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OVERVIEW OF INDEPENDENT SPENT FUEL STORAGE INSTALLATIONS (ISFSIs) IN THE NEW MADRID SEISMIC ZONE (NMSZ) AND WABASH VALLEY SEISMIC ZONE (WVSZ)

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ABSTRACT

There are 104 nuclear power plants currently operating in the United States. Thousands of spent nuclear fuel (SNF) assemblies from these reactors are being stored (in the interim) in dry cask storage systems (DCSS) at facilities known as Independent Spent Fuel Storage Installations (ISFSIs) throughout the country. With the increased awareness of the potential risks to facilities and infrastructures located within the New Madrid Seismic Zone (NMSZ) and the Wabash Valley Seismic Zone (WVSZ) in the Central and Eastern United States (CEUS), this paper will present the overall perspective of the scenario of a large seismic event in these zones and effects, if any, at these facilities.

Located within the NMSZ and WVSZ (States of Missouri, Illinois, Indiana, Kentucky, Tennessee, Alabama, Mississippi, Arkansas), there are eleven (11) operating ISFSIs licensed by the United States Nuclear Regulatory Commission (NRC), with number of spent fuel assemblies stored at these facilities approaching seventeen thousand. The magnitude (Mw) 5.8 earthquake that struck central Virginia on August 23, 2011, was a noteworthy reminder that the Stable Continental Region (SCR) within the CEUS may be sensitive to rare, but large seismic events.

Recognizing the potential of existing faults in these seismic zones, and the fact that there are approximately 17,000 (Store Fuel - 14-175) spent nuclear fuel (SNF) assemblies stored at ISFSIs within these areas, it would be helpful to provide an overview of seismic safety of these facilities. This paper provides an overview of the seismic safety of ISFSIs in these seismic zones.

INTRODUCTION

Thousands of SNF assemblies are being stored (in the interim) in dry cask storage systems (DCSS) at facilities known as Independent Spent Fuel Storage Installations (ISFSIs) throughout the country. These ISFSIs are mostly collocated at the reactor site at 58 locations across the nation. A few of these reactor locations are within the NMSZ and WVSZ (consisting of states of Missouri, Illinois, Indiana, Kentucky, Tennessee, Alabama, Mississippi, Arkansas), having eleven (11) operating ISFSIs licensed by the US NRC, with the number of spent fuel assemblies stored at these facilities approaching 17,000. The earth's crust in these seismic zones has been known to be fractured with a number of tectonic plates that have indicated seismic activities in the past and although unlikely have the potential to activate at any time, with very little notice. The magnitude (Mw) 5.8 earthquake of central Virginia on August 23, 2011, caused no deaths and few injuries, but did damage buildings and other structures within a 100-mile radius of the epicenter. This event was unusual and the first of a kind in the recent memory of most communities in the CEUS. As reported in EERI (2011), the quake caused widespread interruptions to communications and transportation systems, numerous school closings in the epicentral area of Louisa County, other closures in the greater Washington, D.C. area including some damage to national monuments, and an automatic shutdown of the North Anna Nuclear Power Plant. The epicenter of the earthquake was located in Mineral, VA, approximately 17 km (10.5 miles) from the plant.

SEISMIC HAZARD

In 1976, the NRC funded a multi-year six-state cooperative project to better assess the seismic-hazards posed to potential nuclear power plants. This project involved state agencies and universities and it began accumulating the scientific data including earthquake magnitude and frequency that are critical to developing a probabilistic hazard assessment for the central U.S. Since then, seismologists have developed a considerable amount of seismic hazard data, and as a result our understanding of these hazards in the CEUS has increased considerably. This paper will discuss two specific major seismic zones, NMSZ and WVSZ. The areas of these two seismic zones are shown in Figure 1.

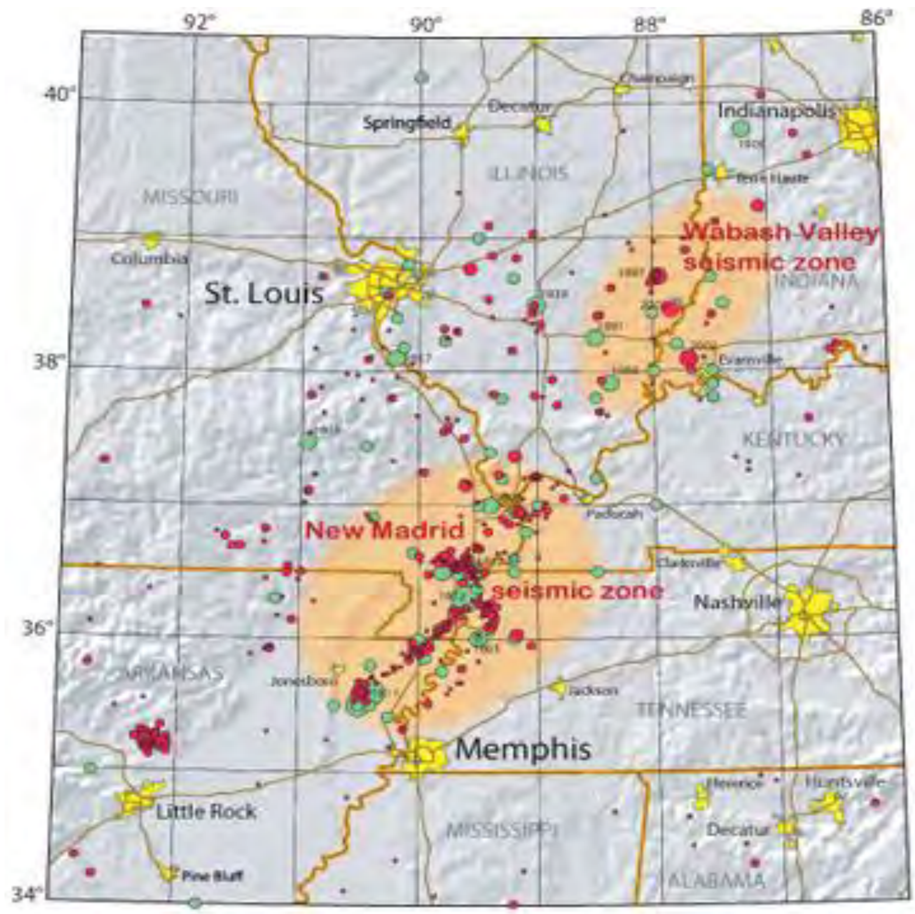


Figure 1. NMSZ and WVSZ (USGS)

NMSZ: St. Louis University geophysics professor Otto Nuttli (Otto Nuttli, 1974) wrote in the U.S. Geological Survey's "Earthquake Information Bulletin" for March-April 1974, that the Dec.1811-Jan.1812 quakes caused 96 km (60 miles) of the New Madrid Fault to rupture. This caused waterfalls on the Mississippi river just northeast of New Madrid to run backwards for several hours. It also created Reelfoot Lake in Northwest Tennessee. Today a 244 km (800-feet) power generation smokestack in St. Jude Industrial Park at Marston (just south of New Madrid) marks the approximate center of that quake. The geologic record of pre-1811 earthquakes reveals that the New Madrid seismic zone has repeatedly produced sequences of major earthquakes, including several of magnitude 7 to 8, over the past 4,500 years. NMSZ is the most seismically active area of the United States east of the Rocky Mountains.

WVSZ: The Wabash Valley Seismic Zone (WVSZ) is located along the southern border of Illinois and Indiana within a spoon-shaped depression known as the Illinois Basin. The Illinois Basin is bounded on the east by the Kankakee and Cincinnati Arch, on the west by the Ozark Dome and Mississippi River Arch, on the north by the Wisconsin Arch, and on the south by the Mississippi Embayment. The WVSZ is the second most active source zone dominating Central U. S. seismicity. Historic and instrumental records suggest that, although the seismic rate is much lower than a typical plate boundary region, activity is by no means what could be called "zero." The WVSZ is thought to be responsible for M 5+ quakes in 1968, 1987, and 2008. On 18 April, 2008 a M 5.2 earthquake centered near Mt. Carmel, Illinois was felt more than 500 km (310 miles) away and 35 aftershocks were recorded on the Advanced National Seismic System (ANSS) detection array (Herrmann et al., 2008; Yang et al., 2009).

At the Earthquake Engineering Research Institute (EERI) Annual Meeting/Conference held in Memphis, TN during April 11 through 14, 2012, several plans and results of New Madrid Earthquake Scenarios (NMES) were presented – mainly for commercial and essential industrial facilities. Nuclear structures were not addressed since they are built to comply with more rigorous standards when compared to commercial and non-nuclear facilities. Resolutions to narrow down the locations of the scenarios to six areas were also discussed at this meeting. Hazards to be further assessed were determined as two earthquakes as follows: A Mw 6.3 event within the NMSZ or Mw 6.0 event within the WVSZ having a 50% chance of occurrence in any 50-year period.

The overall subject of potential increase in seismic demand and its impact on analysis/design of ISFSIs located in the CEUS was discussed in a paper presented at SMiRT-21 (Tripathi, B. P., November 2011). The NRC project "Generic Issue - 199, Implications of Updated Probabilistic Seismic Hazard Estimates in Central and Eastern United States on Existing Plants" (GI-199 Project, 2005 ~ 2012) has been incorporated into a larger project known as: Japan Lessons Learned Directorate (JLLD; USNRC 2011) subsequent to the Great Tohoku Earthquake in the Northeast Coast of Japan with Mw 9.0, followed by a tsunami, that affected Fukushima Daiichi Nuclear Power Stations. The NRC JLLD project is currently tasked to investigate and assess the aftermath at Fukushima and incorporate lessons learned.

A project known as the Next Generation Attenuation for Central and Eastern North America (NGA-East) has been ongoing for the last several years. This project is jointly sponsored by NRC, the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI) and the US. Geological Survey (USGS). NGA-East is a multi-disciplinary research project coordinated by the Pacific Earthquake Engineering Research center (PEER). The project involves a large number of participating researchers from various organizations in academia, industry and government. The objective of NGA-East is to develop a new ground motion characterization (GMC) model for the Central and Eastern North-American (CENA) region. CENA will envelope the NMSZ as well as the WVSZ, and many more seismic zones in CENA.

The GMC model will consist of a set of new ground motion prediction equations (GMPEs) for median and standard deviation of ground motions (GMs) and their associated weights in the logic-trees for use in probabilistic seismic hazard analyses (PSHA). NGA-East consists of two parts: 1) a science development phase and 2) a model building phase. Senior Seismic Hazard Analysis Committee (SSHAC) - Level 3 probabilistic risk assessment will be a part of this project. In order to develop new GMPEs, NGA-East will rely on ground motion simulations to supplement the ground motion database developed for the project. Important scientific issues will be addressed through targeted research projects on the regionalization of seismic source, path and attenuation of motions, local linear and nonlinear site response characterization, and the treatment of variability and uncertainties.

The existing ISFSIs in NMSZ and WVSZ have conservatively used Design Basis Earthquake (DBE) for analysis/design of ISFSIs, the same as the power plant safe shutdown earthquake (SSE), as they are co-located with the nuclear power plant. SSE for nuclear power plants in the US is based on a 10% probability of exceedance in 1,000 years, i.e., an event with a return period of 1 in 10,000 years. Commercial and industrial facilities on the other hand, are designed for seismic events with a 50% chance of occurrence in any 50-year period, i.e., an event with a return period of 1 in 2,500 years.

EXISTING ISFSI DESIGN AND POTENTIAL IMPACT OF A SEISMIC EVENT

Within the NMSZ and WVSZ there are currently eleven (11) operating ISFSIs licensed by US NRC as shown in Table-1 below.

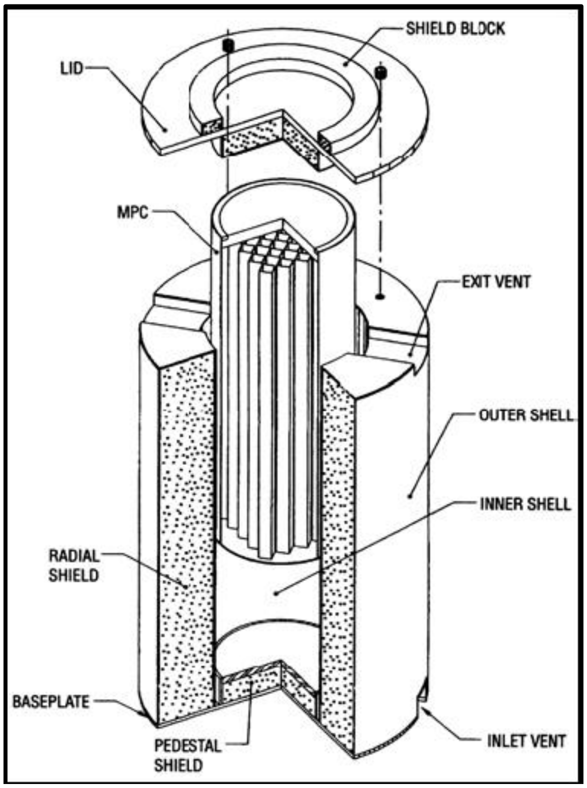
Table 1: Operating ISFSIs in NMSZ and WVSZ

US - State	Nuclear Power Plant	Power Plant SSE *	Number of Stored Spent Fuel Assemblies ** [DCSS Unless Noted]
Alabama	Browns Ferry	0.20gH 0.14gV	2,720
	Farley	0.10gH 0.07gV	672
Tennessee	Sequoyah	0.22gH 0.16gV	1,024
Illinois	Braidwood	0.20gH 0.14gV	96
	Byron	0.20gH 0.14gV	448
	Dresden	0.20gH 0.14gV	3,604
	G. E. Morris	-	3,217 [Wet Storage in Fuel Pool]
	LaSalle	0.20gH 0.14gV	408
	Quad Cities	0.24gH 0.16gV	2,380
Arkansas	ANO	0.10gH 0.07gV	1,616
Mississippi	Grand Gulf	0.15gH 0.10gV	1,156
			Total ∑ = 17,341

***SSE = Safe Shutdown Earthquake**
****Number of spent fuel assemblies shown in Table-1 above is current as of March 5, 2013**

These ISFSIs, constructed over approximately the last 20 years have been designed and built per the NRC's regulatory guidance documents, in compliance with Title 10 Code of Federal Regulations (10CFR) Part 72, and are licensed by the NRC, in wet or dry modes of storage. The spent fuel assemblies stored are typically those that have cooled down in power plant spent fuel pools for at least 5 years. The dry mode of storage of the spent fuel and other high-level nuclear waste generally consists of a multi-purpose canister (MPC) and an overpack system (see Figure 2). A typical MPC is cylindrical in shape and is made of structural steel. The MPC is placed in either a cylindrical overpack system made up of steel or concrete and steel, or a concrete vault-type overpack system.

The overpack protects the MPC against external man-made events and external natural phenomena, and functions as a shielding and thermal barrier. The DCSS is placed as a free-standing structure on a concrete pad supported on a firm foundation.

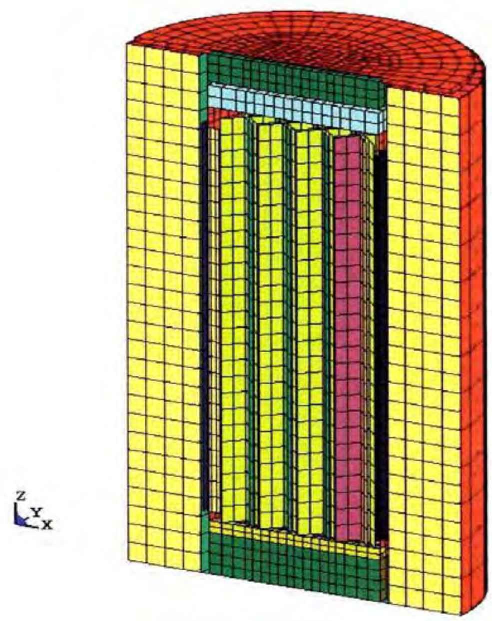


Spent Fuel assemblies are stored in a stainless steel basket within the MPC surrounded by inner and outer shells and a radial shield.

Figure 2. Representative, MPC and Overpack System

The NRC Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility, NUREG-1536, and the Standard Review Plan for Spent Fuel Dry Storage Facility, NUREG-1567 provide the NRC staff guidance in reviewing the license applications, and suggest that the storage cask be designed not to tip-over for all man-made events and external natural phenomena. However, consistent with the NRC's defense-in-depth policy, these guidelines suggest that the DCSS structural integrity should be evaluated for a non-mechanistic tip-over event. An independent structural analysis of a DCSS was performed by the staff, for a cask tip-over event using the explicit method of dynamic analyses in the finite-element (FE) computer code LS-DYNA, Version 960. The analysis was performed for a cask angular velocity of 1.7 radians per second, at the time of impact on the pad (see Figure 3 and Figure 4) The cask angular velocity of 1.7 radians per second was based on the gravity fall with an initial zero velocity at the start of the tip-over (center of gravity over the cask corner), plus an additional 10 percent increase to account for a potential for a non-zero initial velocity during an earthquake event. Based on the results of this analysis, it was concluded that the DCSS has a significant margin of safety to maintain the structural integrity during a non-mechanistic tip-over event. Moreover, variations in foundation material properties within the first two layers below the concrete pad [84 inches thick (2134 mm)] by ± 50 percent did not appear to have significant effects on the concrete pad impact forces and the accelerations at the center of the cask lid.

The cask tip-over side impact force of 45g, used for most of the storage casks licensed by the NRC staff to-date, is more than two orders of magnitude higher than the Design Earthquake (DE) base shear used as % of "g" load. In the cask vendor Final Safety Analysis Report (FSAR), the DCSS has been shown to be capable of performing its confinement and shielding safety functions during and after the DE. The Seismic robustness of DCSS was demonstrated by the cask tip-over analysis, which results in cask decelerations that more than bound the g-loads applied to the cask during a DE event.



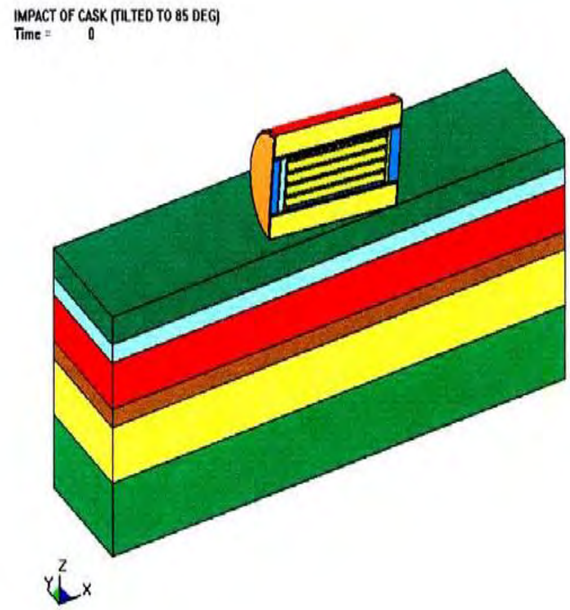


Figure 3. LS-DYNA Model - Representative Cask **Figure 4. FE Model for the Tip-over**

It should be emphasized that the DCSS is classified as important to safety (ITS). While the supporting pad is categorized as not important to safety (NITS), when Soil Structure Interaction (SSI) effects are considered as required by the 10 CFR Part 72 regulations, it will necessitate that the seismic demand on the pad must be calculated using analysis methods consistent with the analysis of ITS components.

The national consensus standards used for the analyses/design for the ISFSI support pads are per NRC's guidance, and the supporting pads typically are considered structures systems and components (SSCs) NITS. However, a few licensees have analyzed and designed the ISFSI support pads as ITS structures. The basic difference between analysis/design of structures classified as NITS and ITS, are that the former could use ACI-318 Code, and the latter requires use of American Concrete Institute (ACI) - 349 Code. Compared to ACI-318 Code, the ACI-349 Code has more rigorous requirements for combining seismic loads with other operational design loads.

The ISFSI pad supports ITS components (storage casks) and is required by 10 CFR Part 72.212(b)(2)(i)(B) "to adequately support the static and dynamic load of the stored casks, considering the potential amplification of earthquakes through soil-structure interaction..." For the case where the general licensee chooses to classify the ISFSI pad as NITS, a condition exists where a NITS structure (the pad) supports ITS components (casks). In such a case the NITS structure may be qualified using codes and standards acceptable for the design of NITS structures. However, because the NITS structure supports ITS components, the seismic demand on the ITS components must be calculated using analysis methods consistent with the analysis of ITS components.

NRC (NUREG -1536, 2005) states …"ISFSI pads are usually relatively thin structures (i.e., small thickness to length ratio) and generally do not incorporate integral walls to stiffen the pad. While the cask itself is relatively rigid, the rigid cask resting on a flexible pad has a lateral mode frequency that is generally low enough to fall within the amplified range of most design earthquake spectra.

Thus, in determining the inertia forces that act at the center of gravity of the cask for the purpose of evaluating the onset of sliding or tipping, the reviewer should ensure that the applicant has either accounted for the out-of-plane flexibility of the pad in the seismic analysis or demonstrated that it is not an important parameter in determining the response of the cask…". This standard further states "Cask systems are not required to survive a design earthquake without permanent deformation. However, the maximum extent of damage from a design earthquake must be predicted, and the capability to provide principal safety functions shall not degrade."

The NRC staff considers that storage casks being ITS components are adequately supported by the pad when: (1) the seismic demand on the storage casks and pad has been calculated using SSI methods that have been accepted by the NRC staff; (2) the effects of pad flexibility have been accounted for in developing the seismic analysis model; (3) all significant loads occurring during the life of the ISFSI have been accounted for in the load combinations found in the vendor FSAR, and ACI-318 code or ACI-349 code as applicable, and (4) the extent to which storage casks may rock or slide has been evaluated using appropriate methods for the nonlinear time history analysis of ITS components, where the uncertainty in the coefficient of friction between the cask and the pad has been considered.

Arrays of DCSSs have been installed at ISFSIs licensed under 10 CFR Part 72 at many U. S. nuclear power plant sites. Most of these storage casks are freestanding on a reinforced concrete pad. As such, these cask systems have been assessed for their adequacy under dynamic response, in terms of sliding displacements, rotations, and the integrity of cask internals under transient seismic loads.

NUREG/CR-6865 (SAND2004-5794P) "Parametric Evaluation of Seismic Behavior of Freestanding Spent Fuel Dry Cask Storage System" issued in February 2005 was developed as a comprehensive methodology for evaluating the nonlinear seismic behavior of these storage systems. This report characterized 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. Nomograms of median cask responses +/- one standard deviation of maximum cask top sliding displacements and angular rotations vs. peak ground accelerations are provided.

REPRESENTATIVE GENERIC ISFSI SUPPORT PAD in NMSZ and WVSZ:

Note: Design values shown below are typical of all ISFSI sites in NMSZ and WVSZ.

Storage Cask Weight: 163,293kg. (360,000lbs.)
Cask: 3.36m (11.02') D, 6.01m (19.7') H, Aspect Ratio: 0.5D/0.5H = 0.56
ISFSI Pad Size: 60.96m x 30.48m x 0.6096m (200'L x 100'W x 2'T)
Number of Casks and Spacing: 78 Casks @ 4.572m c/c (15' c/c) each way
ISFSI Pad Concrete = f'_c = 20,684kP_a (3,000psi)
Rebar = #10 @ 22.86 cm c/c (9" c/c) T & B each way
Fy = 413.685mP_a (60 ksi)
Mud-mat (plain structural concrete) underneath the pad = 5.08cm ~ 10.16cm (2" ~ 4") thick
Engineered Fill under the mud-mat = 0.92m (3') thick
Average Shear Wave Velocity in Native soils = 549m/sec (1800 ft/sec). [Very conservative]
Plant SSE = 2.94m/sec^2 H, 1.96m/sec^2 V, (0.30gH, 0.20gV)

[See Figure 5 Below for a typical DCSS layout]

Vast experience gained by the NRC staff over last 20+ years in reviewing these DCSS has shown that the cask/pad/soil system can significantly amplify the acceleration response at the cask center of gravity to levels well above the acceleration at the top of the pad. The results of an investigation to determine the influence of three parameters on cask response: pad flexibility (i.e., pad thickness), soil properties and cask layout were reported in a paper at the "Packaging and Transportation of Radioactive Materials" PATRAM (2010), (Bjorkman. G. S., 2010). A total of 16 soil-structure interaction (SSI) analyses were performed with various combinations of these parameters using the computer program System for Analysis of Soil-Structure Interaction (SASSI).

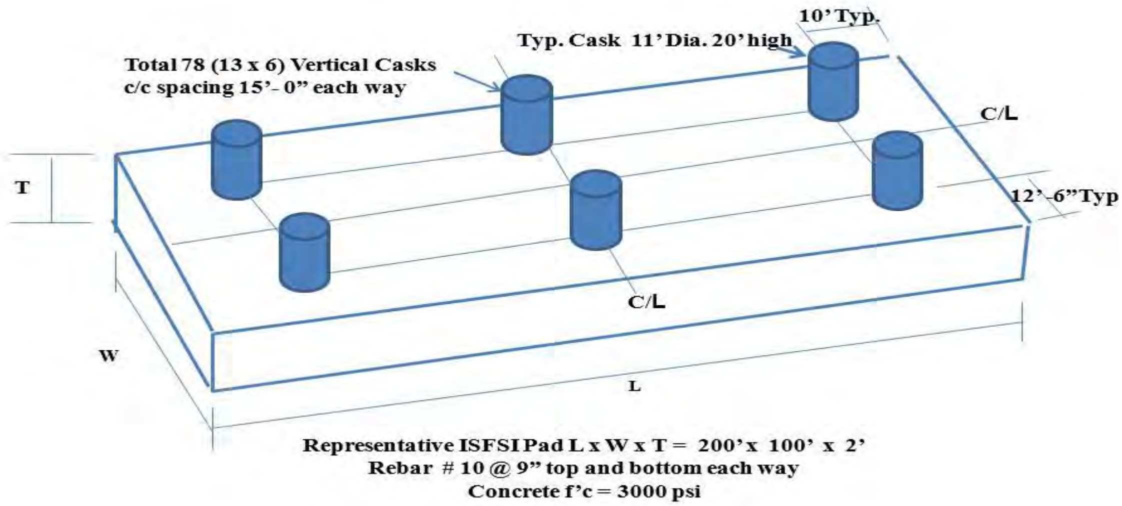


Figure 5. Typical Dry Cask Storage System

The results showed that the most important parameter affecting cask response is the out-of-plane flexibility of the pad, and that this parameter can significantly amplify cask acceleration response at the cask center of gravity. It was clearly demonstrated that increasing pad flexibility resulted in increased amplification. In addition, it was also noted that in all nine SSI analyses for the 3-cask case, the single isolated cask always produced the maximum response. It was observed that the shear wave velocity influenced maximum cask response, although not as significantly as pad thickness and cask arrangement, and that these results only apply to the prediction of the onset of sliding or tipping. Once tipping or sliding has occurred these results no longer apply, and one must perform either an uncoupled linear/non-linear analysis or a coupled non-linear analysis, much like that in NUREG/CR-6865, or a nonlinear time history analysis using an explicit dynamic analysis program, such as LS-DYNA.

According to the USGS based on recent paleoseismic studies, a magnitude 6.0 or greater earthquake has an estimated 25-40% chance of occurrence in the next 50 years. Such an earthquake could pose serious risk of damage to schools and masonry buildings between Memphis and St. Louis. The USGS also estimates a 7% - 10% chance of a Magnitude 7.5 – 8.0 earthquakes occurring in the next 50 years (equal to the four largest quakes in 1811-1812). Most experts in the seismology field estimate that potential future earthquakes, given the tectonic structures in these areas of SCR, could produce Peak Ground Accelerations (PGA) ranging from 0.20gH ~ 0.30gH.

Nuclear structures such as DCSS are much more robust and have been designed to more stringent standards for materials, analyses/design, construction, quality assurance and quality control than commercial structures. In view of this fact, coupled with strict design requirements mandated by 10 CFR Part 72 regulations for safety of the general public, there is reasonable assurance that potential impact if any, on these DCSS and ISFSIs located in the NMSZ and WVSZ areas due to a scenario earthquake postulated in the future, will be relatively minor and almost negligible.

CONCLUSION

Dry cask storage system casks are designed for hypothetical accident conditions, such as drop and tip-over. *These accidents create deceleration effects in the order of 40 g to 60 g compared to maximum seismic acceleration values in the order of 1g to 2 g.* Since the casks are rugged, they tend to have relatively high natural frequency; consequently damage from the hypothetical drop or tip over accidents are expected to be far greater and more severe than the seismic inertia loads. Thus, seismic inertia loads are bounded by other design loads.

The dry storage cask designs are very rugged and robust, and are expected to have substantial margin to withstand forces from a rare but severe seismic event such as a potential future earthquake in the NMSZ and WVSZ, with a return period of 1 in 2,500 years. Demands on ISFSI structure from such an event will still be far less severe when compared to an earthquake with a return period of 10,000 years.

During a seismic event, a cask may slide, if lateral seismic forces are greater than friction resistance between the cask and the concrete pad. The sliding and resulting displacements due to earthquake ground motion are computed to demonstrate that the casks are spaced sufficiently apart to preclude impacts with other casks. The cask designer is also required to demonstrate that there will be no tip over of the cask during the design basis earthquake event. However, it follows from the previous discussion on the severity of accidental drop and tip over conditions, that there will be adequate margin for structural integrity of casks during a hypothetical seismic event greater than the proposed design earthquake, even if the casks slide. Therefore, the structural integrity of the cask will be maintained to meet the Part 72 exposure limits for radiological protection, even if the seismic event exceeds the proposed design earthquake.

In comparison with a nuclear power plant, an operating ISFSI is a relatively simple facility in which the primary activities are waste receipt, handling, and storage. An ISFSI does not have the variety and complexity of active systems necessary to support an operating nuclear power plant. Therefore, the radiological risk associated with an ISFSI is significantly smaller than the risk associated with a nuclear power plant. (Tripathi B. P., M. J. Shah, 2001).

In view of discussions presented in this paper, it is concluded, with a high degree of confidence that the spent nuclear fuel assemblies stored at these ISFSI locations within the NMSZ and WVSZ will not pose any undue risks of radiological hazard, even when subjected to ground motions similar to those experienced during the events of 1811 and 1812 in NMSZ, and WVSZ in 2008. The built in defense-in-depth for the analysis/design of these casks, and rigorous construction and periodic maintenance of these facilities required by the applicable regulations provide reasonable assurance that these facilities are safe.

The views expressed in this paper are strictly those of the author and should not be viewed as the agency's official position. The author wishes to thank David Pstrak, Gordon Bjorkman, and Anthony Hsia of NRC for timely review and feedback on the contents of the paper.

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