A Criticality Analysis of a Dry Storage Cask with Advanced Nuclear Fuel Cask Additive

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INTRODUCTION

The number of Nuclear Power Plants (NPP) around the world is continually increasing, and thus, the amount of Spent Nuclear Fuel (SNF) is also increasing rapidly as the number of NPPs rise. In general, the accepted method in the United States for handling SNF is to allow it to cool in the onsite spent fuel pool. It is then transferred to a dry cask. Today, the strain of the current SNF production rate on the limited storage capacity of spent fuel pools necessitates the transfer from wet storage to dry storage. In fact, however, the current design of dry casks decreases the probability of the release of radioactive material compared to wet storage. This is principally because with dry storage the SNF is cooled by passive cooling. Each SNF assembly is separated from others by a spacer, and the cask itself is sealed and robust against external damage. However, the high cost of dry casks, low production rate of dry casks, and the introduction of human error due to increased fuel handling, impedes this transfer. These considerations have made the nuclear industry reluctant to move SNF from pools to dry casks. In addition, dry casks are typically filled with helium gas, which allows the decay heat to be removed from the fuel mainly through conduction to the cask outer wall. Gas is an inefficient conductor so the fuel temperature is typically around 400˚C [1]. This high temperature (above the original operating specification of the fuel) and limited neutron absorption capability of the system can potentially allow unintended accidents and fuel integrity decay without long-term monitoring and maintenance. As a solution to this problem, we propose to develop an advanced nuclear fuel cask additive, comprised of coated composite glass beads (borosilicate glass). This product not only increases the shutdown margin (reduces k_{eff}) of the system since it contains 21% boron by weight, but also it efficiently removes heat with maintaining SNF temperature below 150˚C since it provides a conduction path directly between the SNF and the cask walls. With lower fuel temperatures, SNF casks can be readily re-flooded and reopened for the inspection and repackaging of the fuel. Moreover, the additives can be poured through the inner lid of the cask to displace the water so that the cask can always be filled with either borated water from the spent fuel pool or the bead additives throughout the loading process. We expect the advanced nuclear fuel cask additive will be used as the transport/storage SNF casks during the whole life-time of the TSC and also anticipate the advanced nuclear fuel cask additive being deployed to reactor cores during loss of coolant/heat sink accident to prevent fuel damage accident such as what happened at Fukushima in 2011.

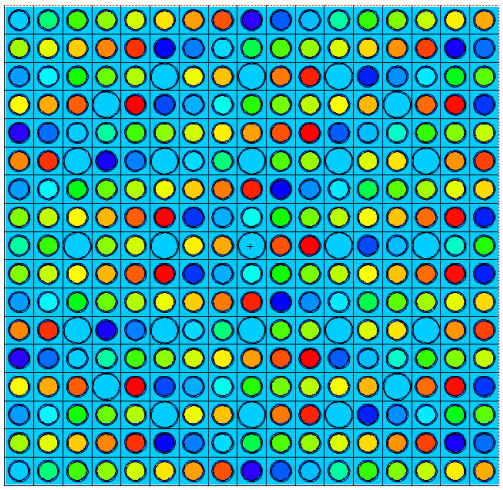

Fig. 1. MCNP Graphic of 17x17 PWR Fuel Assembly.

TSC and VCC Modeling in MCNP6

In our research, we used MCNP6 in order to model the MAGNASTOR TSC (Transportable Storage Canister) and VCC (Vertical Concrete Cask) which were designed by NAC International [2]. The main reason we have chosen the MAGNASTOR TSC design among the wide range of other options which have been commercially used in the United States is that it has met our criteria: a) a capacity of up to 37 PWR Fuel Assemblies (FA), b) cask is applicable both to storage and transport designs and c) able to store SNF with a high maximum burnup. We modeled a 17x17 conventional PWR fuel assembly, with 5% $^{235}_{92}U$ by weight enrichment at beginning of life, a burnup of 60 GWD/MTU and 14 days of cooling time. The PWR assembly model was designed and provided by the National Nuclear Security Administration's Spent Fuel Measurement project [3]. In the 17x17 PWR fuel assembly design, there are 264 fuel pins which are symmetrically located in the array and 25 guide and instrument tubes which are filled with water. Also, each fuel pin has its own isotopic composition which are assumed as being uniformly distributed within the fuel pin. Fig. 1 shows the fuel pin and guide/instrument tubes (same color with the water in the channel) distribution in the 17x17 array. There are 37 identical 17x17 PWR fuel assemblies in the TSC

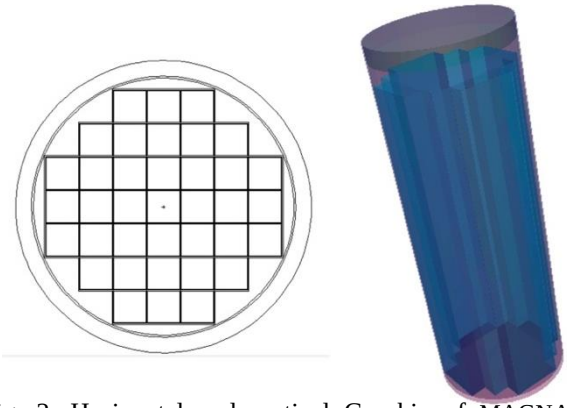

Fig. 2. Horizontal and vertical Graphic of MAGNASTOR

which are stored in the Stainless-Steel 304 (SS304) cross-shaped frame and separated by SS304 wall. This frame is surrounded by a cylinder also made of SS304, and the TSC itself is also surrounded by the thick concrete lid as shown in the Fig. 2.

Homogeneous Additive Model (HAM)

The geometrical type of the newly designed additive is a spherical bead. Each bead is made of borosilicate glass, chromium and helium which has a diameter of 2.286mm. The core of the bead is filled with helium gas and the glass is coated with chromium as shown in the Fig. 3. The first approach to the criticality analysis was to model the additive (beads) as homogeneous or assuming as a fluid. The validation of Homogeneous Additive Model (HAM) or the Fluid Additive Model (FAM) for the criticality analysis is assumed based on the following assumptions: a) a bead size is considerably small compared to the mean free path of neutrons in the system b) a size of beads and the friction between beads and materials are small enough to be considered as a fluid in the cask. According to HAM, since additives are assumed as fluid particles, every void space which is not occupied by water or uranium fuel is filled with additives. For example, the space between the fuel pins, inside of the guide/instrument tubes, and the TSC is filled with additives.

TABLE I
k_{eff} in Storage, Normal and Off-normal Conditions.

		Results (k_{eff})	
Case	**Description**	**Reference [5]**	**MCNP HAM**
Storage condition	Onsite SNF pool environment (submerged in the boric acid water)	0.8692	0.8642
Normal condition	Operation in a dry air cooled environment	0.3425	0.3218
Off-normal condition	100% water flooding environment	0.9262	0.8975

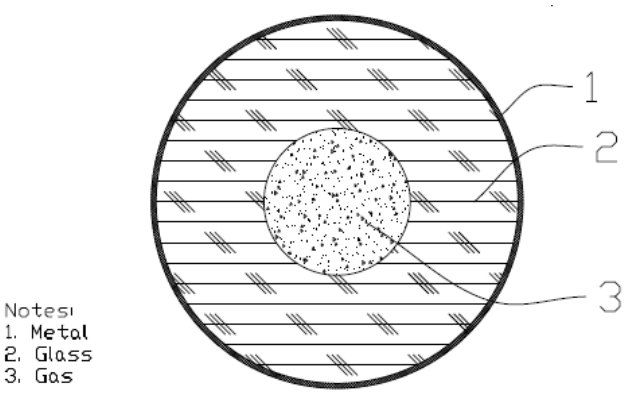

Fig. 3. Cross-sectional Image of Bead Design.

RESULTS

We developed the MCNP HAM to understand the neutron behavior and criticality condition of the TSC VCC system. In order to evaluate the validation of HAM with FAs, TSC and VCC design in MCNP6, we simulated the criticality analysis of the system. One neutron source located in the center of the system is used to initiate the reaction. According to HAM, additives act like fluid particles and they are able to be fully stacked if there is a space. In the research, we simulated three different conditions, namely storage, normal and off-normal conditions. According to the preceding simulation of Nuclear Criticality Safety Analysis (NCSA) with Used Nuclear Fuel Assemblies (UNFAs) in the GBC-32 cask, k_{eff} result is calculated around 0.8692 when UNFAs are stored in the water pool [4]. Similarly, the k_{eff} calculation of HAM in MCNP is shown k_{eff} is 0.8642. Other conditions we considered are normal and off-normal conditions. According to the results demonstrated by T. Kim et al. [5], k_{eff} values of dual purpose metal casks with nuclear FAs in normal condition is 0.3425. In the off-normal condition (natural disaster condition) which is perfectly flooded by the natural water, the k_{eff} is 0.9262. Both k_{eff} values are similar with MCNP HAM simulation results. In the former case, MCNP HAM shows k_{eff} is 0.3218 and the latter case, MCNP HAM shows k_{eff} is 0.8975 (TABLE I).

Effect of Packing Fraction (PF)

In accordance with the theory of packing, there is a limited packing fraction of material. Theoretically, the maximum packing fraction can reach up to 74% with hexagonal closest packing (HCP) and our model also have a packing fraction limit which is given as follows.

$$PF_{HCP,max} = \frac{N_{bead} V_{bead}}{V_{unit\ cell}} \approx 0.74048 \quad (1)$$

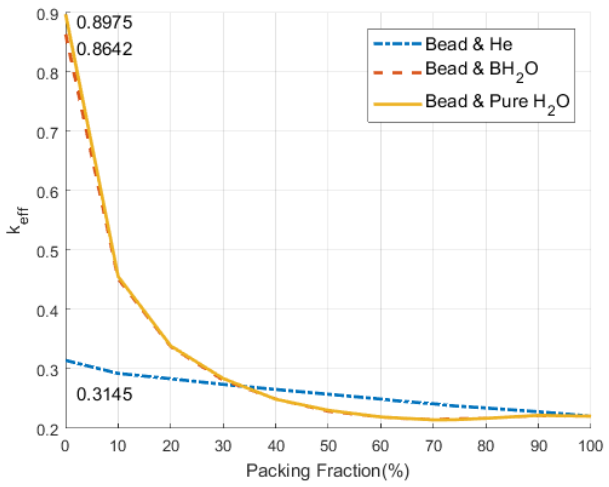

Fig. 4. k_{eff} Changes When Bead PF Increases from 0% to 100% with Different Supplement, He, BH_2O and Pure H_2O.

where N_{bead} is the number of beads in unit cell, V_{bead} is the volume of a single bead, and $V_{unit\ cell}$ is the volume of the HCP unit cell.

Based on the most recent experiment [6], it analytically predicts that the packing fraction of solid spherical objects cannot exceed 63.4% assuming a RCP (Random Close Packing) structural model. In the analysis, we varied the packing fraction gradually from 0% to 100% in a 10% steps; however, 63.4% and 74% were also included since they represent the RCP and HCP densest packing fractions, respectively. We then ran three cases, the void fraction around the beads being filled with a) He, b) H_2O with boric acid (donated simply as BH_2O), and c) Pure H_2O. All three cases are meaningful in each SNF storing process. Initially, the SNF is stored in the onsite borate water pool. Then, the water in the TSC is drained out and the cask is backfilled by helium. In the abnormal situation such as water permeation through cracks or a broken cask, ground water can be flooded into the cask. The k_{eff} results for different packing fractions are shown in Fig. 4 and the Bead & BH_2O and Bead & Pure H_2O curves have a minimum k_{eff} value near 70%, not at 100%.

Effect of Moderators

We suspect that k_{eff} drop phenomenon (k_{eff} increases again after exceeding the certain threshold level when PF increases) is because of the neutron thermalization effect by the moderator such as H_2O. Theoretically, since the absorption cross section of ^{10}B increases when the neutron energy decreases, we expect that there is an optimized ratio between the beads and the moderator with respect to

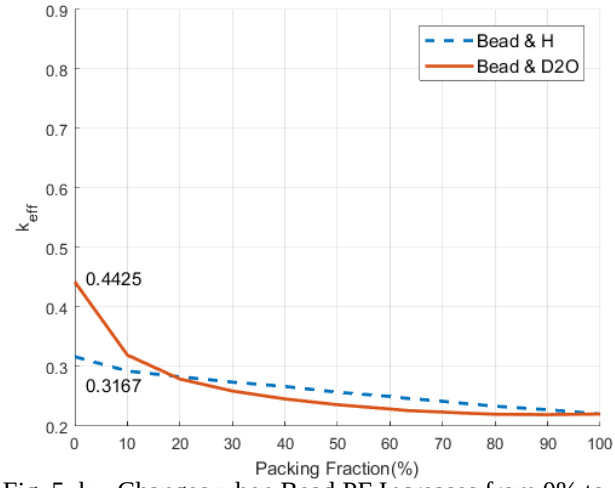

Fig. 5. k_{eff} Changes when Bead PF Increases from 0% to 100% with Different Moderator, H and D_2O.

multiplication of the system. In order to verify our hypothesis, we simulated with different moderators, namely D_2O and hydrogen. The k_{eff} results of other moderator cases are shown in Fig. 5. Similar to the case of water, heavy water also has a minimum k_{eff} value at a PF of 80%. The k_{eff} drop phenomenon is also observed with the D_2O moderator. This result supports the moderator effect idea which is assumed in the previous H_2O moderator case. On the other hand, Bead & H, a theoretically effective moderation material, does not show the same result and the k_{eff} drop phenomenon is not observed. This seemingly inconsistent result can be explained by moderator state (gas or liquid). Since we used natural hydrogen gas for the calculation, it shows a similar curve or trend as the helium case. At a low-density gas, those materials are almost invisible to neutrons.

Effect of Helium Density

We explained the inconsistency of effect between hydrogen and other moderators (H_2O and D_2O) as its state (gas or liquid) and density. In order to verify the effect of the gas state of the moderator to the neutron thermalization and criticality of the system, we ran MCNP to simulate the criticality change by increasing PF of the system with four different helium densities, ρ=0.000166, 0.000332, 0.000664, and 0.001382 [g/cm^3]. The k_{eff} data is plotted in accordance with PF is shown in Fig. 6. There is no noticeable variance of k_{eff} between the different helium densities. This was to be expected as even "high" density helium gas is still a low-density material with a very small neutron interaction cross section.

Effect of Boron Concentration in the Water

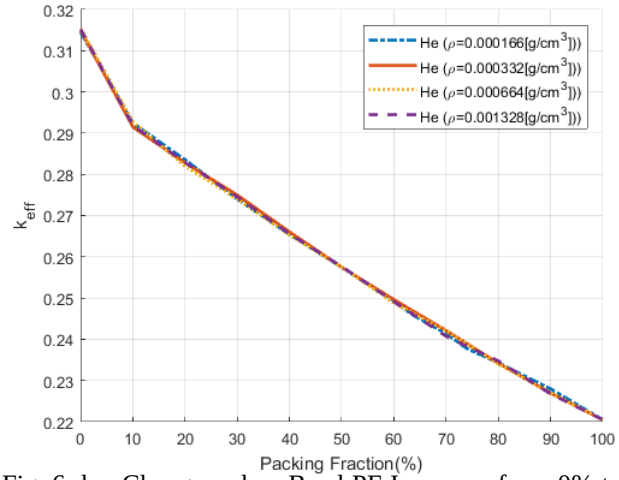

Fig. 6. k_{eff} Changes when Bead PF Increases from 0% to 100% with Different Helium Density.

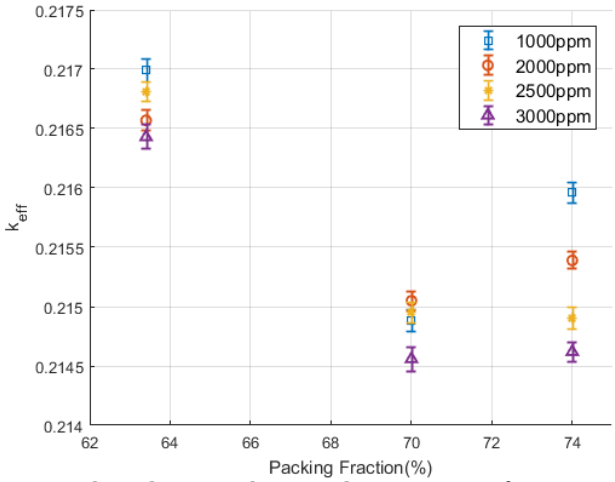

Fig. 7. k_{eff} Changes when Bead PF Increases from 63.4% to 74% with Different ^{10}B Concentration.

When the spent nuclear fuel assemblies are stored at the NPP site, they are generally submerged in the spent fuel pool which is filled with water containing boron as a poison. Depending on the conditions of the plant, the boron concentration may vary from site to site and over time. Therefore, we analyzed the k_{eff} change when PF increases from 63.4% to 74% in a system with different boron concentrations, 1000, 2000, 2500 and 3000ppm. The k_{eff} results with error bar is shown in Fig. 7. According to results, the k_{eff} variation with different boron concentrations does not change significantly (within 5%). Therefore, we can assume that boron concentration of the cooling water in the cask does not affect system criticality very much because 99% of the ^{10}B in the system came from the additive (enriched in ^{10}B), not boron solution in the water (natural boron).

CONCLUSIONS

We have developed and simulated the advanced nuclear fuel cask additives by using MCNP6 in order to analyze their application. For studying the effect of the additives in the spent nuclear fuel storage system, we suggest the homogeneous additives model as the first approach. We used the concept of the effective multiplication factor to estimate the validity of our suggested model, and simulated this under three different conditions: onsite storage, normal, and off-normal conditions. In the case of the onsite storage conditions which is FAs and TSC are completely filled with borate water, the k_{eff} result of our simulation in MCNP HAM is 0.8642. In normal and off-normal conditions, FAs are surrounded by dry air and water in the TSC, the resultant k_{eff} values are 0.3218 and 0.8975, respectively. We demonstrated calculated k_{eff} values in the MCNP HAM simulation are consistent with preceding research results [4][5]. After the estimation of validity, we studied further about the neutronics of our design. First, we looked at the k_{eff} changes with different packing fractions of additive. We found there is an optimized packing fraction at around 70% in terms of the criticality of the system, in other words, there is a minimum k_{eff} value of 0.2170. Also, in order to understand the k_{eff} drop phenomenon, we focused on the effects of moderators such as light water and heavy water. Consequently, the k_{eff} drop phenomenon was also observed in another moderator, D_2O, and we found k_{eff} drop phenomenon is the result of the moderator effect. In the gas state fluid, gas has a negligible effect on the k_{eff} of the system. In cases of dry air, hydrogen and helium, k_{eff} are 0.3218, 0.3167, and 0.3145 respectively. We also examined the effect of ^{10}B concentration on k_{eff} and found different ^{10}B concentrations have not significantly affected the k_{eff} value of the system.

ACKNOWLEDGMENTS

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