

MULTI-HAZARD ASSESSMENT OF DRY CASKS FOR INTERIM STORAGE OF SPENT NUCLEAR FUEL

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ABSTRACT

In the absence of a long-term nationwide storage facility, the number of dry cask storage systems will increase dramatically in the nuclear industry in the near future. A comprehensive study is warranted to better understand the performance of dry cask storage systems under multiple hazards, in particular, when the systems are aged for 40, 60, or even hundreds of years and subjected to extreme events such as earthquakes. This paper summarizes an ongoing research project that aims at developing a probabilistic multi-hazard assessment framework for dry cask storage systems through experimental and analytical research on aging and seismic effects.

INTRODUCTION

Over the past four decades, the nuclear industry has produced 67,500 metric tons of spent nuclear fuel (SNF) in the United States, and this amount grows by about 2,000-2,300 metric tons each year (Nuclear Energy Institute, 2013). The fuel removed from the reactor core is initially stored in spent fuel pools. In the late 1970s and early 1980s, the need for alternative storage began to grow when pools at many nuclear reactors began to fill up with SNF. Utilities started looking at options such as Dry Cask Storage Systems (DCSS) to increase SNF storage capacity (United States Nuclear Regulatory Commission, 2013). DCSS are cylindrical structures, approximately 20 ft in height and 11 ft in diameter, with typically 2 ft of concrete shielding walls, placed on concrete pads in an upright position or horizontally stacked. There is a total of 1589 DCSS in the United States. Among all, 882 are vertical (56%), and the rest 707 are horizontal casks (44%). A majority of the vertical casks have a concrete overpack (more than 80%), which is also the focus of studies presented in this paper. The number of interim DCSS will increase drastically in the near future in the absence of a long-term nationwide storage facility. A comprehensive study is warranted to analyze the performance of DCSS under extreme events (e.g. earthquakes, tornados) combined with material aging effects.

The ongoing project summarized in this paper aims at developing a probabilistic multi-hazard assessment framework for DCSS through experimental and numerical research, evaluating material deterioration induced by environmental aging and seismic effects. Although the focus of this research is reinforced concrete (RC) vertical DCSS, the developed procedures are expected to be readily extendable to steel casks or horizontal concrete casks in stacked configurations. Under an extreme event like an earthquake, DCSS are subjected to potential sliding, rolling and tip-over. There are concerns over the integrity of 100-200 metric ton DCSS when they are subjected to hazards after being aged for 40, 60, or even hundreds of years.

PROBABILISTIC MULTI-HAZARD ASSESSMENT

Development of a probabilistic framework to assess the performance of DCSS under multiple hazards is essential for decision-making purposes. In this framework, various sources of uncertainty (e.g. randomness in hazard parameters, variability in material properties, etc.) are systematically propagated to evaluate both the conditional (on time and intensity) and total probabilities of failure for different damage states.

Quantify the inputs to the risk assessment framework is an essential component of the probabilistic framework. For multi-hazard risk assessment with a set of mutually exclusive and collectively exhaustive hazards, the risk of damage to the system can be assessed as (Ellingwood, 2001):

$$P[DS] = \sum_i P[DS|H_i]P[H_i] \quad (1)$$

Where $P[DS|H_i]$ is the conditional probability of damage state DS due to hazard H_i , and $P[H_i]$ is the probability of hazard H_i . In the context of this project, the emphasis is placed on seismic threats coupled with aging, although the framework can be extended to other hazards such as tornados or surge events. Furthermore, the convenient decoupling of the models to evaluate, for example, the probability of cask damage given tip over, can enable constituents of the framework to be used for risk assessment from various hazards. By expanding the above equation through application of the theorem of total probability, the risk assessment is commonly posed as:

$$P[DS] = \sum_{im} \sum_d P[DS|D = d]P[D|IM = im]P[IM = im] \quad (2)$$

where $P[IM = im]$ is the probability of the hazard intensity measure IM (e.g. peak ground acceleration, PGA), $P[D|IM = im]$ is the conditional probability of a structural demand or response quantity given the intensity measure, and $P[DS|D = d]$ is the conditional probability of damage state DS given the response quantity D . The last term reflects the uncertainty in the capacity of the system to sustain demand D before a certain damage state occurs. Furthermore, these demand and capacity models can be integrated and presented in the form of a fragility curve, which states the probability of damage state exceedance given the hazard intensity measure (i.e. $P[DS|IM = im]$). This project will derive fragility curves and damage risk estimates for DCSS driven by their importance for operational assessment, safety analysis and decision-making.

The term $P[D|IM]$ is often depicted in terms of a probabilistic seismic demand model relating structural response quantities to the hazard intensity. Examples of critical demand parameters for DCSS include displacement due to sliding, angle of rotation due to rocking motion, or component stresses in the case of a tip-over and impact. While appropriate forms of the regression models and demand probability distributions have been widely studied for probabilistic seismic response assessment of other structures, such as buildings, bridges, or nuclear containment structures, which typically adopt a power law model with lognormal error estimate (Cornell *et al.*, 2002), this assessment has not been carried out for DCSS. Therefore, viable probabilistic seismic demand models for DCSS are being explored based on statistical analysis of the results of nonlinear dynamic analyses using both the hazard intensity measures as predictors in the model as well as design parameters of the casks. Additionally, critical damage states for DCSS may include various levels of residual displacement (after sliding), tip-over, yielding or cracking which need careful consideration.

A unique emphasis of the proposed framework is the joint consideration of aging effects and hazard impacts in the risk assessment of DCSS. The aging of DCSS can affect both the probabilistic capacity (typically reducing the capacity to resist load prior to damage occurrence) and also affect seismic demand placed on the structure due to potential changes in the dynamic behavior of the aged system. Therefore the DCSS fragility curves will be posed as a function of time and exposure condition. Fig. 1 illustrates this concept. The derivation of such time-dependent fragility curves offer distinct advantages over traditional

structural reliability or seismic fragility models by reflecting the hazard vulnerability associated with the aged condition of DCSS. The resulting risk estimates derived from the time-dependent fragility curves help evaluate the probability of unacceptable consequences of joint hazard exposure across various time horizons, exposure conditions, and structural configurations; and can be used to assess and schedule needed interventions to mitigate the risks to DCSS.

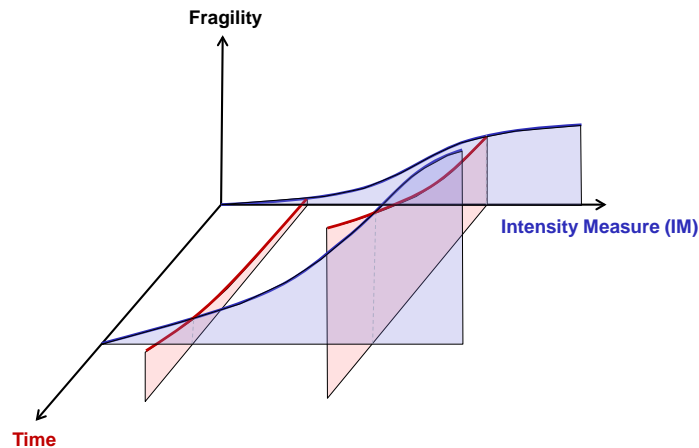


Figure 1. Illustration of a time-dependent fragility model, depicting the probability of damage state exceedance given hazard intensity measure as a function of time

As mentioned earlier, determination of inputs and model parameters that contribute to the uncertainty is crucial for an accurate risk assessment of DCSS under multiple hazards. The random variables considered in the performance assessment can be classified under two traditional uncertainty definitions: aleatoric (due to inherent variability) and epistemic (due to lack of knowledge). For this project, the main contributor to the aleatoric uncertainty is the variability in ground motions. With regards to epistemic uncertainty, the variability in the model parameters are: DCSS material properties (i.e. time dependence due to aging), properties of the underlying soil (i.e. shear wave velocity, density, material damping, and thickness of various strata), pad properties (i.e. elastic modulus, Poisson's ratio and density) and cask-pad interface friction (which is expected to be dependent on time due to rusting of the cask steel base plate). Sensitivity studies will be conducted to reveal those parameters which have the most significant effect on the dynamic response of DCSS. Probabilistic seismic demand models as well as fragility estimates will be conditioned upon such parameters thereby providing flexible and efficient fragility models of DCSS performance for use in risk assessment.

FINITE ELEMENT MODELING AND ANALYSIS

Moore et al. (Moore et al., 2000) used the program SASSI (Stevenson & Associates Inc, 1996) to perform seismic analysis of the HI-STORM 100 cylindrical cask. They used beam elements for the cask, plate elements for the foundation pad, and spring elements to simulate the contact between the cask and pad. The soil profile was generated using the program SHAKE91 (Idriss and Sun., 1992). Friction elements were used to simulate the contact between the cask and pad. Shaukat and Luk (Shaukat and Luk, 2002) used the program ABAQUS to conduct a parametric study of different factors affecting the seismic behavior of cask structures. Their model consisted of 3D-Solid elements, and contact elements to simulate the frictional effects. The parameters studied were the cask design, soil properties, friction coefficient, and earthquake records. Similar more elaborate studies were conducted by Luk et al. (Luk et al., 2005), and Ko et al. (Ko et al., 2009). The Nuclear Regulatory Commission (NRC) requires consideration of tip-over and cask-to-cask impact as potential accidents in the analysis (U.S. Nuclear Regulatory Commission, 2010). Early study on nonlinear impact analysis of cask structures was conducted by McGreesh et al. (McGreesh

et al., 1995) and Braverman et al. (Braverman et al., 2003), who analyzed casks dropped from different heights on three surfaces-concrete, asphalt, and gravel-using the computer program LS-DYNA. A recent study by Huang and Wu (Huang and Wu, 2009) used LSDYNA to account for interface debonding between the concrete cask and steel liner.

In all previous numerical studies, the effect of material aging of dry casks, which could be used for more than 100 years, has been ignored. Furthermore, uncertainty of model parameters has not been accounted for. This portion of the study will develop an analytical modeling paradigm that can be used in the probabilistic framework for fragility and risk assessment of DCSS.

IMPACT OF RADIATION AND ELEVATED TEMPERATURE

Impact of elevated temperature and temperature gradients as well as radiation damage over extended period of time must also be taken into account when assessing the health of DCSS under hazardous conditions. Simulations will be carried out to evaluate the fluence as well as the temperature profiles in the concrete structure. We plan to simulate the fluence on the dry cask concrete based on the properties of higher duty fuel that is currently being discharged from the spent fuel pools into the dry casks. A simple MCNPX model will be developed and simulation will be carried out to determine the gamma ray dose rate to the concrete for different time instances over the ~100 year planned duration. The fluence determined will contribute to the uncertainty analysis.

Past estimates of temperature variations (U.S. Nuclear Regulatory Commission, 2007) show that the inside concrete shell temperature can reach as high as 80 °C under normal operation. It is also known that concrete temperature of nearly 95 °C is the threshold above which the degradation effects are pronounced; and increase with increasing temperature and time exposure. Properties that are known to be affected are compressive strength, creep resistance and conductivity. Hence, a thermal analysis of the dry cask model will be carried out using the commercial CFD code to accurately determine the temperature distribution in concrete, which will in turn be used to estimate the thermal degradation of stiffness and strength properties of concrete over time.

EXPERIMENTAL PROGRAM FOR TESTING OF AGED CONCRETE CASK STRUCTURES

Many nuclear power plants are located in a close vicinity of the sea. Since dry casks may now remain at the power plant site for a significantly long time, the moist environment may cause several durability problems. While carbonation-induced corrosion of reinforcement may affect a far wider range of reinforced concrete structures, chloride-induced corrosion is generally more pernicious and expensive to repair. Above a critical chloride concentration, the passive layer on the reinforcing steel is destroyed, leading to the development of corrosion product at the interface between the steel and surrounding concrete. The volume expansion of this rust leads to cracking, spalling, and delamination of the concrete. In addition, the corrosion damage may significantly reduce the load-bearing capacity of the structure by a reduction of cross-sectional area of steel bars.

The elevated temperature can accelerate the chloride penetration process significantly (Isteita, 2009). Therefore, the service conditions of concrete overpack are actually more severe than that of concrete bridge decks, which have been considered to be under a very harsh environment. The compressive strength of concrete decreases with increasing temperature, and it has the down-up-down trend under elevated high temperatures (Freskakis, 1979; Willam et al., 2009). A recent study showed that there was no degradation of the compressive strength up 200°F in the case of normal strength concrete (Kodur et al., 2008). The behavior of reinforced concrete flexural members subjected to high temperatures was reported to be closely dependent on the force-temperature paths they experience (Shi et al., 2002). The rate of the splitting tensile strength loss is higher than the rate of the compressive strength loss at elevated temperatures for high strength concrete (Ghandehari et al., 2010). Temperature has significant influence on thermal conductivity, specific heat, and thermal expansion of high strength concrete, fly ash concrete and self-consolidating

concrete. The thermal conductivity generally decreases with temperature, while the thermal expansion increases with temperature up to 800°C (Kodur and Khaliq, 2011).

Relative humidity has an influence on shortening of vertical elements in reinforced concrete buildings (Jayasinghe and Jayasena, 2005). Under the dry-wet cycles, the variation of the interior humidity of concrete occurs mainly within a certain depth from the drying/wetting face. The interior relative humidity of concrete within the influencing region periodically changes under dry-wet cycles (Zhang et al., 2012). Concrete carbonation rate is also strongly affected by the humidity (at 60°C): the lower the relative humidity, the higher is the carbonation rate (Matsuzawa et al., 2010).

In addition, the type of aggregate has a significant influence on the thermal properties of high strength concrete at elevated temperatures. The presence of calcareous aggregate in high-strength concrete increases fire resistance (Kodur and Sultan, 2003) and relevant to DCSS when hazards such as missile attacks are considered. The carbonation of concrete is influenced by the ambient humidity, humidity cycling, and surface geometry of concrete. In a recent study, it was observed that the largest coefficient of carbonation occurs at a constant 70% relative humidity, and the coefficient of carbonation decreases with humidity cycling (Chen and Ho, 2013).

Alkali-Silica Reaction (ASR) is a chemical process that takes place in concrete between the alkali in cement and reactive silica in the aggregates. Combined with moisture, the product of ASR gel introduces high volume expansion, resulting in cracking on the surface of concrete. High moisture level in concrete is a necessary condition for the formation of expansive ASR gel. Thus, the concrete overpack located near seawater is particularly susceptible to ASR damage.

Experiments will be performed both at the material and structural levels. RC specimens will be subjected to accelerated aging to represent the in-situ material properties at different instants of the cask lifespan. The aged specimens will be used to obtain the relevant material properties for FEA. Structural level accelerated aging and tip-over tests will be performed on 1/4 or 1/3 scale aged cask models.

Material Level Tests

Accelerated material aging tests will be conducted in laboratory to simulate the potential deterioration of materials used in DCSS after 40, 60 or even hundreds of years. Aging of the materials can be accelerated by exposing the specimens into chloride solutions, sustained high temperatures and various relative humidity environments. These material aging tests can last from 3-12 months. In addition, a series of material property tests will be carried out during and after the aging process to monitor the material degradation. Our interested material properties include elastic modulus, tensile strength, compressive strength, flexural strength and fracture energy, etc. Results from the material aging tests will be interpreted and concluded to support structural-level tests. Effective material aging procedure will be applied to the subsequent reduced-scale (1/4 or 1/3) DCSS.

Structural Level Tests

Following the accelerated aging, a tip-over test of a reduced-scale (1/4 or 1/3) DCSS will be performed. An additional mass will be inserted in the specimen to represent the effect of the internal canister. The cask structure will be subjected to sodium chloride solutions, similar to salt ponding methods, but through spraying over a 15 month period. Such method is deemed more practical for the purpose of this study. The specimen will be then subjected to a tip-over event to investigate its behavior in an extreme scenario that might happen during an earthquake. Earlier research indicated that, within certain limitations, the predictions of scaling theory are applicable to reinforced concrete subjected to extreme impact loads (Sato et al., 1989). A high degree of randomness is involved in impact load conditions (e.g., orientation at impact) and inelastic material behavior (e.g., concrete cracking). More accurate results are obtained from larger scale specimens due to the reduced influence of strain-rate effects on concrete tensile strength and compressive strength.

The test will be performed at the large-scale testing facility in the University of Houston. The impact surface will be designed to represent the actual properties of the pad. Additionally, the surface will be instrumented with load cells (capable of high frequency sampling) to measure the impact loads. The cask structure will be instrumented with accelerometers as well as surface and embedded strain gauges for concrete and steel rebar. A unique part of the tip-over test will be the use of high-resolution digital image correlation (DIC) system to obtain information about the damage conditions of the cask after impact. The unique test data from these experiments will provide new understanding of the cask behavior and its performance after the tip-over event.

CONCLUSIONS AND EXPECTED OUTCOMES

The multi-hazard performance assessment on dry cask storage systems to be obtained in this study will be accompanied by sensitivity studies to cast the probabilistic framework into a risk-informed format of life cycle analysis. This project has a three-year timeline. By the end of the project, it is expected that the aging and structural tests will lead to better understanding of the material and structural behavior over extended periods of time and under extreme events including impact resulting from earthquake induced tip-over. The numerical seismic and impact analysis of casks will allow derivation of time-dependent fragility plots describing the probability of various failure scenarios.

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