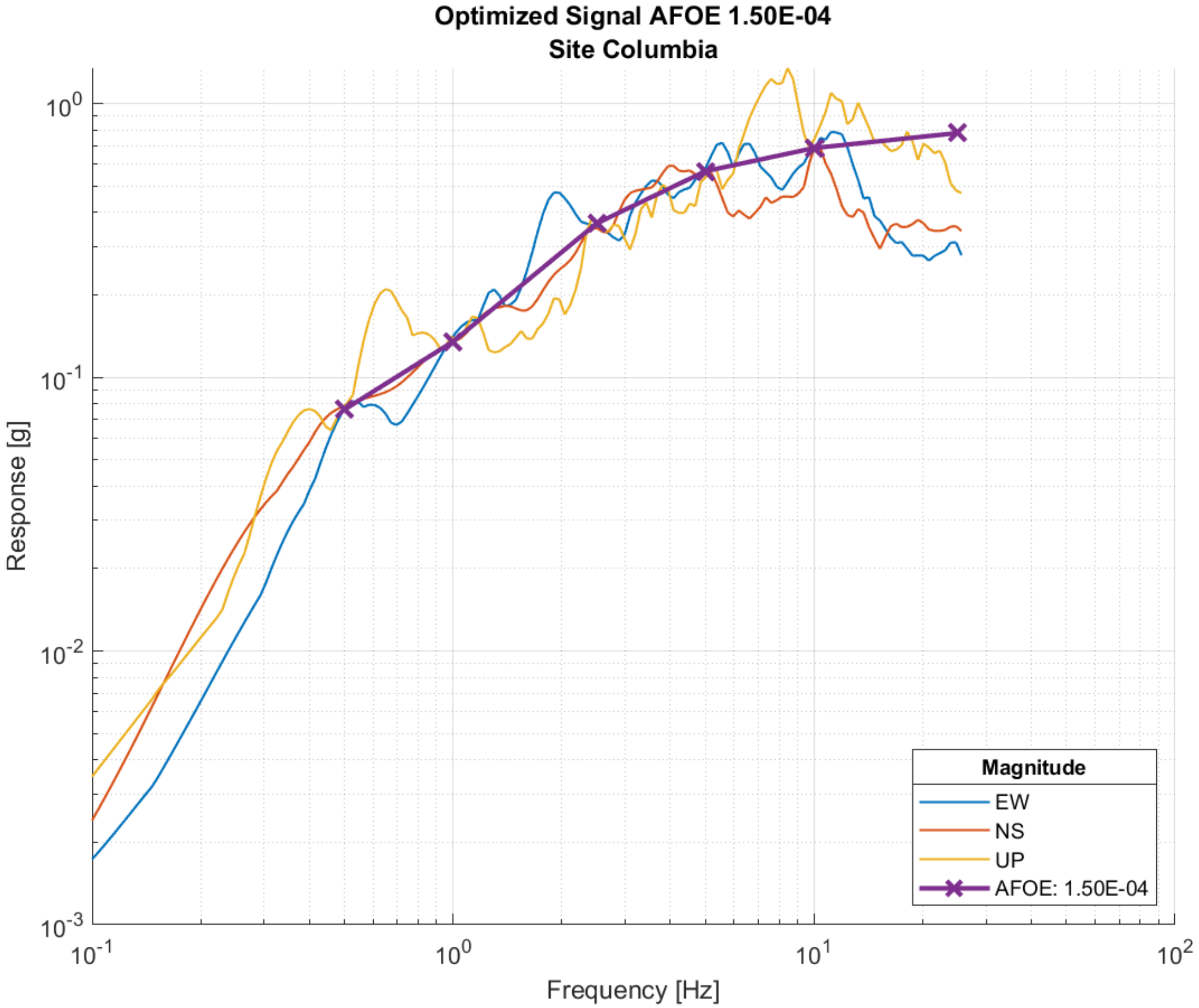
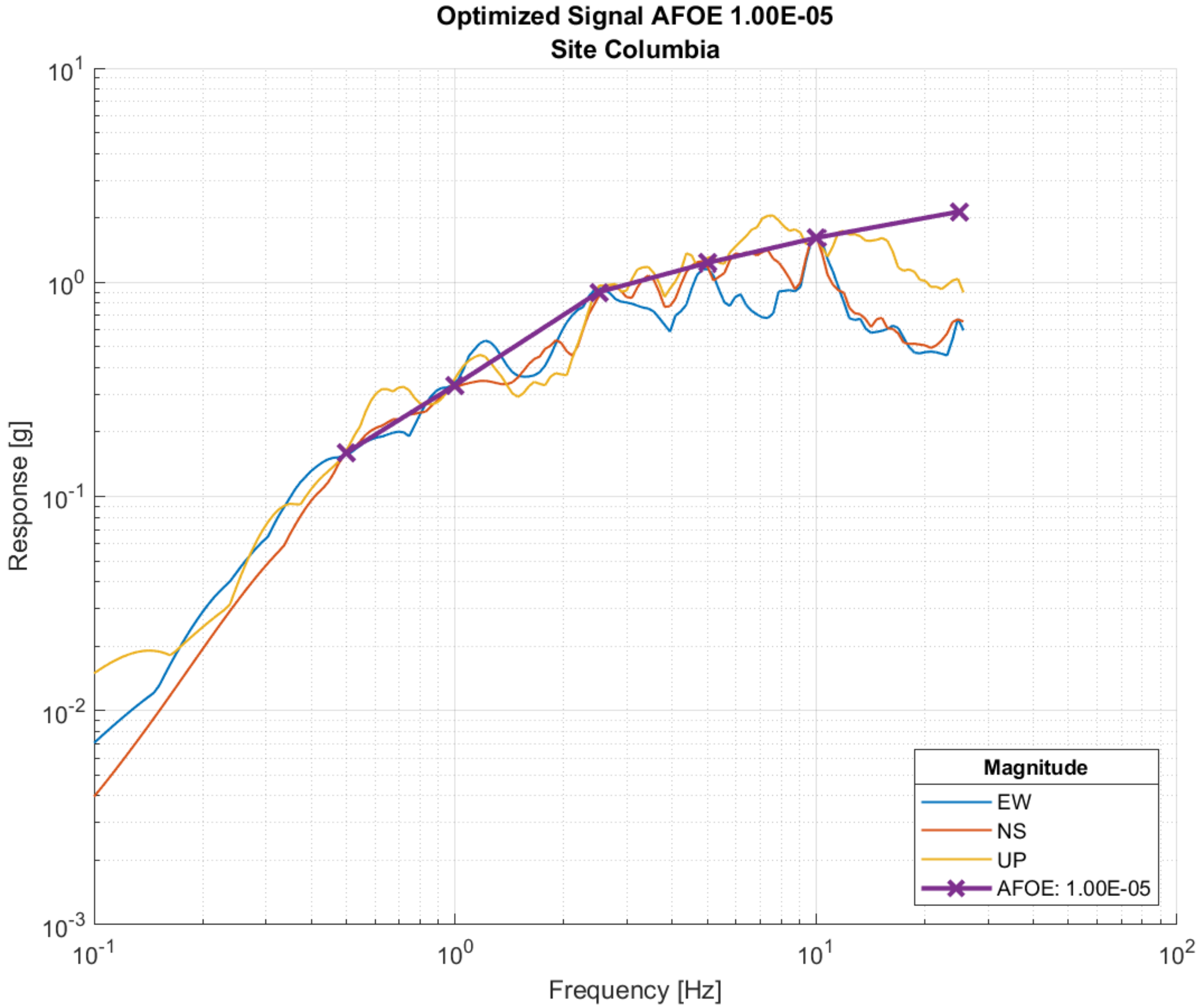


Figure 2.2.2-1: Mean Base Rock Hazard Curves for Oscillator Frequencies of 0.5, 1, 2.5, 5, 10, 25 and 100 Hz at Columbia Generating Station (PNNL, 2014) at 5% Spectral Damping

Model Development Ground Motions: Modify Historical Earthquakes to Match Target Spectra

Methodology: Select an AFOE value. Construct the AFOE target Spectra from site hazard information. Search a short database of earthquake data to find a starting time history. Adjust the time history (signal) Fourier components by hand to optimize agreement with target spectra. Matching 25 Hz is low priority because base data is sampled at 50 Hz.

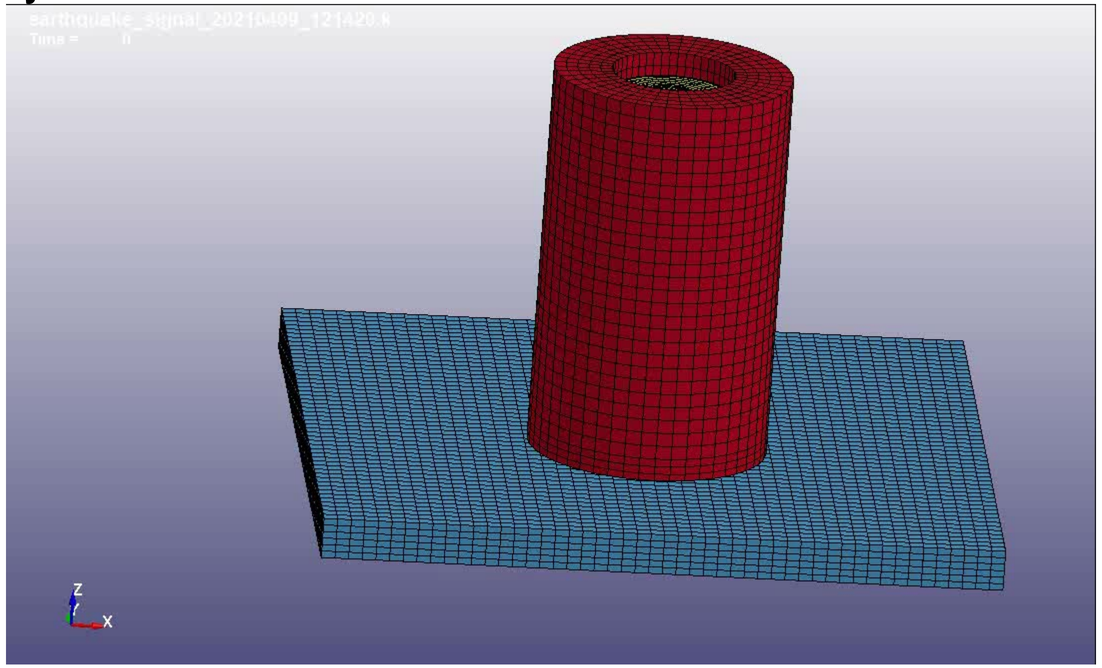




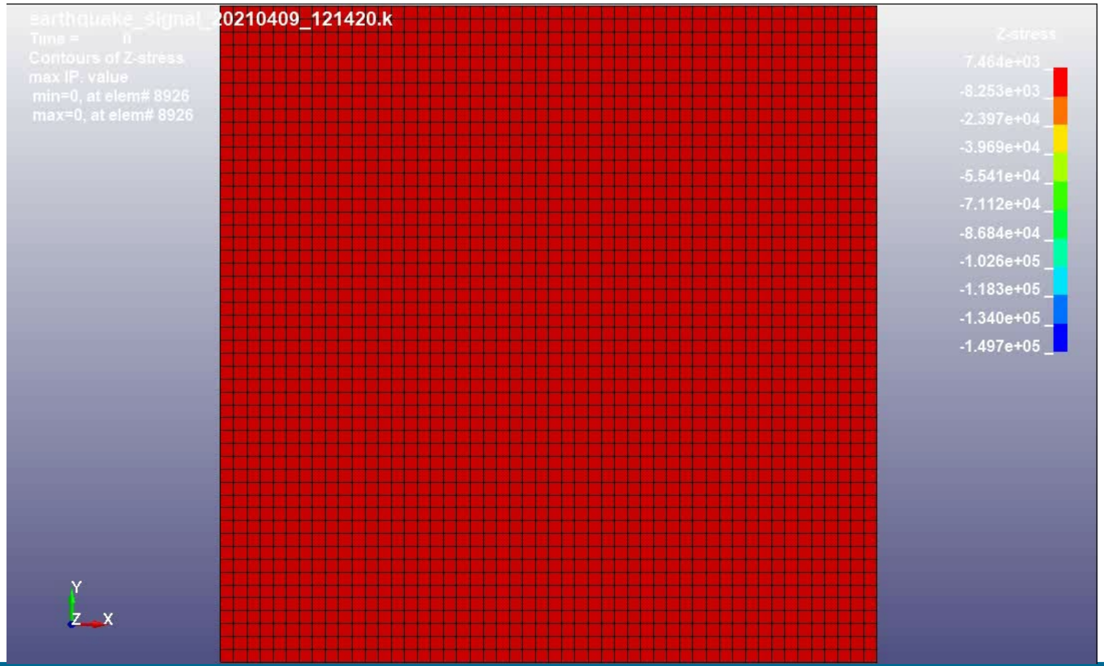
Model Development Case: Columbia Generating Station, AFE 1.5E-4

- AFE 1.5E-4
  - 6,700 Year Return Period
  - ~2% chance of exceedance in 150 years
- Base Rock Motion Applied to Pad
  - No Soil/Structure Interaction
- Low Friction (~0.01)
- 0.29 g (peak horizontal)
- 0.18 m/s (peak horizontal)
- ~27 mm Cask Relative Sliding
- Shifting Weight Observed in Contact Stress

System Motion



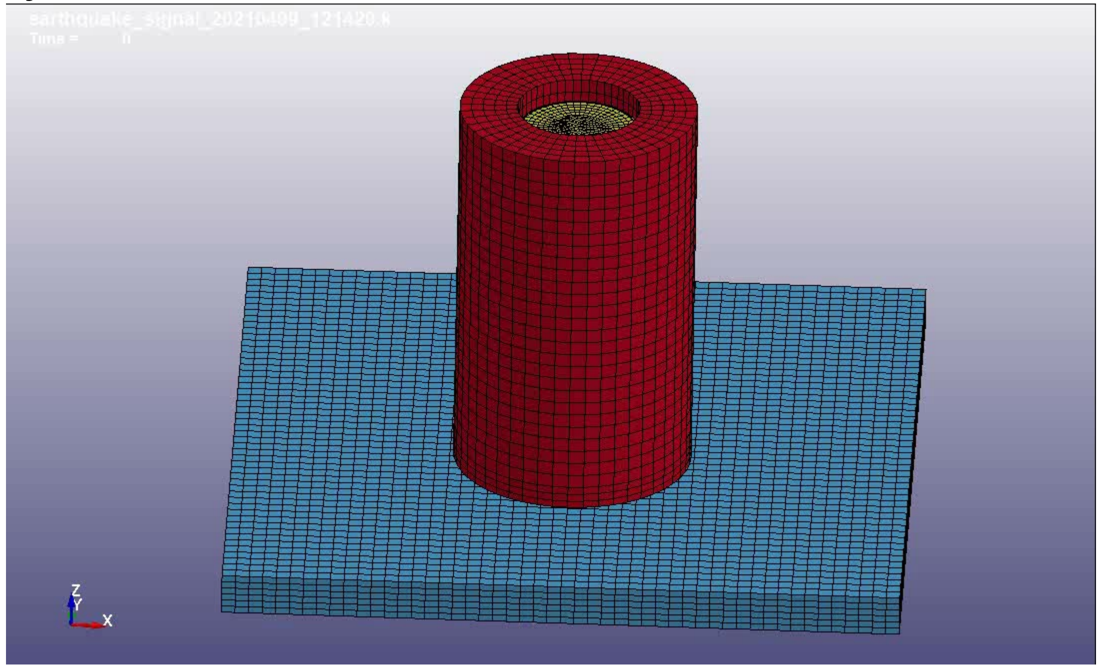
Contact Pressure on Pad



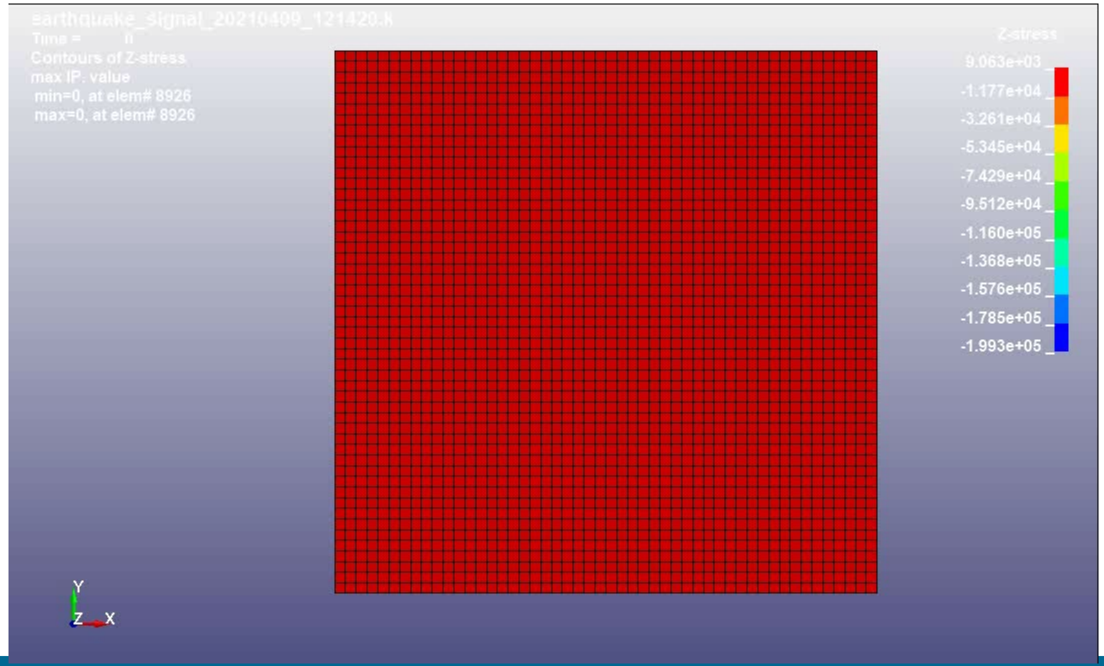
Model Development Case: Columbia Generating Station, AFE 1E-5

- AFE 1E-5
  - 100,000 Year Return Period
  - 0.3% chance of exceedance in 300 years
- Base Rock Motion Applied to Pad
  - No Soil/Structure Interaction
- Low Friction (~0.01)
- 0.38 g (peak horizontal)
- 0.32 m/s (peak horizontal)
- ~120 mm Cask Relative Sliding
- Shifting Weight Observed in Contact Stress
- ~5 mm Max Lift-up (<0.1°)

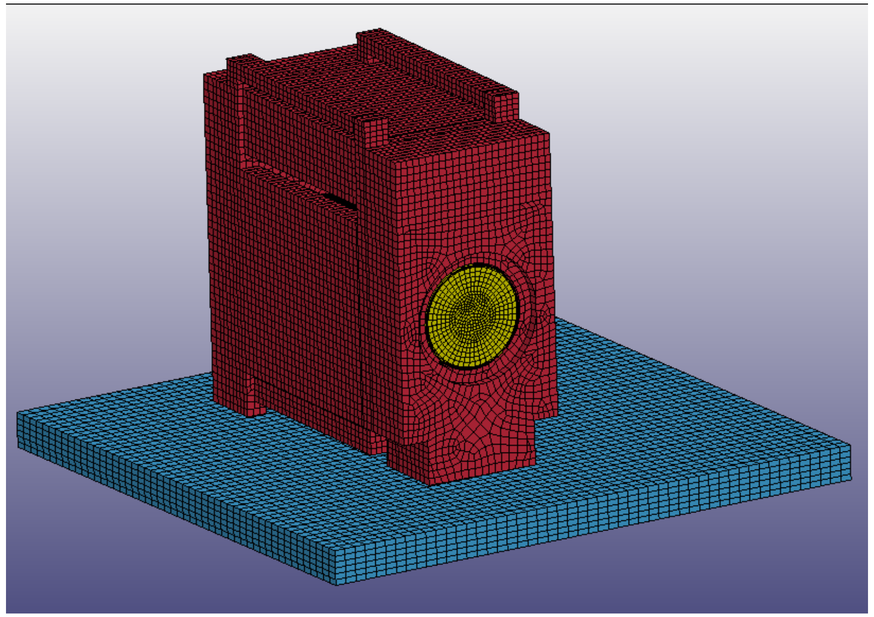
System Motion

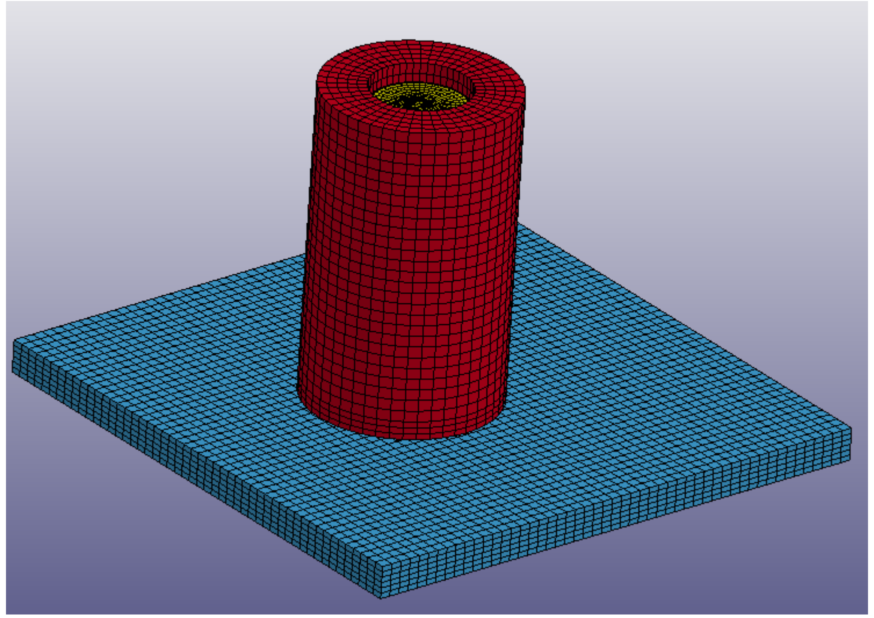


Contact Pressure on Pad



PNNL Model Development Next Steps





1/3 Scale Cask Model TBD

Upgrade the plain concrete pad model.

Detailed Shake Table Model
for As-Tested Configuration:
- Pre-Test Predictions
- Model Validation

Detailed ISFSI & Soil Column Model
for Realistic Dry Storage Analysis:
- Connect/Reconcile with Shake Table Motion
- Closing the Knowledge Gap

Conclusions

- DOE SFWST program is preparing a full-scale shake table test of SNF casks.
  - The goal is to determine SNF mechanical loads in a realistic range of earthquakes.
  - Not interested in canister safety or integrity, which is already assured by the regulations.
- Shake table inputs being developed by SC Solutions.
  - Broad range of ground motion that represents US sites. (1E-3 to 1E-5 AFE)
  - Soil-Structure interaction will be considered for a full ISFSI pad on soil.
- PNNL explicit finite models focus on the pad, cask, and SNF response.
  - To be validated with test data.
- Next modeling steps:
  - Pretest predictions
  - Model validation with test data
  - Model application to irradiated, ISFSI storage configuration

Questions?

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