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Shaker Table Test Plan

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology
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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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SUMMARY

Currently, spent nuclear fuel (SNF) is stored in onsite independent spent fuel storage facilities (ISFSIs), which is a dry storage facility, at 55 nuclear power plant sites [1]. The majority of SNF in dry storage is in welded metal canisters (2,917 canisters at the end of 2019). The canisters are loaded for storage in storage overpacks (vertical casks or horizontal storage modules) and placed on outdoor concrete pads. Because the SNF will be stored at ISFSIs for an extended period of time, there is growing concern with regards to the behavior of the SNF within these dry storage systems during earthquakes. To address these concerns, the SFWST program is considering conducting an earthquake shaker table test. The goal of this test is to determine the strains and accelerations on fuel assembly hardware and cladding during earthquakes of different magnitudes to better quantify the potential damage an earthquake could inflict on spent nuclear fuel rods.

The seismic integrity of the storage system has been addressed in the past by the US Nuclear Regulatory Commission and is not the focus of this potential test. Instead the DOE would benefit from knowing the condition of the fuel cladding from storage, transportation, to disposal so that it can ascertain repository performance for the fuel and packaging in its final state. A seismic event is part of the possible loading events that the fuel could experience in its lifetime.

This report proposes several earthquake shaker table tests with different degrees of complexity. Alternative 1 was defined in the FY20 work scope. Alternatives 2 and 3 were recently developed to take advantage of the NUHOMS 32PTH dry storage canister that may be available in FY21 for this test at a minimum cost to the project. The selection of the alternative(s) will depend on the available budget and the SFWST program priorities for the near future.

Alternative 1: Test with Surrogate Assembly

In this test, the surrogate assembly will be attached to a steel plate for support and placed on a standard shaker table. This alternative will require significant pre-test analysis to determine how the earthquake-induced ground motion can be converted to shaker table inputs to be applied to the surrogate assembly.

Alternative 2: Test with NUHOMS 32PTH Dry Storage Canister

In this test, one surrogate assembly and 31 dummy assemblies will be loaded into a NUHOMS 32PTH canister and placed on a special large capacity shaker table. This alternative will require pre-test analysis to determine how the earthquake-induced ground motion can be converted to the shaker table inputs to be applied to the dry storage canister. The test data will be better than Alternative 1 because it has a full fuel basket and canister. The test data will include valuable data related to fuel assembly and basket interaction.

Alternative 3: Test with Dry Storage Overpack

In this test one surrogate assembly and 31 dummy assemblies will be loaded into a NUHOMS 32PTH canister. The canister will be loaded in a dry storage overpack (vertical and/or horizontal). The overpack will be placed on a special large capacity shaker table. This test will produce the strain and acceleration responses of a surrogate spent fuel assembly when all the components of a dry storage system are subjected to simulated earthquakes of different magnitudes and different spectral content. This option is most expensive, but it provides the most important information because it is a complete system. The test data will include the nonlinear interaction between the fuel assembly, basket, canister, and overpack. The models validated by this data will be the most reliable ones.

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REVISION HISTORY

Revision	Date	Description of Revision
0	09/24/20	Initial Issue

ACRONYMS

DCL	Dynamic Certification Laboratory
DOE	US Department of Energy
ENSA	Equipos Nucleares, S.A., S.M.E.
FY	fiscal year
ISFSI	independent spent fuel storage installation
MMTT	multi modal transportation test
MTU	Metric Tons of Uranium
NAPS	North Anna Power Station
NCT	normal condition of transport
NHERI	national hazards engineering earthquake research infrastructure
NRC	Nuclear Regulatory Commission
PGA	peak ground acceleration
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
SFWST	spent fuel and waste science and technology
SNL	Sandia National Laboratories
SNF	spent nuclear fuel
SONGS	San Onofre Nuclear Generating Station

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SPENT FUEL AND WASTE DISPOSITION
EARTHQUAKE SHAKER TABLE TEST PLAN

1. INTRODUCTION

As of 2020, the US reactor fleet consists of 96 operating reactors with 2 new units under active construction [1]. Twenty-three US reactors have ceased operations and the spent nuclear fuel (SNF) is stored on site. Three of these reactors are located on sites with ongoing nuclear operations. Twenty of these reactors were located on 17 sites with all reactors shutdown. The current SNF inventory stored on sites either in pools or dry storage or both is almost 84,500 MTU [1]. The inventory stored in onsite dry storage facilities (ISFSI) is 39,207 MTU (46% of total). The onsite dry storage inventory is projected to increase by about 3,500 MTU every year until the SNF is transported to a repository. Alternatively, the onsite SNF might be transferred to a consolidated dry storage facility, if such facility (federal or private) is licensed, where it will be stored until a repository becomes available.

91.4% of the SNF inventory in dry storage is in welded metal canisters. There are 2,917 of such dry storage canisters with 122,740 SNF assemblies. The remaining 8.6% is stored in bare fuel casks (8%) and welded metal canisters in transport overpacks (0.6%). The dry storage canisters are placed for storage either in vertical overpacks or horizontal modules as demonstrated in Figure 1-1 (reproduced from [1]). There are 3 major dry storage canister and overpack vendors in the US. As a result, there are a variety of different types of canisters and overpacks.

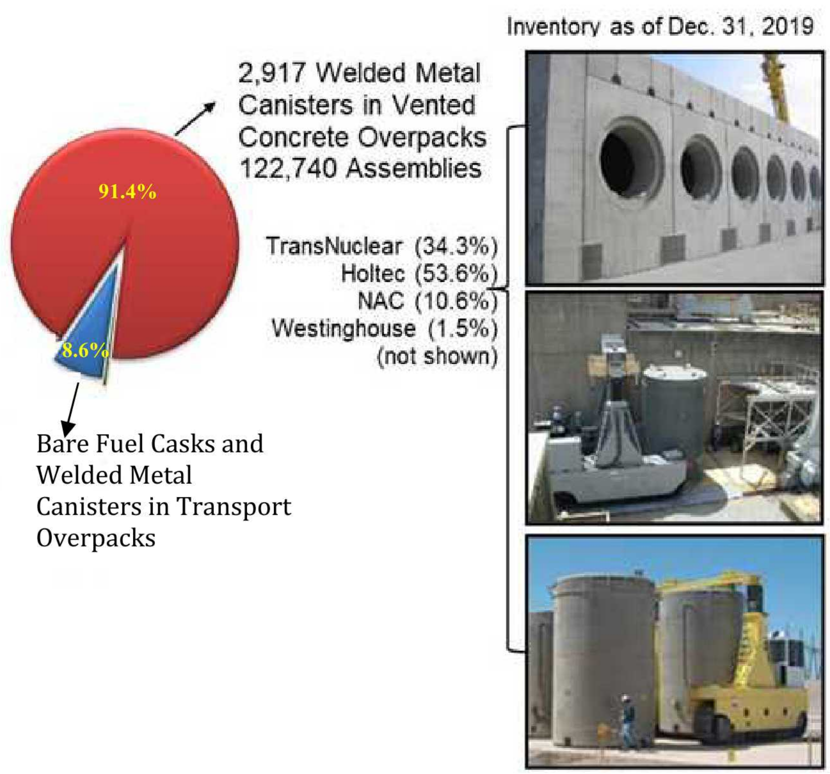


Figure 1-1. Commercial SNF Dry Storage Systems Inventory [1].

Figure 1-2 shows the operating and shutdown reactor sites reproduced from [1]. The reactors sites with onsite dry storage facilities are circled. Figure 1-3 shows the 2008 earthquake hazard map of the

US from the USGS [2]. The hazard values are expressed in percent of peak ground acceleration (PGA). The PGA contours are generated for a 50-year time period. As estimated in [3], there is a potential for a dry storage cask to slide during an earthquake if it is located in red-orange PGA areas. A number of ISFSIs shown in Figure 1-2 are located in red-orange areas shown in Figure 1-3.

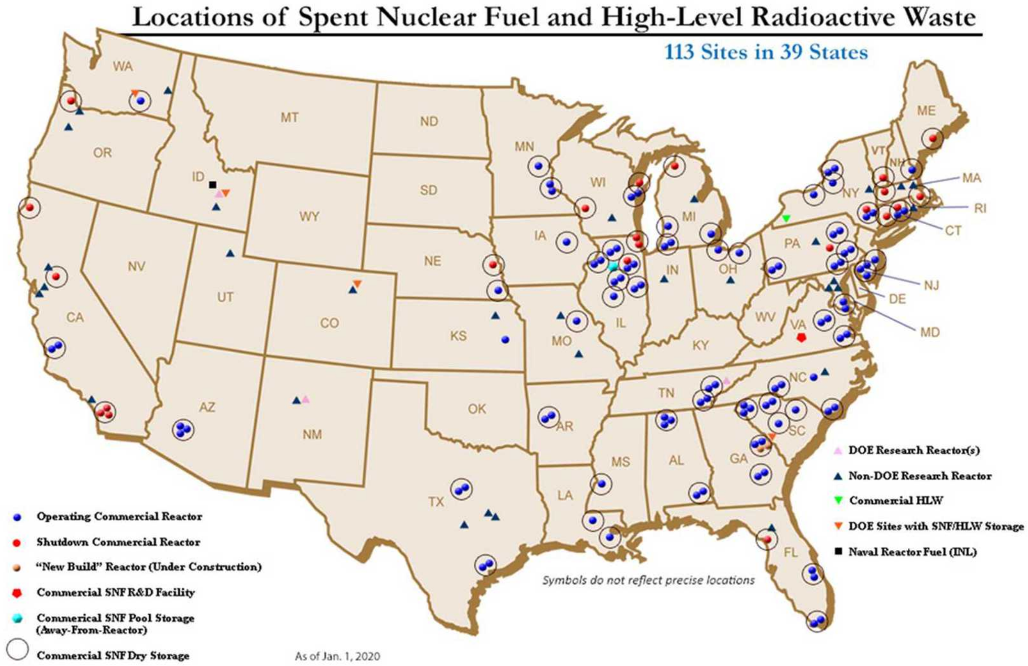


Figure 1-2. Locations of the Commercial Reactor Sites.

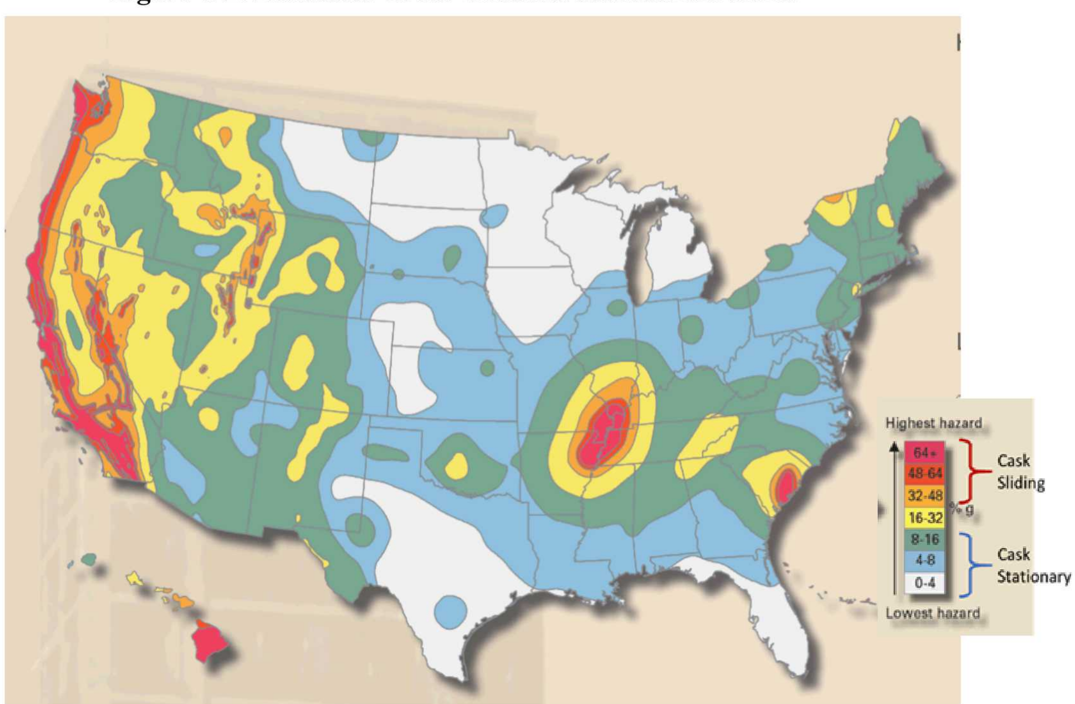
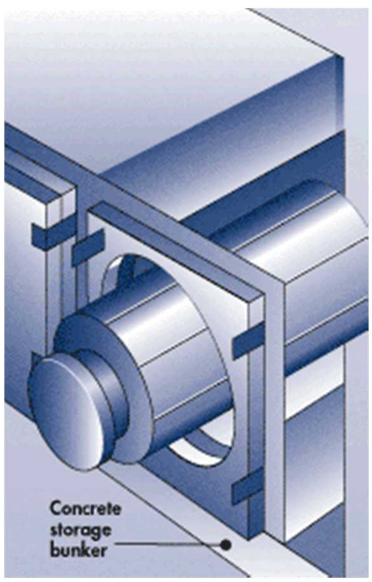


Figure 1-3. 2008 Earthquake Hazard Map [2].

Some vertical dry storage overpacks at the North Anna Power Station (NAPS) moved up to 4.5 inches during the 5.8 magnitude earthquake in 2011. The earthquake epicenter (Mineral, VA) was about 18 km from NAPS. Note that NAPS is located in a green zone in Figure 1-3. Beside sliding, a large magnitude earthquake has the potential to cause rocking, toppling, and cask-to-cask pounding. Because of the potential earthquake hazards, the US Nuclear Regulatory Commission (NRC) requires the licensees to address seismic loads from earthquakes in their ISFSI license applications [4].

The ISFSI licensees use analytical solutions (old license applications) or finite element models to calculate seismic loads on the casks for the design-basis earthquake. The seismic loads on the SNF are not calculated and the integrity of SNF is not addressed. Because the dry storage system is a nonlinear system, the response of SNF cannot be simply obtained from the response of the cask. 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. Figure 1-4 reproduced from [5] illustrates conceptual design of a typical horizontal (left) and vertical (right) dry storage system.



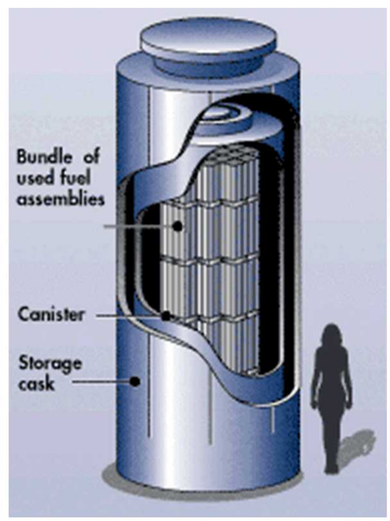


Figure 1-4. Conceptual Design of a Typical Horizontal (left) and Vertical (right) Dry Storage System [5].

The only full-scale experiment that considered all the components of the dry storage system was performed in Japan in 2007 [6]. The test unit consisted of a full-scale concrete cask (simplified model, not an actual cask), dry storage canister, 20 dummy and one surrogate PWR fuel assemblies and a concrete pad. The test was conducted using a three-dimensional shaker table in a 3-D full-scale earthquake testing facility. Two recorded waves during typical natural earthquake and one artificial seismic wave were used as inputs to the shaker table. During the test, sliding up to 0.83 m was observed for the input wave corresponding to an earthquake with horizontal ground motion accelerations of 0.94 g. No sliding was observed for the other input waves which had horizontal ground motion accelerations of 0.25 - 0.6 g.

A series of shaker table experiments on scale-model representations of free standing vertical dry storage systems (a dry storage cask with a canister) are described in the 2016 final NEUP report "*Seismic Performance of Dry Casks Storage for Long-Term Exposure"* [7]. The canister in these tests did not contain fuel assemblies. Instead, additional mass was added to the test units using 16 lead panels. The shaker table inputs in these tests were developed to simulate both near field and far field ground motions. The casks were scaled due to shaker table payload constraints. Two generic cask systems were designed: "a slender cask that is more likely to tip over due to large rocking displacements, and a squat cask that may slide on the concrete pad" [7]. The scaling effects and the generic representation of a cask limit the applicability of the results of this study to an actual vertical dry storage system. This work did not consider horizontal dry storage systems.

To address concerns regarding the behavior of the SNF within dry storage systems during earthquakes, especially one with a large magnitude, the SFWST program is considering conducting a series of shaker table tests. The goal of this test series is to determine the response of fuel assembly hardware and cladding during earthquakes of different magnitudes.

2. RESEARCH IN SUPPORT OF THE SHAKER TABLE TEST

An initial analysis in support of the shaker table test was conducted by PNNL and is documented in an internal white paper [3]. The white paper presents some background information on earthquake hazards and describes initial models and simulation results. It identifies the pre-test work that needs to be advanced before the final test recommendations can be made.

The major input into the shaker table test is the earthquake ground motion. PNNL has started collecting historical earthquake data and has developed an approach to synthesize ground motion data. More work needs to be done to develop a strong technical basis for choosing a range of earthquake magnitudes and ground motions that are relevant to the SFWST program. PNNL proposed to develop analysis methods that is applicable for magnitude 7.0 and greater earthquakes and then determine where the Multi Modal Transportation Test (MMTT) [8 and 9] equivalent, Normal Condition of Transport (NCT) shock and vibration, loading range is. As it was noted in [3], "Initial 1D models of fuel rod response to earthquakes suggests that there is a threshold of earthquake magnitude that is needed to have similar loading to the MMTT". The proposed approach and the related data need to be reviewed by subject matter experts. Only after this work is completed can the inputs to the shaker table test be developed.

PNNL has developed structural dynamic finite element models in support of the shaker table test. The cask structural model simulated the 2011 earthquake at NAPS. The simulation showed "promise in matching the movement of casks on an ISFSI pad". Figure 2-1 reproduced from [3] illustrates the model. The model did not include soil layers. A more detailed model needs to be developed to improve the match between the modeling results and the data. This will help to understand the displacement to be expected in the shaker table test under different earthquake magnitudes.

The response of a vertical SNF storage cask to different types of earthquakes was modeled in [10]. The model of the cask, concrete pad, and soil column beneath the pad reproduced from [10] is shown in Figure 2-2. . Expected displacements of the cask were calculated for different soil types.

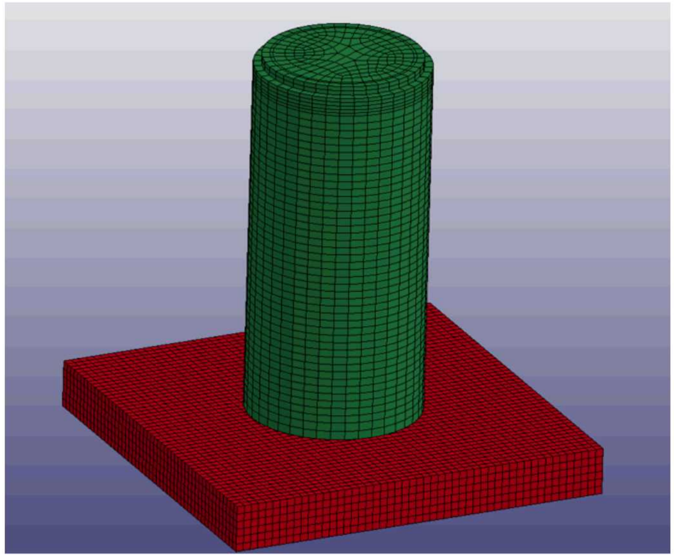
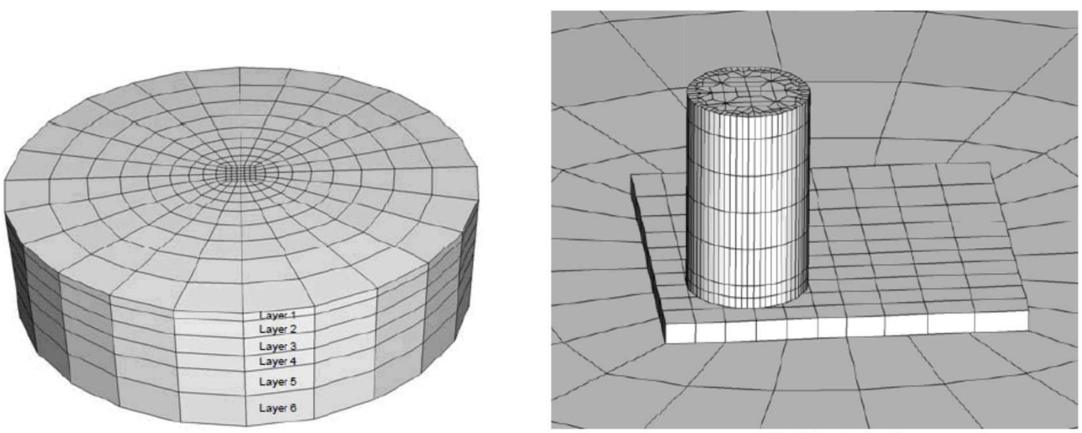


Figure 2-1. Structural Model of the NAPS Vertical SNF Storage Cask from [3].



Soil Column Layers

Figure 2-2. Structural Model of a Vertical SNF Storage Cask from [10].

PNNL has developed 1D models of a fuel rod to evaluate the initial fuel rod cladding response to the recorded ground motion. A 3D model is needed to evaluate a response of the entire fuel assembly. This model will provide insights into the assembly instrumentation in the shaker table test.

In summary, the defensible ground motion inputs and improved cask response and fuel assembly response models need to be generated to inform the development of the shaker table test plan. This work will take place in FY21. As a result, a detailed shaker table test plan will be developed in FY21.

3. PROPOSED ALTERNATIVE SHAKER TABLE TESTS

As discussed in Section 2, the shaker table test plan will be developed in FY21 when the research in support of the test is completed. This report describes several alternative shaker table tests. The selection of the alternative(s) will depend on the available budget and the SFWST program priorities for the near future.

The FY20 work scope for the earthquake shaker table test assumed a test with the surrogate fuel assembly. A new opportunity has arisen since that time. DOE is in the process of potentially obtaining new NUHOMS dry storage canisters from SONGS. DOE will make these canisters available to SNL and PNNL for research. The SNL transportation experiment program has requested a NUHOMS 32PHT canister for the shaker table test. Figure 3-1 shows the NUHOMS horizontal storage module, transfer cask, and NUHOMS 32 PTH dry storage canister reproduced from [11].

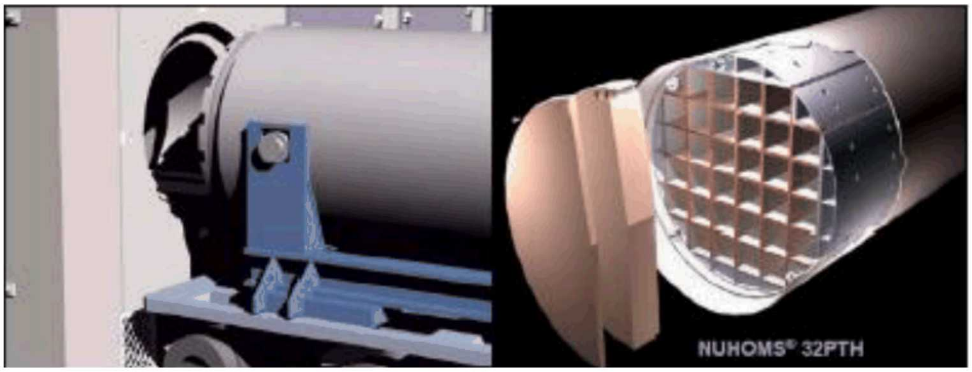


Figure 3-1. NUHOMS Horizontal Storage Module, Transfer Cask, and NUHOMS 32 PTH Dry Storage Canister [11].

The alternative shaker table tests are described below. Alternative 1 is the same as in the FY20 work scope.

Alternative 2 is based on the availability of the NUHOMS 32PTH canister. Alternative 3 is based on the availability of a dry storage cask and/or horizontal storage module.

3.1 Alternative 1: Shaker Table Test with the Surrogate Fuel Assembly

This alternative will require significant pre-test modeling to determine how the earthquake-induced ground motion can be converted to the shaker table input for the surrogate assembly and the platform on which the assembly is placed for the test. Post-test modeling will also be required to relate the response of the assembly in a steel support to the response of a fuel assembly inside a real cask system.

This test option has the least project risk because it is very similar to previous work that has already been done. The gains of this test option are very important to validating the fuel assembly response to earthquake excitation. It will provide an understanding of what is relevant and important in seismic testing and modeling of fuel assemblies under earthquake loading.

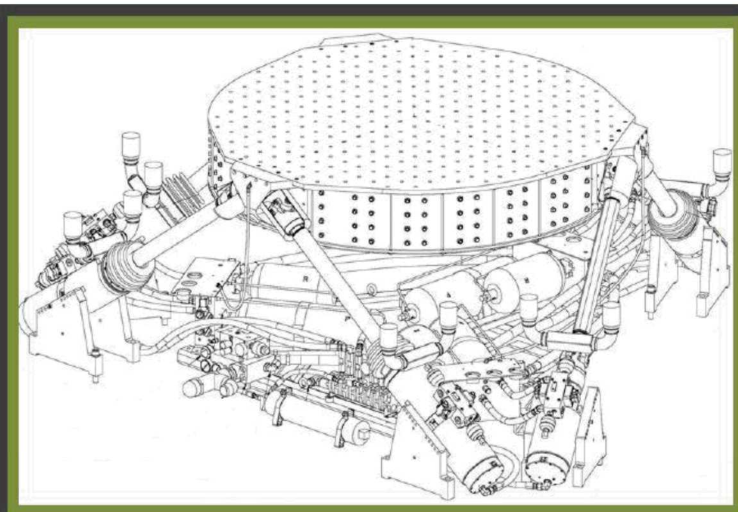
Conducting the test will require purchasing a new 17x17 PWR Westinghouse assembly skeleton. The skeleton can be populated with the rods from the surrogate assembly used in the 30 cm drop test. As discussed in [12], a number of the spacer grids of this assembly buckled during the test, but the rods are in good condition. The nozzles can be re-used as well. The surrogate assembly can be inserted in the same basket tube that was used in the 30 cm drop test.

The test will not require a special facility because the assembly size and weight are suitable for a standard shaker table. However, it may require manufacturing a steel plate on which the assembly is placed for the test because the assembly is much longer than the standard shaker table. The test can be conducted at the

DCL shaker table facility in Reno (Figure 3-2) where the surrogate assembly used in the MMTT was tested in 2015 [13]. The 2015 test setup is shown in Figure 3-3. The DCL hydraulic shaker table is a multi-axis simulation table and it has a frequency range of 1 to 100 Hz, which covers the range of interest (up to 33 Hz) for the earthquake simulations.

The optimal assembly instrumentation will be developed based on PNNL's pre-test modeling.

The assembly will be in a horizontal position during the test. Consequently, the test will best address the horizontal dry storage configuration but can also be used to address fuel response in vertical dry storage configurations.



Multi-Axis Simulation Table (MAST) Specifications

Linear Displacements	Longitudinal, inches (±) Lateral, inches (±) Vertical, inches (±)	5.0 5.0 7.0
Linear Velocities	Longitudinal, in/sec Lateral, in/sec Vertical, in/sec	39.4 39.4 47.2
Linear Accelerations (at 1,500 lb)	Longitudinal, g's Lateral, g's Vertical, g's	10.0 10.0 11.0
Maximum Payload	Pounds	10,000
Maximum Frequency	Hertz	200

Figure 3-2. DCL Multi-Axis Shaker Table Specifications.

Figure 3-3. The 2015 Shaker Table Test Setup [13].

3.2 Alternative 2: Shaker Table Test with Dry Storage Canister

This alternative will require pre=-test modeling work to determine how the ground motion due to earthquake can be converted to the shaker table input on the dry storage canister. Significant post-test analyses will be required because the canister system is incomplete (there is no overpack in this case) but the test data will be better than Alternative 1 because it has a full fuel basket and canister. T

Having the ability to perform this test with a canister is very important because it allows the recording of fuel assembly to fuel basket interaction. In a 30 cm cask drop the momentum of all fuel assemblies was generally moving in the same direction, with some variation based on individual gaps [9]. In a 3D earthquake, there is more uncertainty about how each individual fuel assembly will respond within its basket cell. The test data will include valuable data related to fuel assembly and basket interaction. The model validation data is also superior to Alternative 1 for this reason.

The NUHOMS 32PHT dry storage canister is being transferred by SONGS to DOE and may be available for the shaker table test in the 2nd quarter of FY2021. The cost of these types of canisters is ~$1.5M. It is a great opportunity to have this canister at no cost to the project for many R&D options including shaker table tests.

Figure 3-4 shows a drawing of the NUHOMS 32PTH dry storage canister reproduced from [14]. Table 3-1 provides the canister specifications.

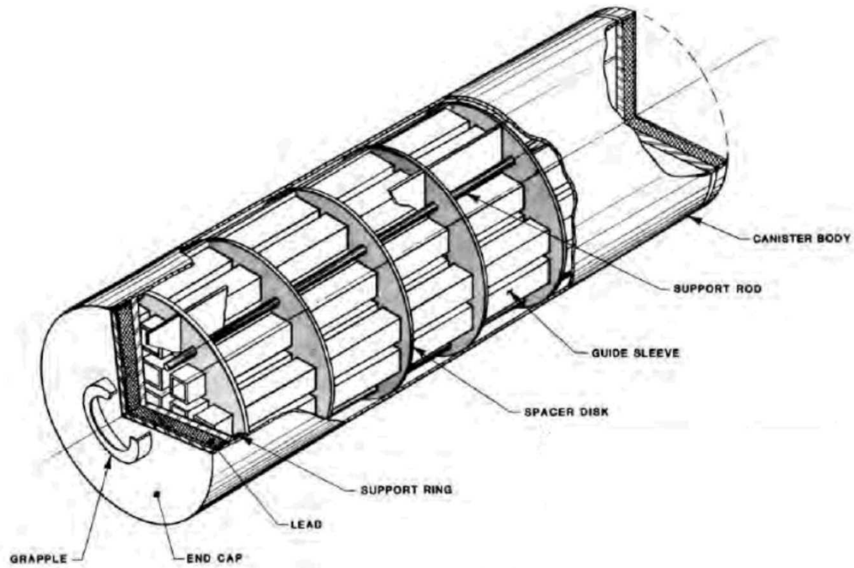


Figure 3-4. Drawing of the NUHOMS 32PTH Dry Storage Canister [14].

Conducting this shaker table test will require 31 dummy assemblies. The 31 dummy concrete assemblies similar to the ones used for the MMTT will be used. The surrogate assembly described in Section 3.1 will be used.

The canister lid will be modified to allow for the instrumentation cables to be pulled from the canister internal cavity.

Table 3-1. Specifications of the NUHOMS 32PTH Dry Storage Canister [14].

Attribute	NUHOMS-32PTH, NUHOMS-32PTH Type 1
a. Capacity (intact assemblies)	32 PWR
b. Weight (lb)	
Empty	58.000
Loaded	108.850
c. Thermal	
Design Heat Rejection (kW)	34.8
Maximum Per Assy Heat Load (kW)	1.2
Maximum Burnup (GWD/MTU)	60
d. Shape	Cylindrical
e. Dimensions (in)	
Overall Length	193.0
Cross Section	69.75
Cavity Length	171.63
Wall Thickness	0.5
f. Materials of Construction	
Canister Body	SS
Basket	SS/B-Al/Boral/MMC
Shield Plugs	Steel
g. Cavity Atmosphere	He
h. Maximum Leak Rate (atm-cm^3/sec)	1 x 10^{-7}
i. Transport Cask	NUHOMS-MP197HB

Both the canister and surrogate assembly will be instrumented. The instrumentation recommendations will be developed based on PNNL's pre-test modeling.

The test will require a special shaker table facility because the canister size (4.9 m height and 1.77 m diameter) and weight (108,850 lbs when loaded) are not suitable for a standard shaker table. One of the candidate facilities is the world's largest outdoor earthquake simulator LHPOST operated by structural engineers at the University of California San Diego [15]. The facility is a part of the Hazards Engineering Earthquake Research Infrastructure (NHERI) program. LPOST is shown in Figure 3-5 reproduced from the NHIERI website.

Figure 3-5. NHIERI LHPOST Outdoor Earthquake Simulator (U.C. San Diego) [15].

Table 3-2 provides the shaker table specifications. The shaker table parameters allow for far-source and near-source earthquake ground motions to be reproduced. A maximum horizontal peak ground and peak table acceleration of just over 1g was selected based on the upper bound for the vast majority of recorded ground motion records.

Table 3-2. LHPOST Outdoor Earthquake Simulator Specifications.

Attribute	Specification
Size	7.6 m x 12.2 m
Peak acceleration: bare table, 400 ton payload	4.2 g, 1.2 g
Peak velocity	1.8 m/s
Stroke	± 0.75 m
Maximum gravity (vertical) payload	20 MN
Force capacity of actuators	6.8 MN
Maximum overturning moment: bare table, 400 ton specimen	35 MN-m, 50 MN-m
Frequency bandwidth	0 - 33 Hz

The LHPOST facility will allow measurements of the canister displacement during the shaker table test. Displacement is possible during strong earthquakes and obtaining the test data are important for bounding the canister responses and for model validation. Figure 3-6, reproduced from the NHIERI website, shows the performance estimate (velocities and displacements) as a function of frequency for the bare table and different loads.

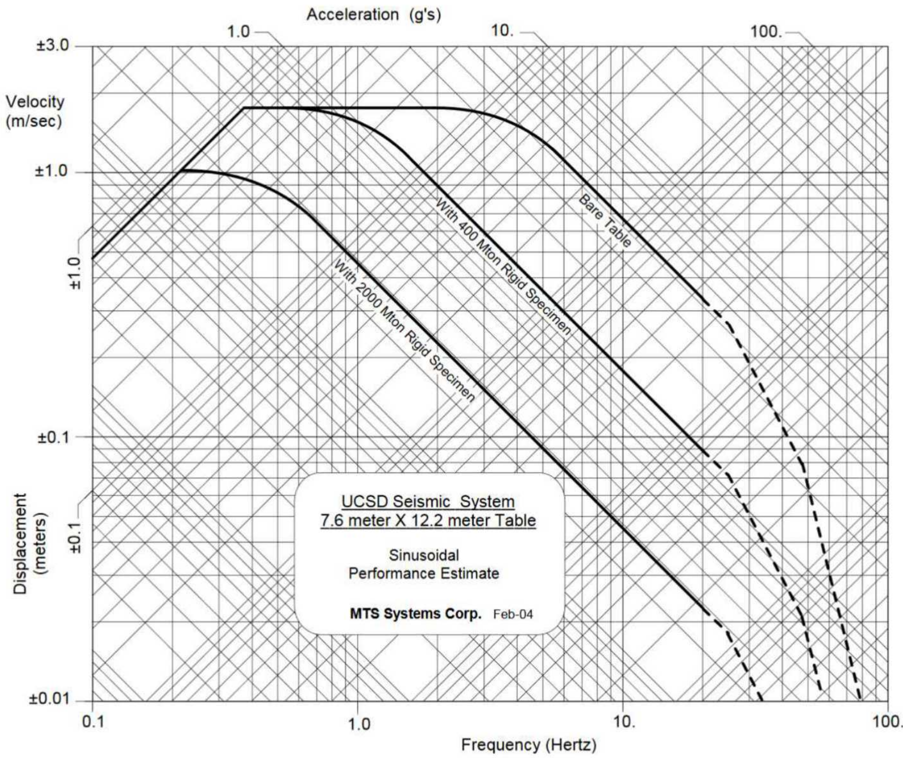


Figure 3-6. LHPOST Outdoor Earthquake Simulator Performance Estimate [15].

The dry storage canister will have to be in a vertical position during the test (Figure 3-7). Consequently, the test will best address the vertical dry storage configuration but can also be used to assess the response of SNF stored in horizontal storage modules to earthquakes.

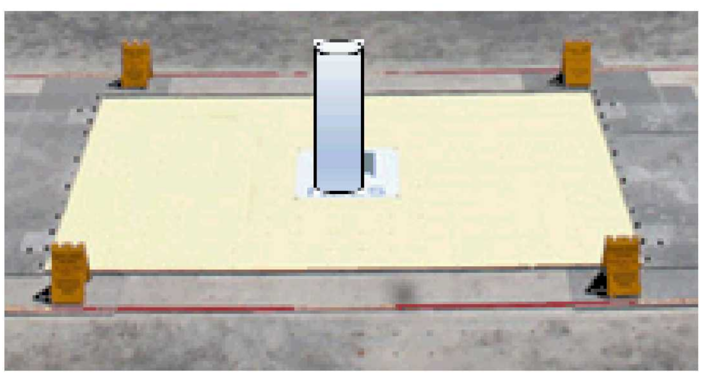


Figure 3-7. Dry Storage Canister Test Unit on the Shaker Table.

3.3 Alternative 3: Shaker Table Test with Dry Storage Cask and Dry Storage Canister

This test will produce the responses of all the components of a dry storage system to simulated earthquakes of different magnitudes and different spectral content. The post-test modeling would be focused on validating the as-modeled configuration so effective modeling methodologies can be established for application to system configurations that were not tested.

The great technical value of this option is that every part of the system can be instrumented to collect data. Having the whole system means that nonlinear interaction between the fuel assembly, basket, canister, and overpack is all captured in the test data. This test is most expensive, but it provides the most important information to the researchers, industry and regulators that cannot be gotten any other way. The models validated by this data will be the most reliable and applying the validated models to estimate the response of other systems to other earthquake conditions (beyond the ones tested) will be the least vulnerable to criticism.

This is the best option because it is a complete system, and all levels of system interaction can be instrumented. This is the best possible option in terms of data collection and model validation.

The test will be conducted with the NUHOMS 32PHT dry storage canister described in Section 3.2, 31 dummy assemblies (Section 3.2), and one surrogate assembly (Section 3.1).

Conducting this test will require purchasing or renting a dry storage overpack. To address both vertical and horizontal storage configurations, it is desirable to acquire a vertical cask and a horizontal dry storage module.

Note that the NUHOMS 32PHT canister is designed for storage in a NUHOMS horizontal storage module. To conduct the test in a vertical configuration, a vertical cask must be suitable to accommodate the NUHOMS 32PTH canister.

One option would be to use a NAC MAGNASTOR dry storage cask. The cask drawing reproduced from [14] is shown in Figure 3-8. The cask specifications are provided in Table 3-3.

The MAGNASTOR cask is designed for the MAGNASTOR transportable storage canisters. The PWR canister is 4.69 m in height, 1.77 m in diameter, and weighs 102,500 lbs. Consequently, the NUHOMS 32PTH canister is a close proxy (4.9 m in height, 1.77 m in diameter, and weighs 108,850 lbs). The MAGNASTOR casks are not transportable and the cask will have to be built by NAC on site.

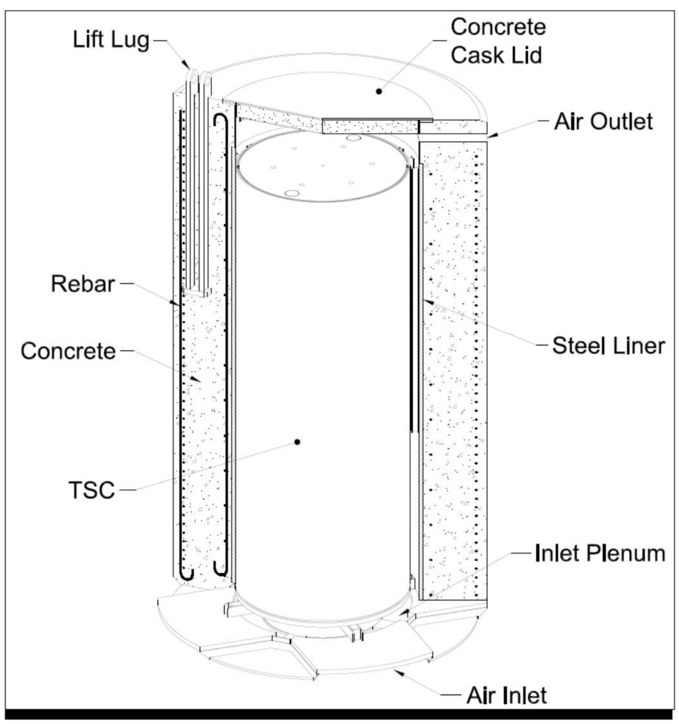


Figure 3-8. NAC MAGNASTOR Dry Storage Cask Drawing [14].

Table 3-3. NAC MAGNASTOR Dry Storage Cask Specifications [14].

Attribute	Vertical Concrete Cask
a. Capacity (TSC)	1
b. Weight (lb)	
Empty	219,000
Loaded (PWR/BWR)	321,500/322,500
c. Shape	Cylindrical
d. Dimensions (in)	
Overall Length	≤ 225.3
Overall Cross Section	136
Cavity Cross Section	79.5
Wall Thickness	28.25
Lid Thickness	6.75
e. Materials of Construction	
Cask Body	Concrete
Lid	Concrete/CS
f. Outside Surface Dose, Side (mrem/hr)	N/A

Another option would be to use a HOLTEC HI-STORM 100 vertical dry storage cask. The cask drawing reproduced from [14] is shown in Figure 3-9. The cask specifications are provided in Table 3-4.

The HI-STORM 100 is designed for HOLTEC MPC canisters. The MPC32 PWR canister is 4.83 m in height and 1.74 m in diameter with 90,000 lbs weight. Consequently, the NUHOMS 32PTH canister is a close proxy with regard to its size, but somewhat heavier (108,850 lbs) than a loaded MPC32 canister. The HI-STORM 100 cask can likely be transported to the test site. However, the transportation logistics can be complex because of the cask dimensions and weight.

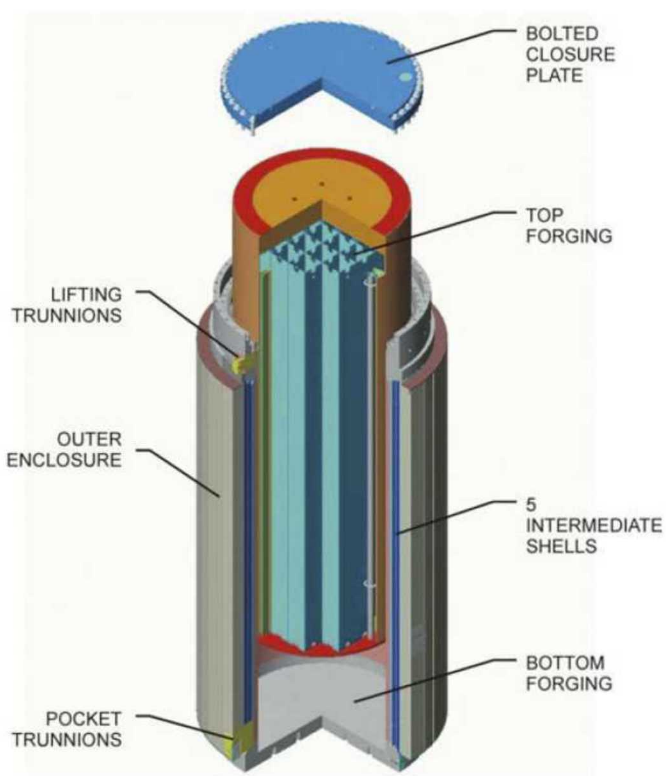


Figure 3-9. HOLTEC HI-STORM 100 Storage and Transportation Cask Drawing [13].

Table 3-4. HOLTEC HI-STORM 100 Storage and Transportation Cask Specifications [14].

Attribute	HI-STORM 100S Vertical Steel/Concrete/Steel Cask
a. Capacity (MPC)	1
b. Weight (lb) (150 pcf concrete)	
Empty	270,000
Loaded w/MPC-24	360,000
Loaded w/MPC-24E, -24EF	360,000
Loaded w/MPC-32, -32F	360,000
Loaded w/MPC-68, -68F, -68FF	360,000
c. Shape	Cylindrical
d. Dimensions (in)	
Overall Length (Reference)	231.25
Overall Cross Section	132.5
Cavity Length (Reference)	191.5 or 203.0
Cavity Cross Section	73.5
Wall Thickness	29.5
Lid Thickness	22.25
Bottom Thickness	19.0
e. Neutron Shield (in)	
Side Thickness	n/a
Lid Thickness	n/a
Bottom Thickness	n/a
f. Materials of Construction	
Cask Body	CS/Concrete
Neutron Shield	Concrete/CS
g. Outside Surface Dose (mrem/hr)	Varies
h. Maximum Leak Rate (atm-cm^3/sec)	Per MPC

The possibility of obtaining a NUHOMS horizontal storage module is under consideration. SONGS has recently offered to transfer 3 horizontal storage modules to DOE. One of them was requested by the transportation experiment program for the earthquake shaker table test.

The cask (horizontal dry storage module) lid will have to be modified to pull out the instrumentation cables from the inside of the overpack unless the instrumentation leads can be routed through the cask vents.

The storage overpack (vertical or horizontal), dry storage canister and surrogate assembly will be instrumented. The instrumentation recommendations will be developed based on the pre-test modeling.

The test can be conducted at the LHPOST facility because the test unit dimensions and weight meet the facility requirements. It will be possible to measure the dry storage system displacement during the shaker table test.

4. CONCLUSIONS

At the end of 2019, the spent nuclear fuel (SNF) inventory in dry storage reached 39,207 MTU. Currently, the SNF is stored in onsite dry storage facilities (ISFSIs) at 55 nuclear power plant sites [1]. Only four operating sites do not have ISFSIs. An ISFSI in most cases is an onsite outdoor concrete pad holding multiple dry storage overpacks. The majority of the current dry storage inventory (91.4%) is in

2,917 welded metal canisters containing 122,740 SNF assemblies. The canisters are placed for storage in storage overpacks (vertical casks or horizontal storage modules).

The onsite dry storage inventory is projected to increase by about 3,500 MTU every year. Because the SNF will be stored at ISFSIs for an extended period of time, there is growing concern regarding the behavior of the SNF inside dry storage systems during earthquakes, especially those of large magnitude. To address these concerns, the SFWST program is considering conducting an earthquake shaker table test series. The goal of this test series is to determine the response of fuel assembly hardware and cladding during earthquakes of different magnitudes.

The seismic integrity of the storage system has been addressed in the past by the US Nuclear Regulatory Commission and is not the focus of this potential test. Instead the DOE would benefit from knowing the condition of the fuel cladding from storage, transportation, to disposal so that it can ascertain repository performance for the fuel and packaging in its final state. A seismic event is part of the possible loading events that the fuel could experience in its lifetime.

Initial research in support of the earthquake shaker table test was conducted by PNNL in FY20 and is documented in an internal white paper [3]. In FY21 this research will continue to develop defensible ground motion inputs and to implement improved cask fuel assembly finite element models needed to inform the development of the shaker table test plan.

This report describes the alternative shaker table tests. The selection of the alternative(s) will depend on the available budget and the SFWST program priorities for the near future.

The FY20 work scope for the earthquake shaker table test had planned the test with the surrogate fuel assembly, but a new development has recently taken place. The SNL transportation experiment program expects to receive a new NUHOMS 32PHT canister from SONGS (vendor's price ~$1.5M) at no cost to the project. This provides an opportunity to conduct the earthquake shaker table test with an actual dry storage canister without significant increase in the test cost. As a result, two additional alternatives (Alternatives 2 and 3) were developed. The original FY20 test remains as Alternative 1.

Conducting the earthquake shaker table tests with an actual dry storage system is very important because the dry storage system is a non-linear system. The response of SNF to seismic loads is different from the responses of the canister and dry storage overpack. 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 only known shaker table experiment with a full-scale dry storage system was performed in Japan [6]. They used a simplified model (not an actual canister) of a 24 PWR canister and vertical overpack. They only considered 2 historical earthquakes – El Cento and JMA Kobe. The results of this experiment may have limited application to the dry storage system and seismic conditions in the US. Scale-model shaker table experiments with simulated freestanding dry storage systems have also studied the behavior of the different cask models under the near field and far field ground motions[7]. These test results cannot be used directly to determine the response of the SNF because the cask models did not contain fuel assemblies.

The summary of the proposed earthquake shaker table test alternatives is provided below. Table 4-1 compares the different alternatives with regard to the hardware, shaker table facility, and relative costs.

Alternative 1: Test with Surrogate Assembly

In this test the surrogate assembly will be attached to a steel plate for support and placed on a standard shaker table, such as the one at the DCL shaker table facility in Reno (NV).

This alternative will require significant pre-test analysis to determine how the simulated earthquake-induced ground motion can be converted to the shaker table input to be applied to the surrogate assembly. The assembly will be in a horizontal position during the test. Consequently, the test will best address the horizontal dry storage configuration but will also inform SNF response in vertical dry storage configurations.

Alternative 2: Test with NUHOMS 32PTH Dry Storage Canister

In this test one surrogate assembly and 31 dummy assemblies will be loaded in a NUHOMS 32PTH canister and placed on a special large capacity shaker table, such as the one at the LHPOST shaker table facility in San Diego (CA).

This alternative will require some modeling work to determine how the simulated earthquake-induced ground motion can be converted to the shaker table input to be applied to the dry storage canister. The dry storage canister must be in vertical position during the test. Consequently, the test will best address the vertical dry storage configuration but will also inform SNF response in horizontal dry storage configurations.

The test data will be better than Alternative 1 because it has a full fuel basket and canister. The test data will include valuable data related to fuel assembly and basket interaction.

Alternative 3: Test with Dry Storage Overpack

In this test, one surrogate assembly and 31 dummy assemblies will be loaded in a NUHOMS 32PTH canister. The canister will be loaded in a dry storage overpack (vertical and/or horizontal). The overpack will be placed on a special large capacity shaker table, such as the one as the LHPOST shaker table facility in San Diego (CA).

This test will obtain responses of all the components of a dry storage system to simulated earthquakes of different magnitudes and different spectral content. If both vertical cask and horizontal storage module are available, this test will address vertical and horizontal dry storage configurations.

This option is most expensive, but it provides the most important information because it is a complete system. The test data will include the nonlinear interaction between the fuel assembly, basket, canister, and overpack. The models validated by this data will be the most reliable ones.

Figure 4-1 shows the relative costs of Alternatives 2 and 3 compared to the cost of Alternative 1. The approximate costs of the Alternative 1 were estimated based on the previous experience of a shaker table test with the surrogate assembly at DCL shaker table facility [13]. The costs of Alternatives 2 and 3 are largely based on best guesses. The costs of Alternatives 2 and 3 were normalized (divided by the corresponding costs of Alternative 1).

Table 4-1. Shaker Table Test Summary.

Shaker Table Test	Surrogate Assembly Alternative 1	Dry Storage Canister Alternative 2	Dry Storage Overpack Alternative 3
Hardware			
One Surrogate Assembly	X	X	X
Basket tube	X	-	-
Supporting plate	X	-	-
31 Dummy Assemblies	-	X	X
NUHOMS 32PTH Dry Storage Canister	-	X	X
Dry Storage Overpack (vertical, horizontal or both)	-	-	X
Facility			
DCL (Reno, NV) or comparable	X	-	-
LHPOST (San Diego, CA) or comparable	-	X	X
Relative Costs			
Hardware	1	3	13
Instrumentation	1	1.4	2
Transportation	1	11	11
Shaker Table Facility	1	6	6

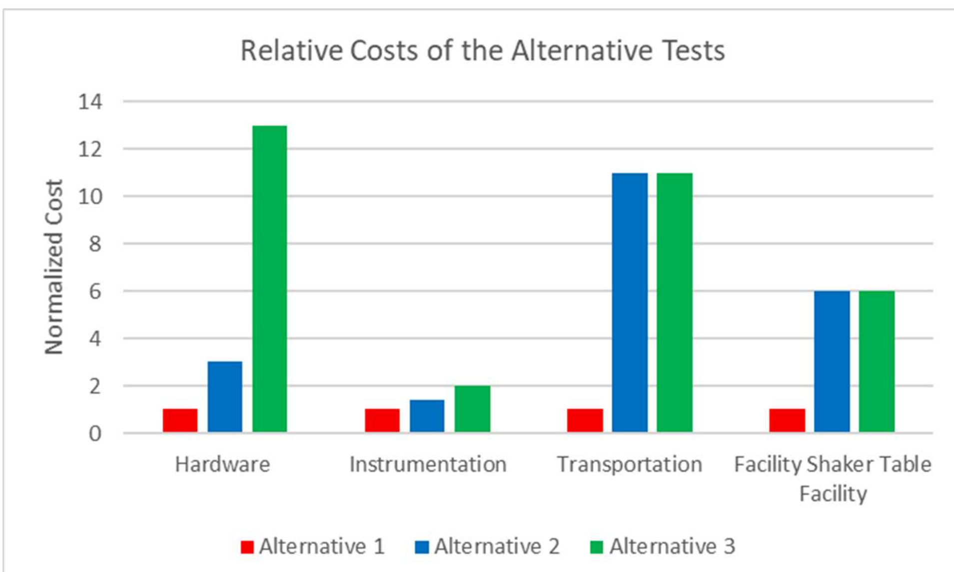


Figure 4-1. Relative Costs of the Different Shaker Table Test Alternatives.

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