Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Division V

PRETEST PREDICTIONS OF SPENT NUCLEAR FUEL IN A SEISMIC SHAKE TEST

Nicholas Klymyshyn[1], Kevin Kadooka[2], and James Fitzpatrick[2]

[1] Senior Research Engineer, Pacific Northwest National Laboratory, Richland, WA, USA (nicholas.klymyshyn@pnnl.gov)
[2] Research Engineer, Pacific Northwest National Laboratory, Richland, WA, USA

ABSTRACT

The US Department of Energy Spent Fuel and Waste Science and Technology (SFWST) program is planning to conduct a series of shake table tests to simulate hypothetical earthquake conditions and record the response of surrogate spent nuclear fuel (SNF) assemblies in late 2022. The full-scale test will use real, production quality fuel assembly and canister components where practical, and fabricate dummy fuel assemblies and canister overpacks as necessary to create a representative SNF storage environment. The main goal of the testing is to record the structural dynamic response of fuel assemblies and fuel assembly components inside the canister system. The role of Pacific Northwest National Laboratory (PNNL) on the SFWST team is to provide modelling and analysis to inform the test plan, to perform pretest predictions of the SNF and canister system response, and then to validate the models and methodologies for application to SNF dry storage configurations that are beyond those tested on the shake table. This paper describes the model development and the pretest modelling results that are available in early 2022.

INTRODUCTION

Over the last several years, the US Department of Energy Spent Fuel and Waste Science and Technology (SFWST) program has performed research to measure the mechanical loads that spent nuclear fuel (SNF) is expected to experience during normal conditions of transportation and dry storage. The purpose of quantifying these mechanical loads is to fill knowledge gaps that are identified and prioritized in Saltzstein et al. (2020). Recent research work has included truck, ship, and railroad transportation (Kalinina et al. 2018, Klymyshyn 2018), and 30 cm package drop scenarios (Kalinina et al. 2020, Klymyshyn et al. 2020). The role of Pacific Northwest National Laboratory (PNNL) on the SFWST External Loads team is to provide finite element modelling and analysis to inform the test plan, make pretest predictions, and ultimately to refine modelling best practices in order to estimate conditions that are outside the bounds of the test. For example, Klymyshyn et al. (2019) estimated rail transportation mechanical loads when carried by a purpose-built SNF transportation railcar and Klymyshyn et al. (2021) estimated the full range of mechanical loads on SNF in a generic 30 cm package drop scenario at any impact angle and a broad range of temperatures and fuel burnups. The state of finite element analysis of the upcoming seismic test is that we are making pretest predictions using LS-DYNA, a commercial explicit finite element code. This paper describes the most current results of the pre-test analyses.

The overall test plan is presented at this conference by Kalinina et al. (2022). A production quality SNF canister and basket will be placed within a mock-up vertical concrete cask (VCC). The VCC in this test was designed and fabricated specifically for this test and it has characteristics that are similar to the MAGNASTOR and HI-STORM 100 cask systems. The test will be performed at the Large High-Performance Outdoor Shake Table (LHPOST) facility near the University of California San Diego main campus. The set of shake table inputs to be tested will represent hypothetical earthquake ground motion in the continental US with 2,000 year to 20,000 year return periods. This range of inputs represents seismic events that have a 0.5% to 5% chance of occurring during a 100 year period of dry storage, with the strongest earthquakes being least likely to occur.

The ground motion and shake table motion to be used in the test was defined by a team at SC Solutions, who are summarizing their soil structure interaction work at a presentation at this conference (Garcia et al. 2022). Free field ground motions were created (Gregor et al. 2021) and the latest work by SC Solutions considered soil structure interaction using linear elastic modelling methods to provide 6 degree of freedom inputs to the shake table (3 translations and 3 rotations). SC Solutions conducted sensitivity studies to account for different storage pad sizes with different numbers of casks on the storage pads, to calculate cask motions at specific storage pad locations and determine the locations of strongest response.

This paper describes the current state of pre-test predictions using nonlinear explicit finite element analysis (FEA) and the ground motion provided by SC Solutions as shake table inputs.

FINITE ELEMENT MODELS OF TEST ARTICLES

The finite element modelling effort uses several different models to estimate the structural dynamic response of the loaded cask system. The ultimate research program goal is to understand the mechanical loads experienced by SNF, but it is also necessary to understand how the cask and canister respond to seismic excitation. The potential for sliding and tip-over during the test is an important safety consideration. It is also important to understand the VCC system dynamics and transmission of mechanical loads from one major system component to the next. Within the canister, very interesting nonlinear dynamic behavior occurs when the fuel assemblies contact the canister fuel basket walls but including that feature in the finite element model drastically increases the computation time.

Rigid Canister Model

The rigid canister model simplifies all of the canister, basket, and fuel assembly details into a solid, right circular cylinder that is assigned rigid material behavior. The density of the rigid cylinder is assigned to have the correct total mass of the real system. Figure 1 shows the rigid canister system model. Figure 1a shows the complete cask system on a square section of concrete pad. The top layer of the pad is an elastic concrete material. The bottom layer is rigid and represents the shake table that will produce 6 degree of freedom motion (3 translation and 3 rotation). Figure 1b shows the welded steel structure of the cask mock-up. Concrete will be poured into the four open sections to form the VCC. The concrete appears in Figure 1a as light blue hexahedral elements. The rigid canister shown in Figure 1c fits inside the circular central opening in Figure 1b. The finite element model simplifies the contact geometry but features the correct available gap between the side wall of the canister and VCC contact ring. This rigid canister model is primarily used as a first step to estimate the gross dynamic behavior of the VCC system, particularly the potential for sliding during the test and the potential for tip-over. The detailed canister model described in the next section more accurately represents the canister internals and is expected to provide a better estimate of system behaviour at the cost of additional computation time.

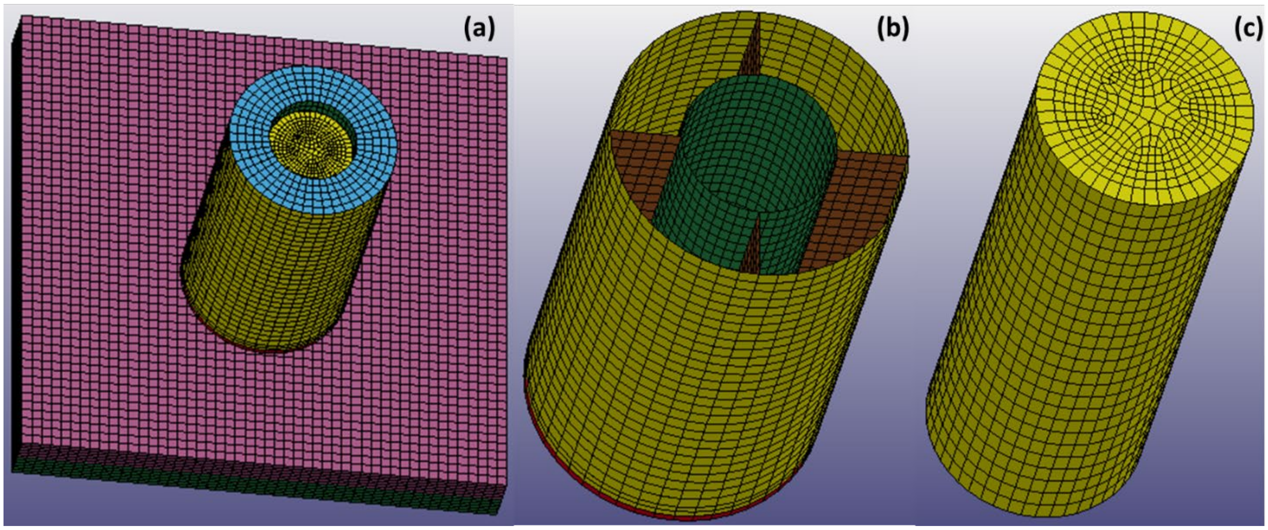


Figure 1: Rigid canister model.

Detailed Canister Model

The detailed canister model is shown in Figure 2. Everything except the canister and its contents in Figure 2a is the same as the rigid canister model. Figure 2b shows the canister, which is open at the top to allow video cameras to film the motion of the assemblies during the test. The fuel assemblies are shown in Figure 2b and they are composed of hexahedral elements with a linear elastic material model. The intent of the greatly simplified fuel assembly models is to have the correct outer envelope and mass of a fuel assembly. The basket inside the cylinder is shown in Figure 2d. The basket is composed of rigid shell elements. The treatment of the fuel assemblies and the basket is intended to allow the fuel assemblies to interact with the baskets, applying contact forces and potentially bouncing back. Previous experience in modelling fuel assemblies inside a basket has indicated that a rigid basket assumption often achieves reasonable results in normal conditions of transport and 30 cm package drop scenario (Klymyshyn et al. 2018 & 2020). One of the modelling questions that the test data will answer is how significant the contact stiffness, basket stiffness, and composition of the fuel assembly finite element models are in achieving reasonable system level behavior. The model is used to estimate the system's potential for sliding or tipping during the test, and it also provides input motion for the fuel assembly level finite element model described in the next section.

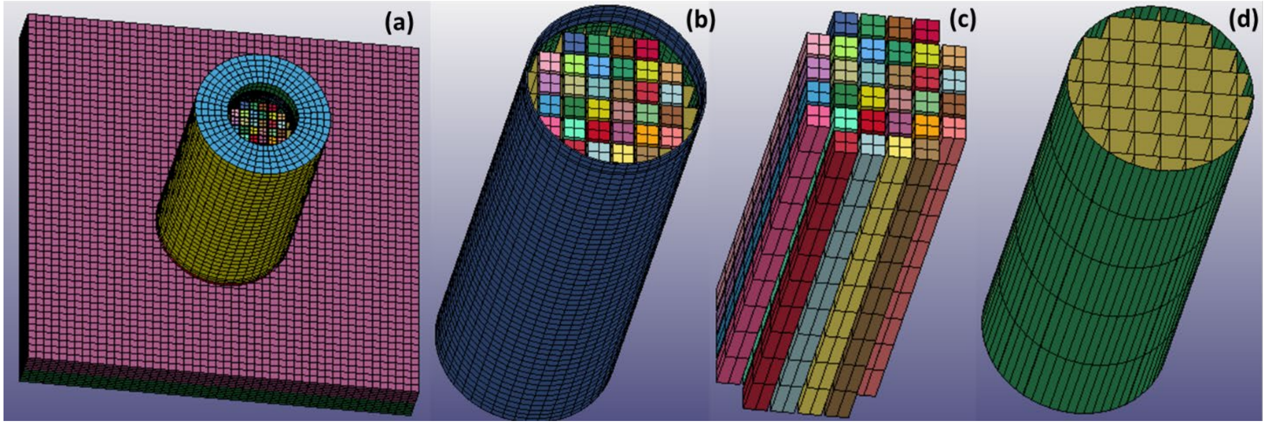


Figure 2: Detailed canister model.

Fuel Assembly Model

The fuel assembly model is a detailed finite element representation of a single 17x17 pressurized water reactor (PWR) fuel assembly within a rigid basket cell (see Figure 3a and 3b). The fuel assembly model is very similar to those used by PNNL to simulate SNF response in 30 cm drop events (Klymyshyn et al. 2020 & 2021), except for how the system is excited. In this work, the model is excited by applying the translational and rotational velocities of the basket in the detailed canister model to the rigid basket.

The fuel rods and guide tubes are represented using beam elements. The fuel rods are assigned equivalent density to account for the mass of the cladding and surrogate fuel. The stiffness of the fuel rods reflects no pellet-to-cladding bonding, using material properties for unirradiated Zr-4 at room temperature (Geelhood et al. 2008). The guide tubes are connected via tied contacts to the top and bottom nozzles, which are simplified as rectangular prisms composed of solid elements. The spacer grids are also represented using beam elements (see Figure 3c). Grids are connected to the fuel rods using nonlinear discrete spring and damper elements to represent the grid springs and dimples and fixed rigidly to the guide tubes using spotweld connections. The basket cell is represented by a box-like rigid body. A gap of 5 mm on each side of the fuel assembly was assumed for this study. Prior modelling of rigid and elastic baskets in drop events suggests that a rigid basket provides slightly more conservative results with respect to cladding strains (Klymyshyn et al. 2021).

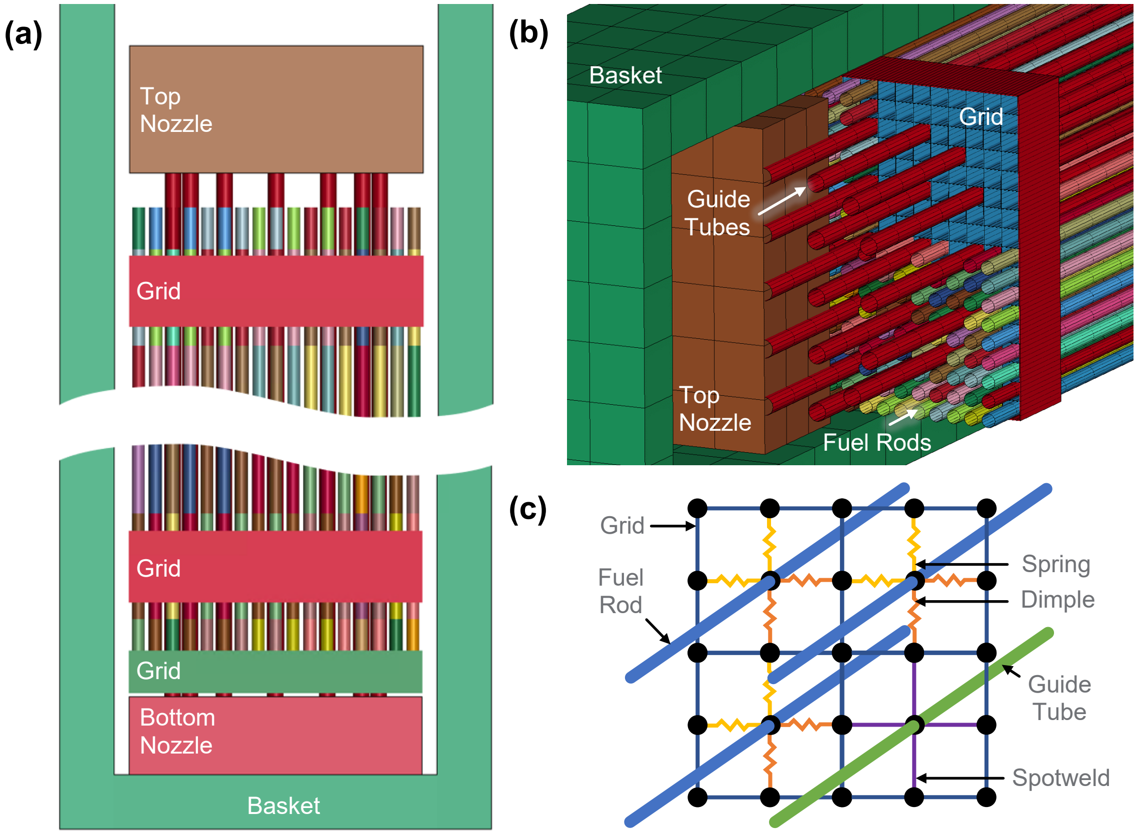


Figure 3. Fuel assembly model.

A contact algorithm is used to simulate impact between the fuel assembly and the basket, as well as between fuel assembly components, such as between neighbouring fuel rods. The model also incorporates a small amount of both mass and stiffness damping, resulting in a damping ratio of approximately 9%. This aligns well with the damping observed in the 30 cm fuel assembly drop test (Klymyshyn et al. 2021).

NONLINEAR FEA RESULTS

Rigid Canister Model Results Compared to Detailed Canister Model Results

The rigid canister and detailed canister models were studied using a 6 degree of freedom ground motion time history set that represents local concrete pad motion at the most limiting cask location on a partially loaded storage pad. Linear soil-structure interaction modelling was used to determine the local pad motion. The peak pad lateral (Y) acceleration is 5.2 m/s^2 and the time history is discussed in more detail in the next section as the soil site condition time history. The earthquake assumptions approximate a 5×10^{-5} annual frequency of exceedance (AFOE) seismic event (a 20,000 year return period event) at a hypothetical SNF dry storage facility located at a soil ground classification site in the central or eastern US.

Table 1 summarizes the cask system response with a few values extracted from the results database. The baseplate peak acceleration is the instantaneous peak acceleration in the horizontal plane (the value is the resultant of X and Y acceleration vectors). The peak VCC acceleration is the acceleration of the centre of mass of all VCC components, including the steel plates and shells and the concrete fill material, in horizontal plane (the peak resultant of the X and Y acceleration vectors). Baseplate final slide is the total change in relative position between the VCC baseplate and the concrete pad in the horizontal plane. The accelerations in the rigid model are significantly higher than the detailed model, but for cask sliding the trend is reversed and the detailed canister model predicts a larger value. While the differences are apparent, the values all indicate a mild dynamic response of the cask system. The potential of the cask to tip over was assessed in the results of both models and no significant amount of tipping or change in angle of the VCC central axis relative to the horizontal plane was predicted. A much more severe earthquake scenario is expected to be needed before a perceptible tipping or rocking cask response would be a concern.

Table 1: Canister Model Response Comparison

	Rigid Canister Model	Detailed Canister Model
Baseplate Peak Accel (m/s^2)	41.1	13.1
Peak VCC Accel (m/s^2)	14.0	6.0
Baseplate Final Slide (mm)	0.8	4.3

Note that LS-DYNA models are solved with a timestep size that is close to 1×10^{-6} seconds, and the results are written with step size of 1×10^{-4} seconds. The instantaneous acceleration values include high frequency content above 100 Hz, so some caution in interpreting these results is advised. Previous testing and modelling work applied low pass frequency filters to eliminate high frequency content that is above the range of interest for SNF (Klymyshyn et al. 2018). We have not yet determined an optimal cutoff frequency to be applied to this work, but a cutoff in the 100 Hz to 300 Hz range is expected to be used. For example, the baseplate peak accelerations in the rigid canister model (41.1 m/s^2) are about 4 times higher than the input motion but applying a 50 Hz Butterworth low-pass filter brings the acceleration peak down to 24.5 m/s^2. A 50 Hz cutoff is lower than is typically used in SNF dynamics applications but is in line with typical seismic analyses. Filtering and the frequency domain of interest are important technical topics that are still being considered.

Detailed Canister Model Results

The detailed canister model described above was excited using two different representative earthquake ground motions. The hard rock seismic case represents a SNF storage facility built on a hard rock site in the central or eastern US that is subjected to a 1×10^{-4} AFOE seismic event (a 10,000 year return period). The soil site conditions are also in the central or eastern US, but soil structure interaction effects are considered, and a stronger seismic event is assumed. The soil case assumes a 5×10^{-5} AFOE seismic event (a 20,000 year return period) and makes certain assumptions about the soil conditions, the size of the concrete storage pad, and the number and arrangement of casks on the pad. The companion paper by (Garcia et al. 2022) at this conference provides those details. The hard rock case does not include soil structure interaction effects because they are assumed to be negligible for SNF dry storage pads that are built directly on hard rock. The translational accelerations from each time history are presented in Figure 4 and the peak values are tabulated in Table 2. Note that the peak ground accelerations were between 1.9 and 3.5 times higher at the soil site. The weakest hypothetical seismic event to be tested is expected to be 5×10^{-4} AFOE (a 2,000 year return period) which is expected to be significantly weaker than the 1×10^{-4} AFOE hard rock case evaluated in this paper.

The translational accelerations of the cask and basket in the detailed canister model are also presented in Figure 4. The basket response is relevant because it is the structure that encapsulates the SNF. The basket and cask response features higher accelerations and contains higher frequency content compared to the input ground motions. This occurs because of the nonlinear interactions (contact or impacts) between the cask and ground, and between the basket, canister, and fuel assemblies. Examples of nonlinear interactions occurring in the system are stick-slip conditions at interfacing surfaces, and impact between neighbouring components in the cask. The peak basket accelerations were roughly 4 to 10 times higher than the peak ground motion acceleration, however the duration of the highest accelerations is very short (approximately 1 ms pulse width at half-maximum).

The translational and rotational basket motions calculated in the detailed canister model were applied to the fuel assembly model. The fuel rod cladding and guide tube strains were extracted from the model. The peak values are reported in Table 3. Note that these values include the static load due to gravity, which is up to approximately 20 uE (where 1 uE equals 1×10^{-6} mm/mm). The peak fuel rod and guide tube strains were respectively 96 and 215 uE for the hard rock site condition, and 297 and 866 uE for the soil site condition. The fuel assembly strains for the soil site condition were about three times greater than for the hard rock site conditions, which is reasonable considering the greater peak ground acceleration at the soil site compared to the hard rock site (Table 2). Figures 5 and 6 show the distribution of fuel assembly strains for the hard rock and soil site conditions, respectively. The highest fuel rod strains tend to occur near the grid elevations, as the grids represent a stiffness discontinuity. Under excitation of the hard rock site condition, the fuel rod and guide tube strains tend to occur near the bottom of the fuel assembly, as the fuel assembly behaves similarly to a cantilever beam fixed at one end. Under excitation of the soil site condition, the higher strains are seen towards the top of the fuel assembly. The higher ground acceleration of the soil site condition results in more powerful impacts between the top nozzle and basket cell, resulting in higher strains near that region.

The main takeaway from this study is that for the two representative earthquakes analysed, the fuel rod and guide tube strains are far below the levels needed to induce yield (roughly 10,000 uE and 7,000 uE for Zr-4 fuel rods and guide tubes respectively at room temperature and low burnup (Geelhood et al. 2008)). This result suggests that SNF in dry storage has significant mechanical margin with respect to seismic excitation.

Table 2. Peak accelerations of input ground motions.

Site Condition	AFOE	Ground Motion Peak Acceleration (m/s^2)		
		X	Y	Z
Hard Rock	1×10^{-4}	2.5	1.9	1.5
Soil	5×10^{-5}	4.8	5.2	5.2

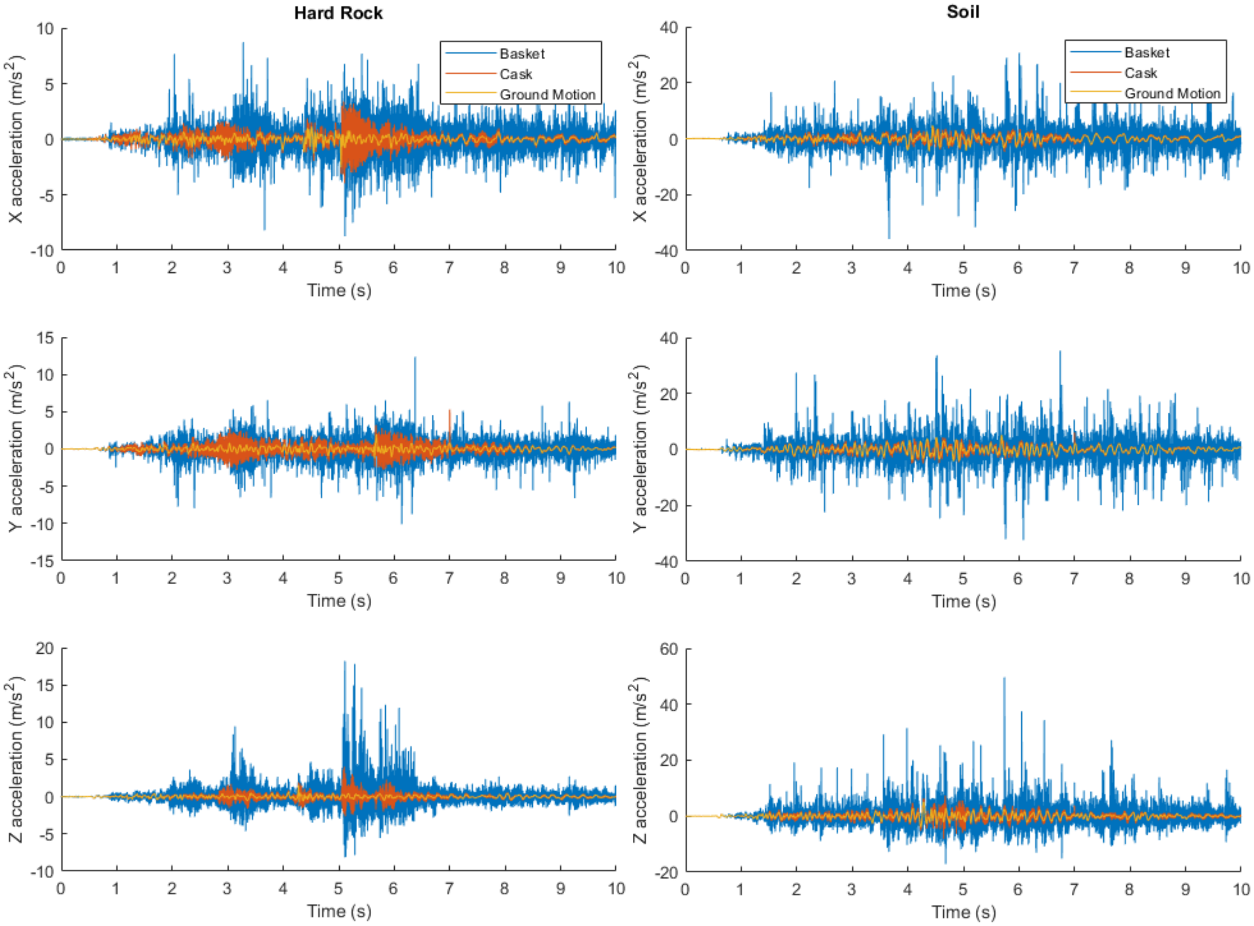
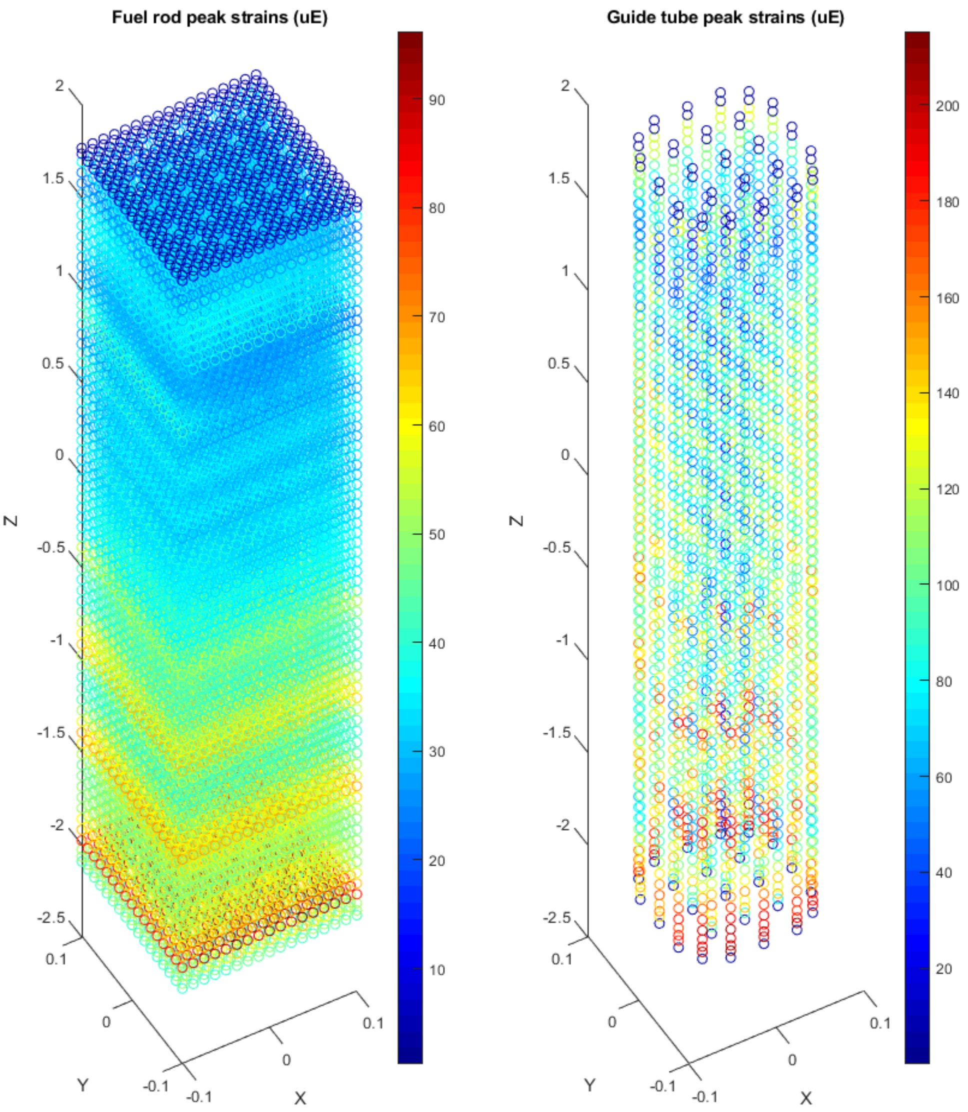


Figure 4. Excerpt of input ground motions and cask and basket response.

Table 3. Peak fuel rod and guide tube strains.

Site Condition	Peak Strain (uE)	
	Fuel Rods	Guide Tubes
Hard Rock	96	215
Soil	297	866



Fuel rod peak strains (uE)

Guide tube peak strains (uE)

Figure 5. Element-wise peak strain in fuel rods and guide tubes, for the hard rock ground motion. Position axes are in meters.

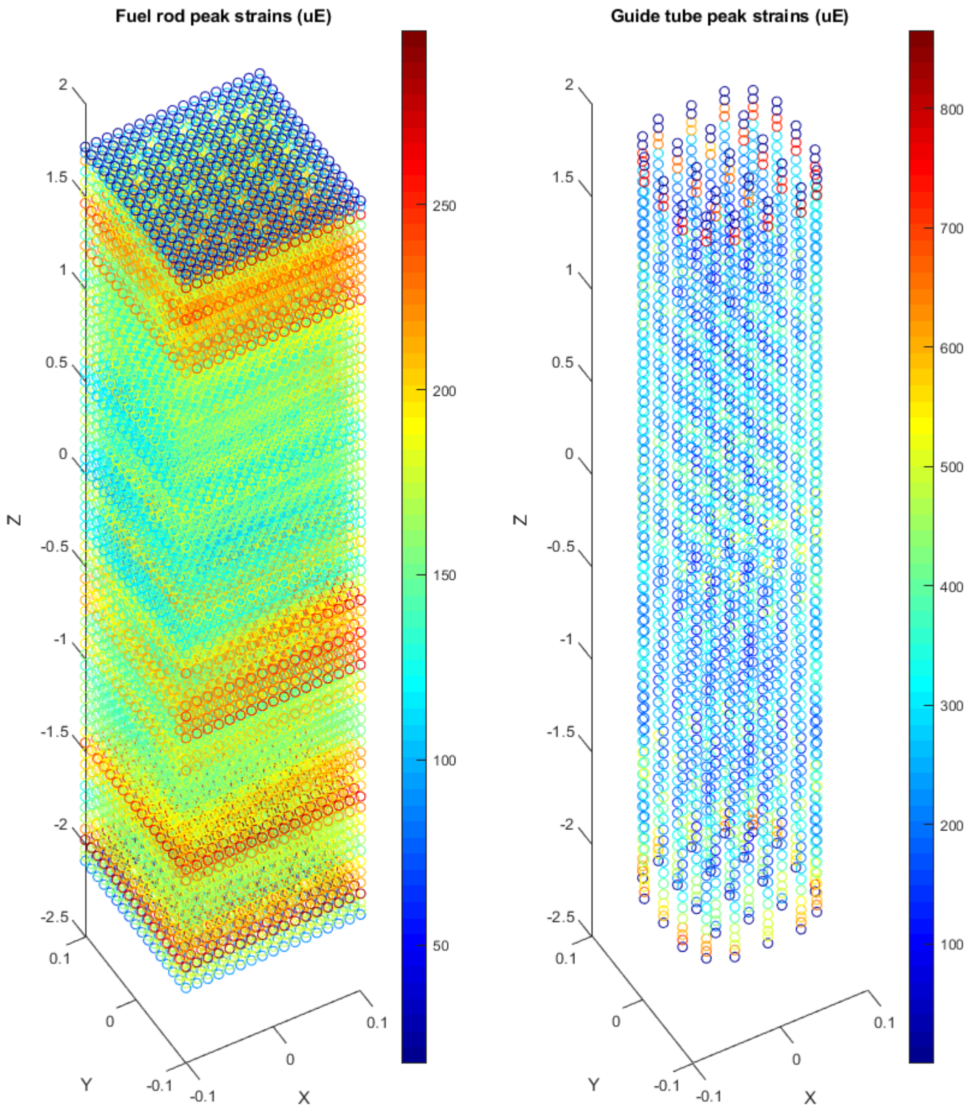


Figure 6. Element-wise peak strain in fuel rods and guide tubes, for the soil ground motion. Position axes are in meters.

CONCLUSIONS

This pre-test analysis study estimates that the strongest seismic test conditions will produce a relatively mild and stable dynamic response from the cask. Cask sliding up to ~5 mm is the maximum predicted amount of motion relative to the concrete pad. VCC tip-over is not expected, and the models predict the base of the VCC will remain approximately horizontal. The peak cladding strain is expected to be below 300 uE and the peak guide tube strain is expected to be below 900 uE. These strains are above those expected from normal conditions of transportation but are much less than those experienced during a 30 cm package drop.

This paper considered two different earthquake and site conditions at a location in the central or eastern US, a strong earthquake at a soil site and a moderate earthquake at a hard rock site. The soil site earthquake is at the high end of seismic response to be tested in the upcoming shake table test and the hard rock site is in the middle of the test range. Pretest predictions for the weakest earthquake conditions of the test will be evaluated before the test occurs, but the current priority is the mid-range to high end to determine if significant sliding or tip-over is expected so proper precautions can be taken in preparing the test.

The next steps of this work are to complete pretest predictions for all test cases to be conducted during the shake table test, study the test data to determine best modelling practices, and then apply the modelling methods as necessary to close the knowledge gap for the SFWST program.

The authors would like to acknowledge Elena Kalinina's (SNL) team and Julio Garcia's (SC Solutions) team for invaluable collaboration on this work.

REFERENCES

Garcia, J., Johnson, W., Tehrani, P., Watkins, W. (2022). "Simulation of Soil Structure Interaction Supporting Seismic Shake Table Test of a Full-Scale Dry Storage of Spent Nuclear Fuel." Paper to be presented at SMiRT-26 Berlin/Potsdam, Germany, July 10-15, 2022.

Geelhood, K. J., Beyer, C. E., Luscher W. G. (2008). "PNNL Stress/Strain Correlation for Zircaloy," PNNL-17700, Pacific Northwest National Laboratory, Richland WA.

Gregor, N., Atik L. A. (2021). "Ground Motions for Shake-Table Testing of Dry Casks," SC Solutions, 2021.

Kalinina, E. A., Wright, C., Gordon, N., Saltzstein, S. J., Lujan, L., Norman, K. M. (2018). "Data Analysis of ENSA/DOE Rail Tests." SFWD-SFWST-2018-000494, Sandia National Laboratories, Albuquerque NM.

Kalinina, E. A., Ammerman, D., Grey, C., Flores, G., Lujan, L., Saltzstein, S., Michel, D. (2020). "Surrogate Assembly 30 cm Drop Test." Sandia National Laboratories, Albuquerque NM.

Kalinina, E. A., Ammerman, D., and Lujan, L. (2021). "Seismic Shake Table Test Plan." SAND2021-11207R, Sandia National Laboratory, Albuquerque NM.

Kalinina, E. A., Ammerman, D. (2022) "Planning for Seismic Shake Table Test of a Full-Scale Dry Storage of Spent Nuclear Fuel." Paper to be presented at SMiRT-26 Berlin/Potsdam, Germany, July 10-15, 2022.

Klymyshyn, N. A., Ivanusa, P., Kadooka, K., Spitz, C., Jensen, P. J., Ross, S. B., Hanson, B. D., Garcia, D., Smith, J., Lewis, S. (2018). "Modeling and Analysis of the ENSA/DOE Multimodal Transportation Campaign." PNNL-28088, Pacific Northwest National Laboratory, Richland WA.

Klymyshyn, N. A., Ivanusa, P., Kadooka, K., Spitz, C. J., Irick, E. D., Jensen, P. J., Ross, S. B. (2019). "Structural Dynamic Analysis of Spent Nuclear Fuel." PNNL-29150, Pacific Northwest National Laboratory, Richland WA.

Klymyshyn, N. A., Kadooka, K., Ivanusa, P., Spitz, C. J., Fitzpatrick, J. F. (2020). "30 cm Drop Modeling." PNNL-30495, Pacific Northwest National Laboratory, Richland WA.

Klymyshyn, N. A., Kadooka, K., Spitz, C., Fitzpatrick, J. F., Jensen, P. J. (2021) "Mechanical Loads on Spent Nuclear Fuel in the General 30 cm Package Drop Scenario." PNNL-32087, Pacific Northwest National Laboratory, Richland WA.

Saltzstein, S., Hanson, B, Sorensen, K. (2020). "Spent Fuel and Waste Science and Technology Storage and Transportation 5-Year R&D Plan." M2SF-20SN010201062. Sandia National Laboratories, Albuquerque NM.