Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Division 05

PLANNING FOR SEISMIC SHAKE TABLE TEST OF A FULL-SCALE DRY STORAGE OF SPENT NUCLEAR FUEL

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ABSTRACT

Currently, spent nuclear fuel (SNF) is stored in onsite independent spent-fuel storage installations (ISFSIs) at 73 nuclear power plants in the U.S. Because a geologic repository for permanent disposal of SNF has not been constructed, the SNF will remain in dry storage longer than planned. During this time, the ISFSIs may experience earthquakes of different magnitudes. The dry storage systems are licensed to withstand large seismic loads. However, there is little data on the response of the SNF assemblies contained within them.

The Spent Fuel Waste Disposition (SFWD) program under the U.S. Department of Energy (DOE) is planning a full-scale seismic shake table test to close the gap related to the seismic loads on the fuel assemblies in dry storage systems. This test will allow for quantifying the strains and accelerations on surrogate fuel assembly during earthquakes of different magnitudes.

Full-scale testing is needed because dry storage systems are complex and highly nonlinear, making it hard to predict their response to seismic excitations even with scale-model testing. The non-linearity arises from the multiple gaps in the system – between the fuel rods and the basket, basket and dry storage canister, and canister and the storage cask. The non-linearities pose significant limitations on tests with scaled systems, especially concerning the loads acting on the spent fuel assemblies.

This paper describes the preliminary test plan including ground motions (inputs to the shake table), test hardware, instrumentation, and facility at which the test will take place in spring of 2023.

INTRODUCTION

Currently, spent nuclear fuel (SNF) is stored at onsite independent spent-fuel storage installations (ISFSIs) at seventy-three (73) nuclear power plants (NPPs). Only three NPPs do not have on-site dry storage. However, two of these are considering building on-site ISFSIs in the near future. Alternatively, the on-site SNF might be transferred to a consolidated dry storage facility, if such a facility (federal or private) is licensed, where it will be stored until a geologic repository becomes available. Two sites, one in Texas and one in New Mexico, are pursuing private consolidated storage facilities.

Because a site for geologic repository for permanent disposal of SNF has not been constructed, the SNF will remain in dry storage at many locations in the US longer than planned. During this time, the ISFSIs and consolidated storage facilities may experience earthquakes of different magnitudes. The dry storage systems are designed and licensed to withstand large seismic loads. When dry storage systems experience seismic loads, there are little data on the response of the SNF assemblies contained within them.

The only full-scale experiment that considered all the components of the dry storage system was performed in Japan in 2007, Shirai (2007). The scaled ground motions recorded during two actual earthquakes and one artificial ground motion were used as inputs to the shake table.

A series of shake table experiments were conducted in the U.S. with scale-model representations of the free standing vertical dry storage systems (a scaled dry storage cask with a scaled canister), Ibarra (2016). The scaled canister in these tests did not contain surrogate fuel assemblies. Instead, additional mass was added to the test units using 16 lead panels.

The Spent Fuel Waste Disposition (SFWD) program is planning to conduct a full-scale seismic shake table test series to close the gap related to the seismic loads on the fuel assemblies in dry storage systems. These tests will allow for quantifying the strains and accelerations on surrogate fuel assembly hardware and cladding during earthquakes of different magnitudes and frequency content.

Full-scale testing is needed because a dry storage system is a complex and highly nonlinear system making it hard to predict (model) the responses to seismic excitations. The non-linearity arises from the multiple gaps in the system – between the fuel rods and the basket, between the basket and dry storage canister, between the dry storage canister and the storage cask (overpack), and ventilation gaps. The non-linearities pose significant limitations on the value of tests with scaled systems.

This paper describes the planning for the seismic shake table test series. The shake table test roadmap is shown in Figure 1. The details regarding each element of the roadmap are provided in the following sections.

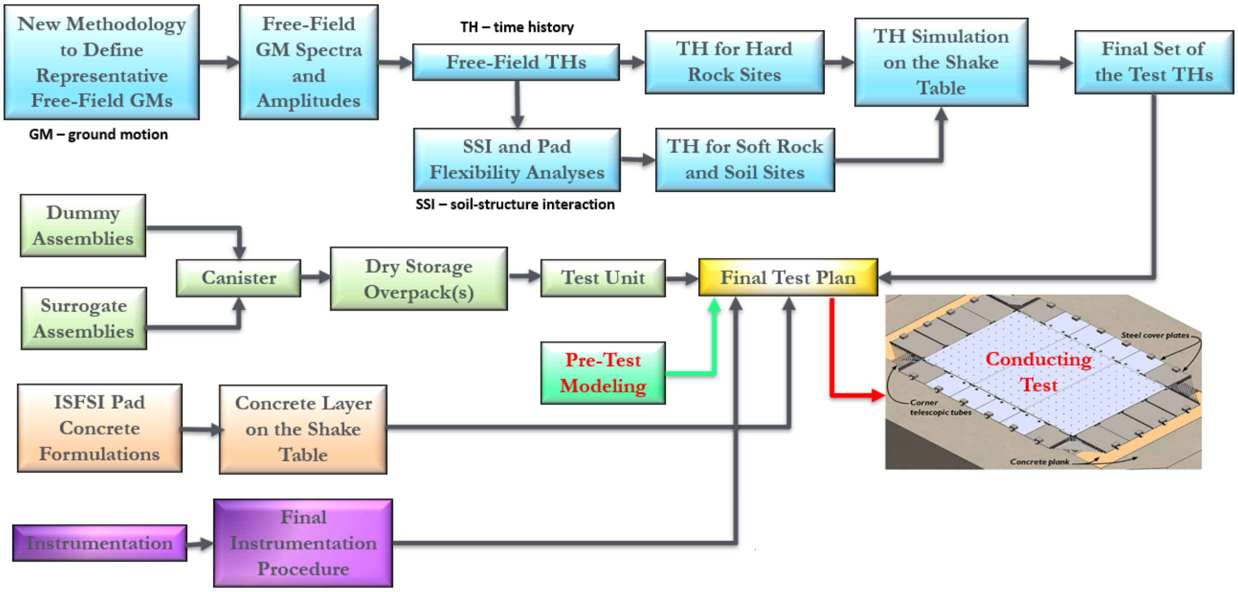

Figure 1. Seismic Shake Table Test Roadmap.

One of the most important tasks is defining the acceleration time histories (THs) to be used as inputs to the shake table. The elements that are part of this task are shown in the blue boxes in Figure 1. This task starts with developing a new methodology for defining free-field THs. The free-field THs are used in soil-structure interaction (SSI) and pad flexibility analyses. Finally, the proposed THs are analysed to confirm that they can be implemented on the shake table.

The test unit consists of a dry storage canister loaded with surrogate and dummy assemblies and placed in a vertical cask. The corresponding elements are shown in green boxes in Figure 1.

A concrete layer will be installed on the shake table. The concrete formulation should be representative of an ISFISI pad. The elements in the orange boxes in Figure 1 are related to defining the appropriate concrete properties.

All the components of the test unit will be instrumented. The elements in the purple box in Figure 1 are related to the instrumentation task.

The pre-test modeling (bright green box in Figure 1) will provide support to all the tasks. All the tasks will be documented in the detailed Test Plan. The Test Plan will go through multiple levels of internal and external reviews before it is finalized and implemented.

SHAKE TABLE ACCELERATION TIME HISTORIES

Development of the shake table inputs (acceleration THs) is a challenging task. This is because they must be representative of the range of seismotectonic and other conditions that any site in the Western US (WUS) or Central and Eastern US (CEUS) might encounter. A new approach was developed to define the representative THs, Gregor and Atik (2021). The representative THs (free-field ground motions) were developed for 3 general site categories: hard rock, soft rock, and soil. At the CEUS sites, all 3 categories are present. At the WUS sites, two categories are present - soft rock and soil. The grouping of the sites was based on the average shear velocity within the top 30 m (Vs30). The soil sites were the sites with Vs30 less than 500 m/sec. The soft rock sites were the sites with Vs30 500 to 1,000 m/sec. The hard rock sites were the sites with Vs30 greater than 1,000 m/s.

Figure 2 shows the conceptual differences between the sites located on hard rock and the sites located on soft rock and soil. At the hard rock sites, the pad motions can be assumed the same as the free-field ground motions as demonstrated in the initial soil-structure interaction (SSI) analysis, Garcia (2021). At the soft rock and soil sites, the pad motions differ from the free-field ground motions due to the amplification or attenuation in the soft rock/soil and to the soil-structure interaction.

There are 24 hard rock sites, 16 soil sites, and 11 soft rock sites in the CEUS. There are 7 NPP (ISFSIs) in the WUS and they are all located on soft rock, except one. The site classification was based on the most up to date data from site screening reports. Each nuclear power plant (NPP) site in the US was required to submit a Seismic Hazard Evaluation and Screening Report, NRC (2012a). In preparing the screening report, each NPP was asked to re-evaluate seismic hazards against present-day NRC requirements (e.g. RG 1.208), NRC (2007). The NPPs submitted the screening reports in the 2014-2017 timeframe.

Figure 3 shows the CEUS sites and their types. Also shown in this figure are the peak ground accelerations (PGAs) from the new ground motion response spectra (GMRS) defined in the screening reports. The new GMRS are based on modern techniques and updated models compared to the ones used for plant licensing. The new GMRS were compared to the previously defined Safe Shutdown Earthquake (SSE). If the new GMRS exceeded the SSE, the NPP site was required to conduct an additional evaluation per the Expedited Seismic Evaluation Process (ESEP). The PGA values for these 36 sites (64% of all sites) are shown in purple font. If the new GMRS was equal to or smaller than the SSE, no further action was required. The PGA values for these 20 sites are shown in black font.

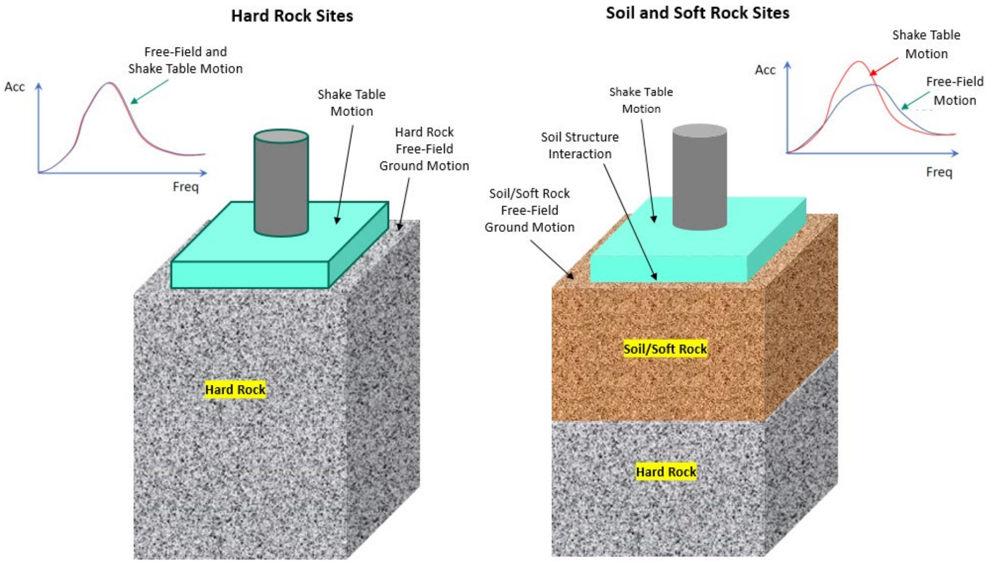

Figure 2. Conceptual Representation of a Dry Storage System Located on Hard Rock and Soft Rock/Soil.

Figure 3. Site Conditions at the CEUS NPP Sites.

Figure 4 shows the depth to bedrock (rock with sheer wave velocity of 3,000 m/s or more) map in the CEUS compiled from the U.S. Geologic Survey (USGS) data. Most sites have deep soil or soft rock, greater than 500 m. The depth of soil or soft rock is an important factor that affects soil-structure interaction.

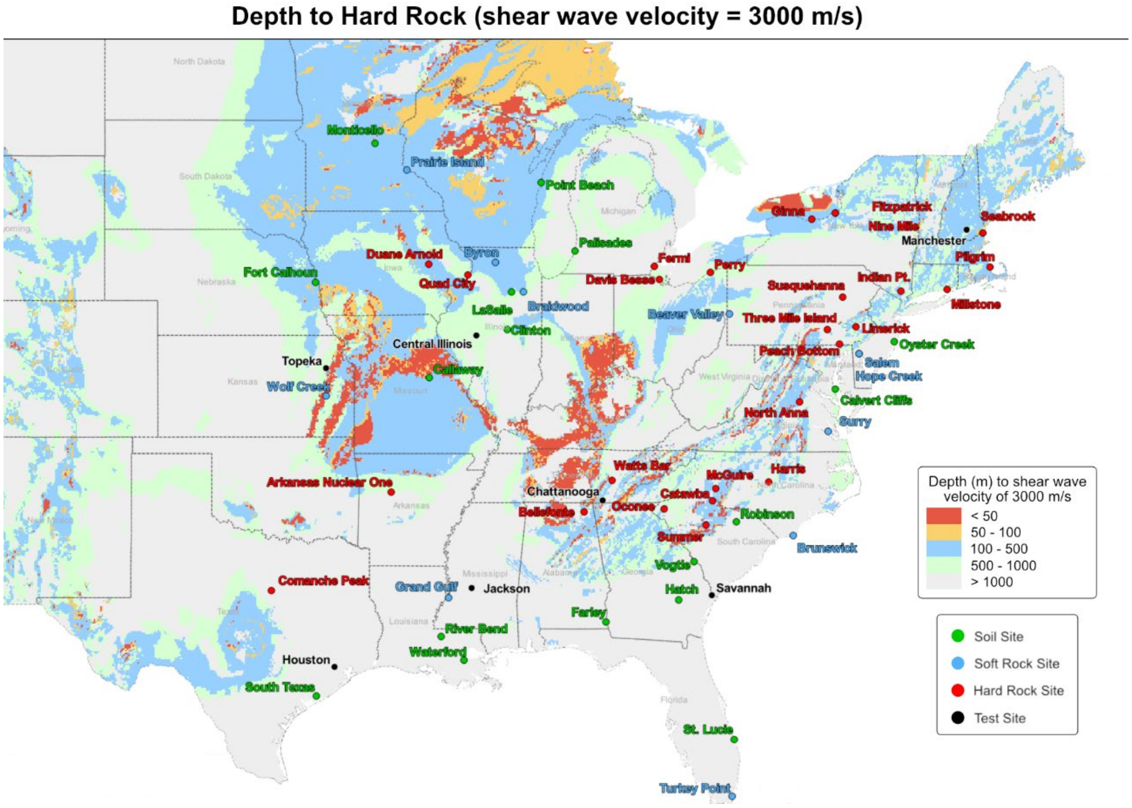

Figure 4. Depth to Bedrock in CEUS.

In developing representative free-field ground motions, an approach taken for the CEUS sites was to leverage a recent extensive study of the CEUS "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities" documented in NUREG-2115, NRC (2012b). The approach for the WUS site was to select 4 representative sites out of 7 NPP sites located in the WUS.

Three scenarios were selected as representative for sites in the CEUS:

- Local event with magnitude **5.5** at **15** km
- Moderate event with magnitude **6.5** at **40** km
- Large magnitude distant event with magnitude **7.8** at **200** km

The median horizontal ground motion spectra were calculated based on the NGA-East Ground Motion Model for a 1E-04 hazard level. The vertical spectral shapes were developed based on an empirical vertical to horizontal (V/H) spectral ratio model, Gülerce and Abrahamson (2011).

Three scenarios were selected as representative for sites in the W**US**:

- Local event with magnitude **6.25** at **10** km
- Large magnitude local event with magnitude **7.5** at **5** km
- Large magnitude distant event with magnitude **7.5** at **200** km

The median horizontal ground motion spectra were calculated based on weighted mean calculated from four NGA-West2 GMMs for a 1E-04 hazard level, Bozorgnia (2014). Scenarios 1 and 2 are applicable to the soft rock sites (Diablo Canyon, Hanford, and others). Scenarios 1 and 3 are applicable to the soil site (Palo Verde). The vertical spectral shapes were developed based on an empirical vertical to horizontal (V/H) spectral ratio model, Gülerce and Abrahamson (2011).

Scaling factors were developed to scale the representative 1E-04 hazard level PGAs to 5E-05 (0.5% exceedance in 100 years) and 5E-04 (5% exceedance in 100 years) hazard levels. The 5E-05 hazard level approximately corresponds to the SSE. Figure 5 shows the statistics of the hard rock site PGAs from the screening reports on the left side. The names of the NPPs are shown for the highest PGAs. The 5E-05 and 5E-04 uniform hazard response spectra (UHRS) level ranges of the PGAs from the response spectra developed for the hard rock sites (3 spectral shapes times 3 earthquake scenarios) are shown on the right side. The PGAs from the developed spectral shapes encompass the PGAs from the screening reports except a few points. These points will be included in the test range.

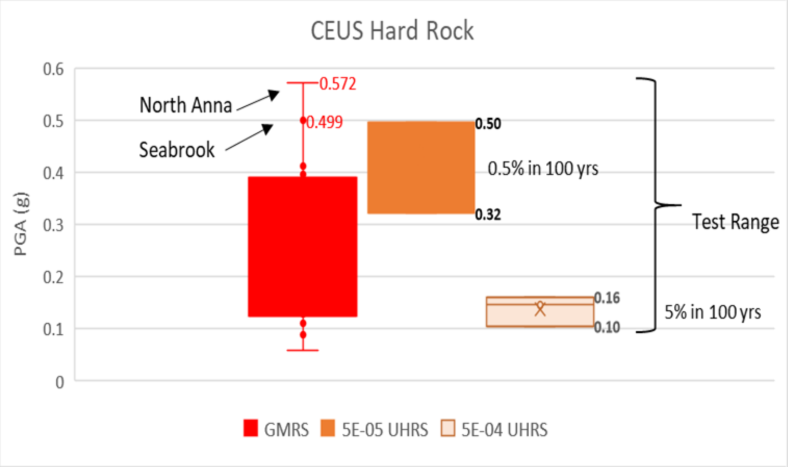

Figure 5. 5E-05 and 5E-04 Hazard Level PGAs Compared to the PGAs from the NPP Screening Reports.

The CEUS hard rock time histories were developed using the candidate seed time histories from the NGA-East2 program database. Seed time histories were matched to the component-specific spectral shapes corresponding to the 1E-04 hazard level. Five time histories were developed for each spectral shape. Scaling factors were used to scale the time histories to 5E-04 and 5E-05 hazard levels. A total of 55 time histories are proposed for the hard rock sites, including the 2 highest PGA cases shown in Figure 5.

The free-field ground motions for soil and soft rock are used as boundary conditions for the SSI and pad flexibility analyses. Two related SMiRT 26 papers, Klymyshin (2022) and Garcia (2022), describe the details of these analyses. The analyses considered:

- All representative earthquake scenarios
- Representative deep soil and soft rock profiles in CEUS and WUS
- 3-4 representative PGAs for each case
- Representative fully and partially loaded pad configurations

The response of the top of the pad is different at different pad locations and also depends on whether the pad is fully loaded or partially loaded with vertical dry storage casks. An example of a representative pad configuration is shown in Figure 6. The modified spectral shapes and corresponding acceleration time histories that include SSI effects at the pad location with the maximum spectral accelerations will be candidates for the test.

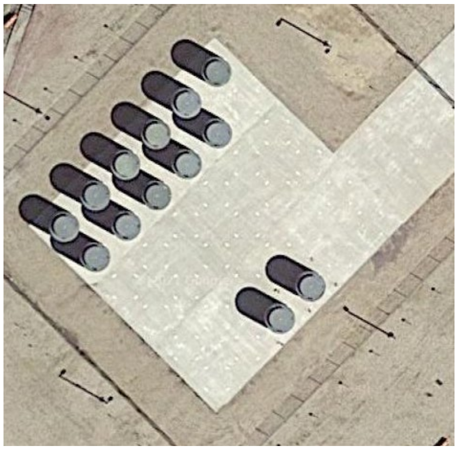

Figure 6. Google Image of a Representative ISFSI Pad with Vertical SNF Dry Storage Casks.

Finally, the hard rock, soft rock, and soil time histories will be analysed to determine whether they can be implemented at the shake table. It is expected that the number of the input time histories in the test series will be around 200.

TEST UNIT

The test unit is a close representation of a vertical full-scale dry storage system of SNF. It consists of:

- NUHOMS 32PTH2 dry storage canister
- Vertical cask (overpack)
- 28 dummy assemblies
- 4 surrogate assemblies

The NUHOMS dry storage canister is an actual dry storage canister that is used to store PWR SNF in horizontal dry storage modules. This specific type has been used by NPPs to store 16x16 SNF assemblies, such as CE or Framatome ones. The canister accommodates 32 assemblies that are placed inside the basket tubes.

For the shake table test the canister will be loaded with 4 surrogate assemblies and 28 dummy assemblies. A surrogate assembly is the closest feasible representation of an actual SNF assembly. It is fabricated using actual SNF assembly hardware, but instead of SNF pellets, the fuel rods are filled with non-radioactive material with a similar density to SNF. The dummy assemblies are concrete filled steel tubes with the cross-section and weight representative of actual assemblies.

Using 4 surrogate assemblies will allow the assessment of the differences related to the assembly type, gap (the distance from the outer assembly surface to the wall), and condition (intact versus slightly damaged spacer grid) and its location in the basket. Two surrogate assemblies will be 16x16 (CE PLUS7 and Framatome) and two will be 17x17 Westinghouse. The 16x16 assemblies will have gap with basket tube ~6.4 mm. The 17x17 assembly will have smaller gap – 2.9 mm.

Twenty-six dummy assemblies will have a cross-section of 207 mm, the same as the 16x16 surrogate assemblies. One dummy assembly will have a cross-section of 210 mm and another one will have a cross-section of 214 mm, the same as the 17x17 surrogate assemblies. Using different cross-sections will allow for evaluating the effects related to the gap.

A dry storage cask is needed to represent a full-scale dry storage system. The cost of acquiring an actual dry storage cask was prohibitive. A simplified vertical concrete cask was designed and manufactured. The cask has outer and inner steel shell and a steel bottom plate (Figure 7). The space between the inner and outer shell is filled with concrete. The dimensions and weight of this cask are very similar to a HI STORM-100. The empty weight of the cask is 234,700 lbs and the loaded weight is 335,952 lbs.

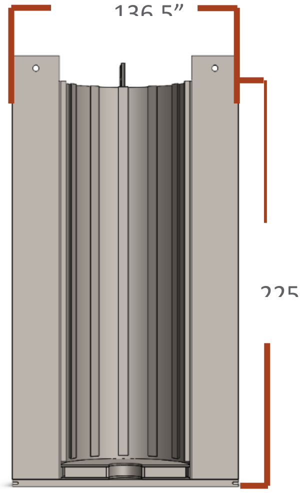

Figure 7. Vertical Concrete Cask Design.

SHAKE TABLE FACILITY

The test will be conducted at the large capacity high-performance outdoor shake table (LHPOST6), at the University of California in San Diego (UCSD). LHPOST6 has the largest payload capacity in the world of 2,040 tonnes and is the only facility in the US that can accommodate the size and weight of the test units.

Figure 8 is a diagram that provides a closeup view of the shake table. Concrete will be poured on the top of the steel table before the test. The concrete surface will have a different finish on the left and right side to provide different friction coefficients to cover the expected friction range of a dry storage pad. Experiments will be conducted with different concrete samples to find concrete finish formulations to achieve the desired steel to concrete friction.

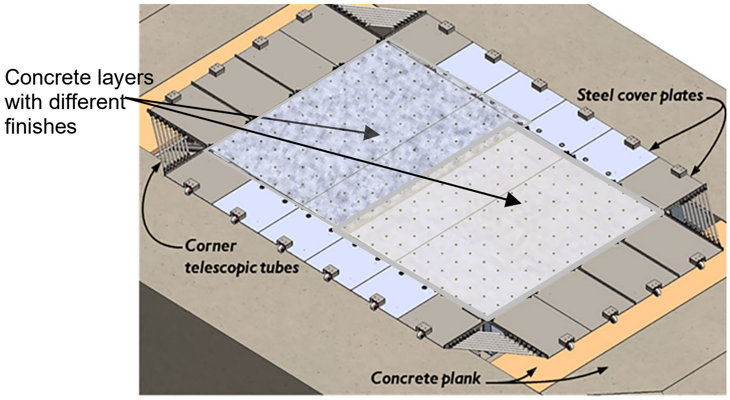

Figure 8. Closeup View of the Shake Table with Concrete Layer.

INSTRUMENTATION

The instrumentation will be guided by the results of the previous experiments and the pre-test modeling. The previous experiments demonstrated that the accelerations on the assembly are very different in different locations in the cask. The accelerations are also different at different locations on the surrogate assembly. The different accelerations result in different strains on the surrogate assembly rods. The test unit will be instrumented with a large number of sensors (accelerometers, strain gauges, and dynamic inclinometers) to capture all the important differences in the responses to the seismic excitations. Table 1provides a summary of the proposed instrumentation. This system will require 288 channels.

Table 1. Instrumentation Summary.

Accelerometers

Instrumented Element	Location	Number of Uniaxial
Dummy Assemblies (28)	Top	(84)
Surrogate Assemblies (4)	tie plate	(12)
Surrogate Assemblies (4)	Rods	32
Canister	Top	(6)
Canister	bottom	(6)
Cask	Top	(6)
Cask	bottom	(6)
Basket	Top	2
Total		**154**

Strain Gauges

Instrumented Element	Location	Number
Surrogate Assembly (4)	Rods	128

Dynamic Inclinometers

Instrumented Element	Location	Number
Canister	Top	2
Cask	Top	2
Shake table	Top	2
Total		**6**

Note: the uniaxial accelerometers shown in parentheses will be assembled in tri-axial blocks (X,Y,Z).

All elements of the system will be instrumented with accelerometers. The cask, canister, basket, and dummy assemblies will be instrumented with uniaxial accelerometers assembled in one X, Y, Z block. Two rods of each surrogate assembly will be instrumented. The proposed locations are within the long spacer grid spans near the top nozzle and bottom nozzle ends. At each location uniaxial accelerometers will be in pairs (0^0 and 90^0) to allow for adequate sampling of the 0^0 and 90^0 components.

The surrogate assemblies will be instrumented with the strain gauges. A number of strain gauges will be installed on the surrogate assembly rods to register the variations of responses as the fuel assembly impacts different faces of the basket wall. Four rods on each surrogate assembly will be instrumented with strain gauges, one in the middle of each assembly face. At each location, the strain gauges will be placed at 0 degrees and 90 degrees to pick up 3-dimensional vibrations. Four locations are proposed on each rod – 3 long spans at the bottom nozzle end and one long span at the top nozzle end. The strain gauges located on the rod instrumented with the accelerometers will be placed next to the accelerometers. The cask, canister, and shake table will be instrumented with the dynamic inclinometers to measure tip angle.

CONCLUSION

The seismic shake table test of the full-scale SNF dry storage system will allow for quantifying the strains and accelerations on the surrogate fuel assemblies during the representative earthquakes scenarios for the Western and Central Eastern U.S. including consideration of ISFISI site conditions (hard rock, soft rock, and soil) and peak ground accelerations. The accelerations and tip angles will be measured on the cask, canister, and basket. High-speed cameras will record the movement of the different elements compared to each other. The data will be collected using ~300 channels. Around 200 time histories will be implemented on each side of the table. The test unit will be exposed to the average ISFISI pad friction coefficient on one side of the table and to a low friction coefficient on the other side. The data collected during the test will allow the determination of seismic loads on the fuel assemblies in dry storage systems. This will be done through analysis of the collected data as well as by finite element modeling. *The authors would like to acknowledge Nick Klymyshyn's (PNNL) team and Julio Garcia's (SC Solutions) team for invaluable support of this work.*

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Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. The SNL review and approval number is SAND2020-11963 A.

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