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A CRITICALITY EVALUATION AND BIAS AND BIAS UNCERTAINTY ESTIMATION OF GBC-32 CASK FROM THE VIEWPOINT OF BURNUP CREDIT

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ABSTRACT: *The capability of on-site storage of used nuclear fuels in South Korea is project to reach the limit from 2024. So it is necessary to utilize a dry storage system of UNFs and perform the accurate safety evaluations. The objectives of this work is to (1) perform the criticality evaluation for burnup credit of the GBC-32 dry storage cask with the domestic fuel assemblies with the axial burnup distributions and average discharge burnups, and (2) determine the bias and bias uncertainty in* k_{eff} *resulted from biases and bias uncertainties in the calculated nuclide concentrations for the cask. First,* k_{eff} *values were calculated for the GBC-32 cask specified in previous subsection as a function of the cooling time for the PLUS7 16x16 fuel assemblies by using SCALE6.1/STARBUCS and MCNP6 code. The* k_{eff} *values were calculated for 3 cooling times of 0, 20, and 30 years. Most of the discharged fuel assemblies were allowed to be stored for the cooling times of 20 and 30 years. Second, The SCALE6.1/STARBUCS, SCALE6.1/TRITON code, and the IBM SPSS Statistics Version 23 program were used to evaluate the bias and bias uncertainty in* k_{eff}*. The* k_{eff} *bias and bias uncertainty value was 0.035151.*

KEYWORDS: *GBC-32 Dry Storage Cask, Criticality Evaluation, Burnup Credit, Bias and Bias Uncertainty, SCALE 6.1 Code.*

I. INTRODUCTION

The capability of on-site storage of used nuclear fuels (UNFs) generated in the domestic nuclear power plants is project to reach the limit from 2024, including re-racking and on-site transportation of UNFs. As an alternative of this awkward situation, it is necessary to utilize a dry storage system (DSS) for storage of UNFs and perform the accurate safety evaluations of the DSS. The current criticality safety evaluation assumes the only unirradiated fresh fuels with the maximum enrichment in a dry storage cask (DSC) for conservatism without consideration of the depletion of fissile nuclides and the generation of neutron-absorbing fission products. However, the large conservatism leads to the significant increase of the storage casks required. Thus, the application of burnup credit (BUC) which takes credit for the reduction of reactivity resulted from fuel depletion can increase the capacity in storage casks. On the other hand, the BUC application introduces lots of complexity into a criticality safety analysis such as the accurate estimation of the isotopic inventories and the burnup of UNFs and the validation of the criticality calculation. In this work, The objectives is to (1) perform the criticality evaluation for BUC of the Generic 32 PWR-assembly Burnup Credit (GBC-32) DSC (Ref. 1) with the domestic fuel assemblies with the axial burnup distributions and average discharge burnups, and (2) determine the bias and bias uncertainty in k_{eff} resulted from biases and bias uncertainties in the calculated nuclide concentrations for the cask. First, k_{eff} values were calculated for the GBC-32 cask as a function of the cooling time for the PLUS7 16x16 fuel assemblies by using SCALE6.1/STARBUCS and MCNP 6 codes. The k_{eff} values were calculated for 3 cooling times of 0, 20, and 30 years. Second, The SCALE6.1/STARBUCS, SCALE6.1/TRITON code, and the IBM SPSS Statistics Version 23 program were used to evaluate the bias and bias uncertainty in k_{eff}. Random numbers were generated from the standard normal distribution, i.e., the normal distribution with the distribution mean of zero and standard deviation of unity.

II. BURNUP CREDIT CRITICALITY EVALUATION

II.A. Used Nuclear Fuel and Dry Storage Cask Design

The UNFs applied to this paper were the PLUS7 16X16 assemblies which were discharged after Cycle 6 of Hanbit Nuclear Power Plant Unit 3. Fig. 1 shows the normalized axial burnup distributions for 20 UNFs discharged after Cycle 6, where the various colored solid lines represent the axial burnup distributions of 20 UNFs with 20 equally-spaced axial regions.

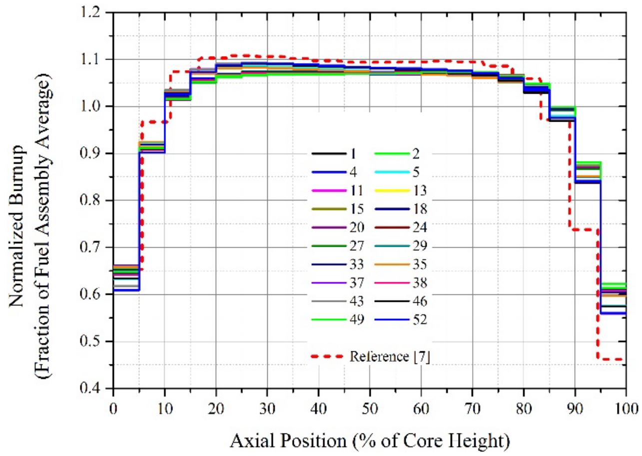

Fig. 1. Axial burnup distributions for 20 UNFs.

In addition, the nuclides considered for the application of BUC were only the nine major actinides: U-234, U-235, U-238, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, and Am-241 (Ref. 1).

II.B. Results and Evaluations

k_{eff} values were calculated for the GBC-32 cask as a function of the cooling time for the PLUS7 16x16 fuel assemblies using STARBUCS and MCNP 6 code. The k_{eff} values were calculated for 3 cooling times of 0, 20, and 30 years and plotted in Figs. 2, 3, and 4. The black square and red circle denote the results calculated by STARBUCS code for the uniform and non-uniform axial burnup distributions, respectively, and the blue triangle and green inverted triangle denote the results calculated by MCNP 6 code for the uniform and non-uniform axial burnup distributions, respectively.

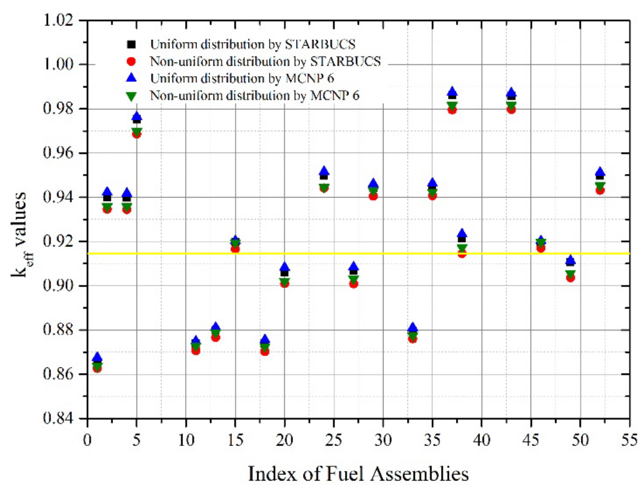

Fig. 2. k_{eff} values for the cooling time of 0 year.

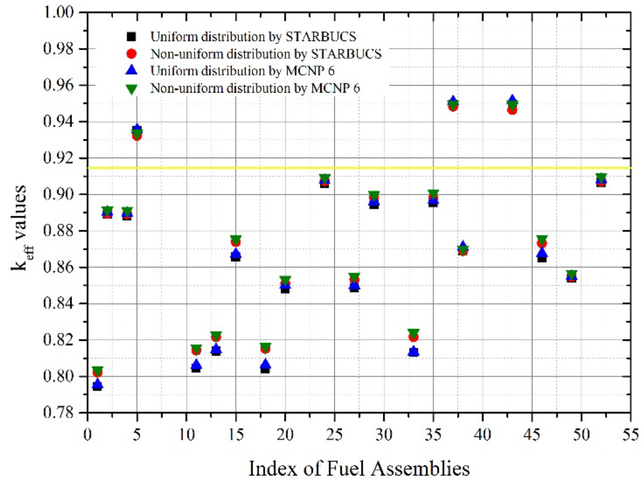

Fig. 3. k_{eff} values for the cooling time of 20 years.

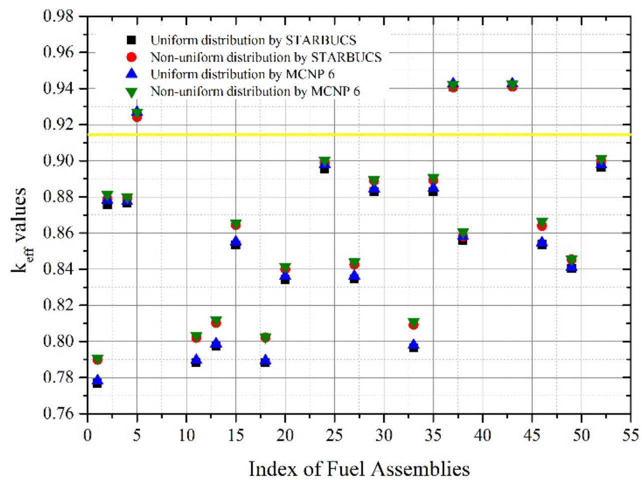

Fig. 4. k_{eff} values for the cooling time of 30 years.

An upper criticality safety limit for the GBC-32 cask was set to be 0.9146 using the bias uncertainties given in Refs. 2 and 3 and the yellow line denotes the upper criticality safety limit. Therefore, Fig. 2 indicates that 12 discharged fuel assemblies for the cooling time of 0 year were not allowed to be stored in the cask because the estimated k_{eff} values exceeds 0.9146. Figs. 3 and 4 indicate that most of the discharged fuel assemblies except for three discharged fuel assemblies were allowed to be stored for the cooling times of 20 and 30 years.

III. BIAS AND BIAS UNCERTAINTY ESTIMATE

III.A. Methodology of Bias and Bias Uncertainty

In a depletion validation, the Monte Carlo uncertainty sampling method is used to represent the effects of nuclide concentration uncertainty on k_{eff} values by sampling isotopic concentrations with uncertainty distributions developed from experimental data. The Monte Carlo uncertainty sampling method requires determination of biases and bias uncertainties in the calculated nuclide concentrations. Isotopic bias and bias uncertainty values for PWR UNF are shown in Table I (Ref. 2).

TABLE I. Isotopic Bias and Bias Uncertainty for PWR UNF (Ref. 2)

Burnup	15 < Burnup ≤ 40 GWd/MTU		
Nuclide	Number of samples	Isotopic bias	Isotopic bias uncertainty
U-234	43	0.9119	0.1749
U-235	69	0.9907	0.0416
U-238	69	1.0017	0.0042
Pu-238	65	1.1500	0.0923
Pu-239	69	0.9587	0.0375
Pu-240	69	0.9801	0.0317
Pu-241	69	1.0108	0.0514
Pu-242	69	1.0647	0.0783
Am-241	27	0.9312	0.2077

The new one-group cross section libraries of the ORIGEN code were generated with respect to the PLUS7 16X16 assembly using the SCALE 6.1/TRITON code. The burnup-dependent nuclide concentrations for the GBC-32 DSC were determined so that the k_{eff}-REF value was 0.94. The appropriate initial enrichment values for which the k_{eff}-REF value of the DSC system was made as 0.94 were searched as a function of specific burnup using the SCALE 6.1/STARBUCS code. The loading curve for the GBC-32 DSC with 32 PLUS7 16X16 UNFAs was developed using these initial enrichment values and final specific burnups. Fig. 5 shows the loading curve for the GBC-32 DSC with 32 PLUS7 16X16 UNFAs, where the region above the red line is k_{eff}-REF < 0.94, i.e. the region is acceptable to store 32 PLUS7 16X16 UNFAs in the DSC, whereas the region below the red line is k_{eff}-REF > 0.94, i.e. the region is unacceptable to store.

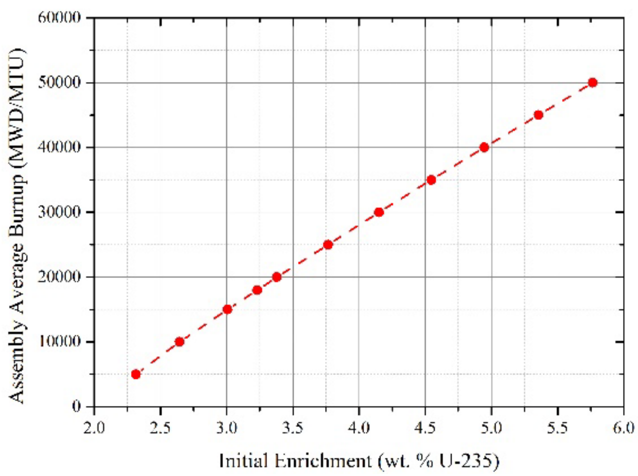

Fig. 5. Loading curve for the GBC-32 DSC.

In the Monte Carlo uncertainty sampling procedure, a normal distribution model is used to determine isotopic bias and bias uncertainty values. Random numbers were generated using the IBM SPSS Statistics Version 23 program. Fig. 6 shows 900 random numbers which have the normal distribution with the distribution mean of about 0.0104 and standard deviation of about 0.9600.

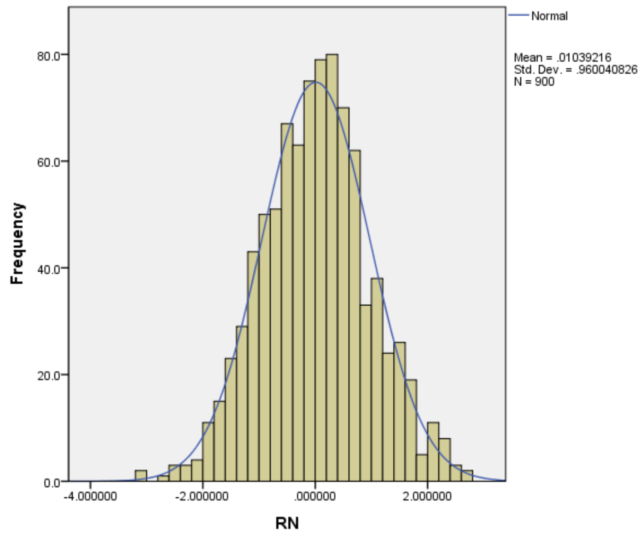

Fig. 6. 900 random numbers with a normal distribution.

III.B. Results and Evaluations

The fundamental parameters to model the GBC-32 DSC with the PLUS7 16X16 UNFAs, the isotopic bias and bias uncertainty values for PWR UNF compositions, the initial enrichments for the k_{eff}-REF value of the DSC, and the random numbers with the normal distribution were obtained. Using these data, 100 k_{eff} values for the final specific burnup of 30,000 MWD/MTU were computed by means of the SCALE 6.1/STARBUCS code and the 238-group ENDF/B-VII cross-section library. Fig. 7 shows the k_{eff} value for each index of a criticality calculation, the average k_{eff} value ranged from the first index to the target index, and the k_{eff} value for the calculated nuclide concentrations with no adjustments, k_{eff}-REF.

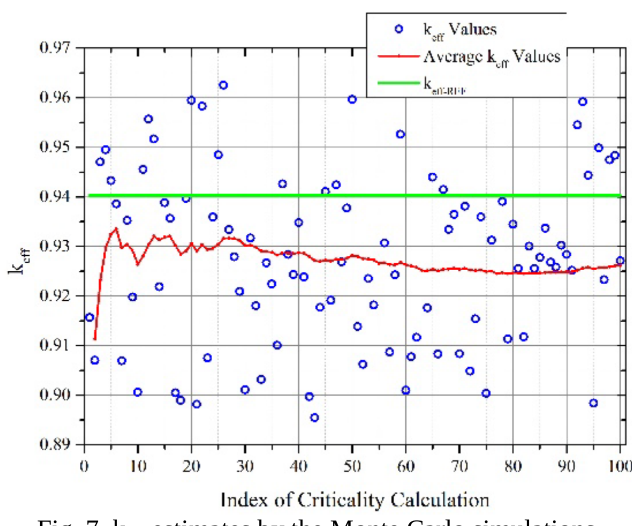

Fig. 7. k_{eff} estimates by the Monte Carlo simulations.

As a result, the bias in k_{eff} was 0.014108 through the result data in Fig. 7. Since the one-sided tolerance-limit factor for the normal distribution corresponding to NC=100, at a 95% probability, 95% confidence level was 1.927 (Ref. 4), the bias uncertainty in k_{eff} was 0.035151 through the result data in Fig. 7. Therefore, since the average k_{eff} value ranged from the first index to the last index was smaller than the k_{eff} value for the calculated nuclide concentrations with no adjustments, k_{eff}-REF as shown in Fig. 7, the k_{eff} bias and bias uncertainty value for this nuclear criticality safety analysis was 0.035151.

IV. CONCLUSIONS

First, the criticality evaluation for burnup credit was performed for the GBC-32 cask with the PLUS7 16X16 assemblies by SCALE6.1/STARBUCS and MCNP6 with the axial burnup distributions and average discharge burnups. k_{eff} values and end effects were calculated for 3 cooling times of 0, 20, and 30 years. Second, the bias and bias uncertainty in k_{eff} resulting from biases and bias uncertainties in the calculated nuclide concentrations were determined for the GBC-32 DSC system with 32 PLUS7 assemblies. From the results calculated in these conditions, the following conclusions are drawn.

- 12 discharged fuel assemblies for the cooling time of 0 year were not allowed to be stored in the cask because the estimated k_{eff} values exceeds 0.9146.
- Most of the discharged fuel assemblies except for three discharged fuel assemblies were allowed to be stored for the cooling times of 20 and 30 years.
- The criticalities evaluated with STARBUCS have good agreements with those evaluated with MCNP6.
- The average k_{eff} value ranged from the first index to the last index was smaller than the k_{eff} value for the calculated nuclide concentrations with no adjustments, k_{eff}-REF for all index of a criticality calculation.
- The k_{eff} bias and bias uncertainty value for this nuclear criticality safety analysis was 0.035151, which was the high value. Because the index of a criticality calculation was not enough and the sample standard deviation of the k_{eff} values from the Monte Carlo simulations was high.
- It is expected to be able to decrease the k_{eff} bias and bias uncertainty value if the index of a criticality calculation increases. Because the sample standard deviation of the k_{eff} values from the Monte Carlo simulations and the one-sided tolerance-limit factor decease as the index of a criticality calculation increases.

ACKNOWLEDGMENTS

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