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Sandia National Laboratories

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Abstract

One of the high priority issues for the continuous operation of nuclear power plants is how to manage and store spent fuel. In recent years, dry storage of spent fuel above ground has become a de facto fuel "repository" solution worldwide. Arrays of dry cask storage systems have been installed at Independent Spent Fuel Storage Installations (ISFSI) at many nuclear power plant sites. Most of these storage systems are freestanding, leading to stability concerns in terms of potential excessive sliding displacements and tipping over in an earthquake event. Sandia National Laboratories has been contracted by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC) to conduct a research project to develop a comprehensive methodology for evaluating the nonlinear seismic behavior of these storage systems. The main objective of this effort is to perform parametric analyses to characterize the sensitivity of the cask response to a number of important input parameters, which provides a guideline to the range of applicability of analysis results. The results from these parametric analyses have been compiled in nomograms to facilitate the safety review of licensing applications by the staff at the Office of the Nuclear Material Safety and Safeguards (NMSS). This report documents the details of analysis models and all parametric analysis findings.

In this research effort, the cask response is investigated using the finite element method with explicit time integration. The ABAQUS/Explicit code is used to analyze three-dimensional coupled models consisting of a freestanding cask, a concrete pad, and a soil/rock foundation interacting with frictional contact at interfaces. This modeling approach allows a realistic simulation of soil-structure interaction effects and the nonlinear cask behavior after the onset of cask rocking or rolling motion due to applied ground motions. The earthquake ground motions applied to the model are derived from actual recorded ground motions, fitted to conform to selected spectral shapes, and adjusted using a deconvolution procedure that enables the ground motion to be applied at the base of the foundation model.

Prior to performing parametric analyses, the coupled finite element models were developed for three site-specific analyses including three-module rectangular Transnuclear West module/cask, and HI-STORM 100 casks at Hatch Nuclear Power Station and at Private Fuel Storage Facility. The lessons learned from the site-specific analyses help guide performing the much broader based parametric analyses.

The parametric analyses involve two cask system designs: the horizontal rectangular module with an aspect ration of 0.58 defined as ½ the shorter width divided by the height of the center of gravity from the base and the vertical cylindrical cask with an aspect ratio of 0.56 defined as ½ the base diameter divided by the height of the center of gravity from the base. The seismic behavior of these cask designs was investigated with three different foundation types (soft soil, stiff soil, and rock) and three coefficients of friction (0.20, 0.55, and 0.80) at the cask/pad interface. Three spectral shapes (Regulatory Guide 1.60, NUREG/CR-0098, and NUREG/CR-6728) were selected, and for each of these spectral shapes, five different earthquake ground motion records were chosen. These ground motion records were linearly scaled to result in surface peak ground accelerations (PGA) ranging from 0.25 to 1.25 g. A total of 1165 analysis cases were performed in this investigation.

Nomograms of median cask responses +/- one standard deviation of maximum cask top sliding displacements and angular rotations versus peak ground accelerations are plotted at a 5% damped 1 Hertz frequency (1 second period) of pseudo spectral acceleration (PSA) after compiling from the pool of parametric analysis results. These nomograms may provide a meaningful and practical tool to cask designers and reviewers in interpreting the seismic behavior of dry cask storage systems.

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Foreword

The U.S. Nuclear Regulatory Commission (NRC) regulates the operation of the Nation's 104 nuclear power plants by establishing regulatory requirements and issuing permits and licenses for plant design, construction, and operation. Many of the Nation's existing plants have operated for a few decades, and the spent nuclear fuel generated by these plants must be stored in a manner that adequately protects the health and safety of the public and the environment. Dry storage of spent fuel above ground is an accepted "repository" alternative through independent spent fuel storage installations (ISFSI), which the NRC licenses under Title 10, Part 72, of the *Code of Federal Regulations* (10 CFR Part 72).

The Engineering Research Applications Branch in the NRC's Office of Nuclear Regulatory Research contracted with Sandia National Laboratories (SNL) to investigate the seismic behavior of freestanding dry cask storage systems containing spent nuclear fuel. The primary objective of this research is to characterize the sensitivity of cask response to an earthquake. Toward that end, SNL developed analytical methods that focus on the important parameters that would affect the seismic behavior of dry cask storage systems. These parameters include seismic ground motion, soil properties, cask design, and coefficients of friction between the cask and the concrete pad on which the cask is freely standing. SNL conducted extensive analyses to determine the behavior of casks under a variety of conditions such as earthquakes of various intensities, and different soil foundations (e.g., soft soil, stiff soil, hard rock).

This report provides insight into important design parameters that could affect cask stability, relative stability of cask geometry (shape and dimension), and the expected behavior of casks in terms of potential tipping and sliding under seismic conditions. In addition, this report provides tools for the NRC staff to use in safety reviews of future licensing applications for dry cask storage systems.

Carl J. Paperiello, Director
Office of Nuclear Regulatory Research
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Executive Summary

The Spent Fuel Project Office (SFPO) in the Office of the Nuclear Material Safety and Safeguards (NMSS) at the Nuclear Regulatory Commission (NRC) is involved in investigating technical issues concerning the dry storage and transportation of spent nuclear fuel. Sandia National Laboratories (SNL) was contracted by the Engineering Research Applications Branch, Office of Nuclear Regulatory Research (RES) at the NRC for investigating the seismic behavior of dry cask storage systems (DCSS) to provide technical support in revising review guidelines. The results of this research are expected to aid the NMSS staff in performing the safety review of licensing applications of DCSSs.

Arrays of DCSSs have been installed at Independent Spent Fuel Storage Installations (ISFSI), licensed under 10 CFR Part 72, at many nuclear power plant sites. Most of these storage casks are freestanding on a concrete pad, leading to concerns of possible tipping over and collision with neighboring casks in an earthquake event. Therefore, in the safety review process of these cask systems, it is important to assess their dynamic response in terms of sliding displacements, rotations, and the integrity of cask internals under seismic loads.

The main objective of the research effort is to perform parametric analyses to characterize the sensitivity of the cask response to a number of important input parameters including cask designs, earthquake ground motions, soil conditions, and coefficients of friction at the cask/pad interface. A well-defined set of parametric analyses has been performed to provide results in nomograms to facilitate the safety review of licensing applications by the NMSS staff. This report documents the analysis methodology, the details of input parameters, and all parametric analysis findings.

In this project, the dynamic response of a freestanding cask system is investigated using the finite element method with explicit time integration. The ABAQUS/Explicit code is used to analyze three-dimensional coupled models consisting of a freestanding cask, a concrete pad, and a soil/rock foundation interacting with nonlinear friction contacts at interfaces. This coupled modeling approach provides a realistic simulation for soil-structure interaction effects and nonlinear cask responses after the cask starts to rock or precess due to applied ground motions. The earthquake ground motions applied to the model are derived from actual recorded ground motions, fitted to conform to selected spectral shapes, and adjusted using a deconvolution procedure that enables the ground motion to be applied at the base of the foundation model.

Three site-specific analyses were performed using the coupled models prior to conducting the parametric analyses. These site-specific analyses include the three-module rectangular Transnuclear West module/cask, and HI-STORM 100 casks at Hatch Nuclear Power Station and at Private Fuel Storage Facility. The lessons learned from the site-specific analyses help guide performing the much broader based parametric analyses. For the parametric analyses, a horizontal rectangular module and a vertical cylindrical cask are the two cask designs selected for investigation. The cask designs are characterized by the aspect ratio that is defined as ½ the base diameter (for a cylindrical cask) or ½ the shorter width (for a rectangular module) divided by the height of the center of gravity from the base. In the parametric study, an aspect ratio of 0.56 was used for the cylindrical cask and 0.58 for the rectangular module.

The selected ground motions are governed by three spectral shapes in NUREG/CR-0098, Regulatory Guide 1.60, and NUREG/CR-6728, and five different earthquake ground motion records were chosen for each of these spectral shapes. The five selected earthquake records for the WUS (western United States) sites appropriate for the NUREG/CR-0098 and the Regulatory Guide 1.60 spectral shapes are:

1) 1978 Iran Tabas
2) 1999 Taiwan Chi-Chi
3) 1992 Landers
4) 1994 Northridge
5) 1979 Imperial Valley

Likewise, five different earthquake records for the CEUS (central and eastern United States) sites appropriate for the NUREG/CR-6728 spectral shape were also selected:

A) 1985 Nahanni
B) 1988 Saguenay
C) 1979 Imperial Valley
D) 1989 Loma Prieta
E) 1994 Northridge

These ground motion records were linearly scaled to result in surface peak ground accelerations (PGA) ranging from 0.25 to 1.25 g. Furthermore, the parametric analyses involve three different foundation types (soft soil, stiff soil, and rock) and three coefficients of friction (0.20, 0.55, and 0.80) at the cask/pad interface. In total, 1165 analysis cases were performed in the parametric evaluation.

The parametric analysis results documented the maximum sliding displacements at the cask top and the maximum angle of cask rotation with respect to the vertical axis. In all cases for the two cask designs under investigation, the DCSS is more susceptible to rolling/rocking motions with cases of high coefficients of friction at the cask/pad interface, and it experiences higher sliding displacements with low interfacial coefficients of friction. The horizontal rectangular module is more seismically stable than the vertical cylindrical cask because the geometry of the rectangular module allows only rocking and sliding, while the cylindrical cask can exhibit rolling about the base edge in addition to rocking and sliding. The cask response can be significantly higher in this rolling mode than in the rocking and sliding mode only.

The parametric analysis results are affected by the dynamic coupling between the DCSS and the foundation due to the soil-structure interaction. It has been demonstrated that directly beneath the pad, the ground motion at the soil surface is significantly affected by the interaction of the soil with the cask and pad. At points on the surface far away from the pad, the ground motions almost duplicate the prescribed input ground motions. These findings indicate that a reasonable modeling procedure has been developed for simulating a semi-infinite foundation using a finite model with appropriate boundary conditions and for performing deconvolution analyses of surface-defined ground motions by preserving their dynamic characteristics of amplitudes and frequency contents.

A large amount of scatter was observed in the analytical responses of the freestanding casks. This scatter is attributed to the fact that the cask is not anchored to the pad. The cask response is highly sensitive to the phasing of the cask motion with respect to the ground motion. Because of this scatter, it is not advisable to base design decisions on isolated analysis results. Instead, these decisions should be based on the statistics from a large number of analyses conducted under a variety of conditions. Regression analysis was employed to condense the analysis results obtained in this study into a usable form. Nomograms in the form of equations that describe the median response, as well as equations for 84% and 16% (median plus and minus one standard deviation, respectively) confidence bands have been developed from the analysis results. These nomograms have been developed for the peak lateral cask displacement magnitude relative to the pad and angular rotation of the cask for the three spectral shapes and the three cask/pad interfacial coefficients of friction.

The peak ground acceleration (PGA), or zero period spectral acceleration, is used extensively in this work as a parameter to describe the ground motion intensity, but this parameter is only useful when associated with a spectral shape. The cask response is more sensitive to the spectral content at lower frequencies than to the PGA. If the design ground motion at a specific site conforms to one of the three spectral shapes used in this study, the nomograms developed for that spectral shape can be used directly for evaluation of that design. However, it is also desirable to develop a procedure to apply these results to other spectral shapes. The results from the three spectral shapes were plotted together, and regression analysis was performed using a number of different parameters to describe the ground motion intensity. These parameters included the pseudo-spectral acceleration (PSA) at a number of frequencies and the peak ground velocity (PGV).

It was found that the PSA at 5% damped 1 Hertz (Hz) and the PGV are both reasonable parameters to describe the cask response, regardless of the spectral shape. The PGV, which is not a direct function of the spectral shape, is influenced by the spectral accelerations across the middle of the spectrum in the period range likely to be important to the cask response. The fitting of the results was slightly better with the 1 Hz PSA as the ground motion parameter than with the PGV. Because of this observation and the fact that the 1 Hz PSA can be directly tied to the design spectrum, it is recommended that the 1 Hz PSA be used as a ground motion parameter if it is desired to apply these results to other spectral shapes. In conclusion, nomograms in terms of 1 Hz PSA have been provided in this report in addition to those for specific spectral shapes.

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Representing NRC interests:

- S. Khalid Shaukat, Goutam Bagchi, Mahendra Shah, and Bhasker Tripathi (NRC)
- Yusef R. Rashid (ANATECH Corporation)

Representing industry interests:

- Robert Kassawara (EPRI), Robert Kennedy (RPK Structural Mechanics), Donald Moore (Southern Company), and Torrey Yee (Southern California Edison)

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Acronyms

CEUS	central and eastern United States
CG	center of gravity
DCSS	dry cask storage system
Hz	Hertz
ISFSI	Independent Spent Fuel Storage Installation
MPC	multipoint constraint
NMSS	Nuclear Materials Safety and Safeguards
NRC	Nuclear Regulatory Commission
PGA	peak ground acceleration
PGD	peak ground displacement
PGV	peak ground velocity
PSA	pseudo-spectral acceleration
SASSI	System for Analysis of Soil-Structure Interactions
SFPO	Spent Fuel Project Office
V/H	vertical/horizontal
WUS	western United States