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A Criticality Safety Analysis of the HI-STORM 100 Cask with Burnup Credit

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1. Introduction

In our country, the safe management of PWR Spent Nuclear Fuel (SNF)s is very urgent issue because the saturations of capacities of the spent fuel storage pools are expected from 2024(for Hanbit Units) even if the saturation points have been extended through high-density storage racks and transport of SNF between power plants. Under these situations, the construction and operation of interim dry storage facilities for PWR SNFs are necessary and the necessities of the criticality safety analysis are increasing for the dry storage and transportation casks of SNFs. In particular, the consideration of burnup credit for such systems is critical to improve the economy of the storage by reducing the excessive conservatisms related to the isotopic depletions of fissile nuclides and productions of fission products.

In this study, a detailed criticality safety analysis with consideration of burnup credit is performed for the HI-STORM 100 Cask System with the Westinghouse (WH) type 17x17 OFA spent fuel assemblies. In particular, we considered the several misloading configurations of low burnup spent fuels and the various axial burnup distributions for the well-known end effects.

2. Materials and Methods

2.1. HI-STORM 100 cask system and bounding burnup axial profiles

In this work, the MPC-24 of the HI-STORM 100 cask system was modeled as a reference dry storage cask of which the design data are from the HOLTEC report[1]. Figs. 1 and 2 show the configuration of the HI-STORM 100 cask and its detailed geometric modeling of basket cell for the criticality analysis using SCALE 6.1. HI-STORM 100 cask is a dry storage container surrounded by over-pack of concrete.

The Multi-Purpose Canister (MPC-24) which is a cylindrical structure accommodating lattice-shaped SNF storage space is considered to be placed inside the HI-STORM 100 cask system. The MPC-24 canister can store up to 24 light water reactor SNFs. In each basket cell of the MPC-24, a 0.055 inches thick boral plate in which 0.055 inches thick core of B_4C and Al mixture is surrounded successively by 0.01 inches Al cladding, 0.0035 inches gap, and 0.0235 inches SS (Stainless Steel) sheathing is placed and WH 17x17 OFA type spent fuel assemblies with an initial uranium enrichment of 4.00 w/o are loaded in the basket cell, as shown in Fig. 1.

Tables 1 and 2 summarizes the main specifications of the HI-STORM 100 cask system with MPC-24 and WH 17x17 OFA data from HOLTEC report[1].

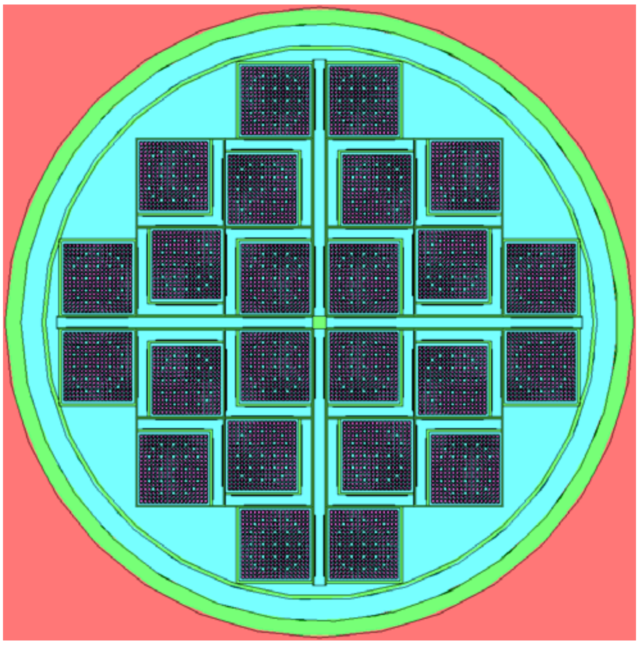

Fig. 1. Configuration of the HI-STORM 100 cask

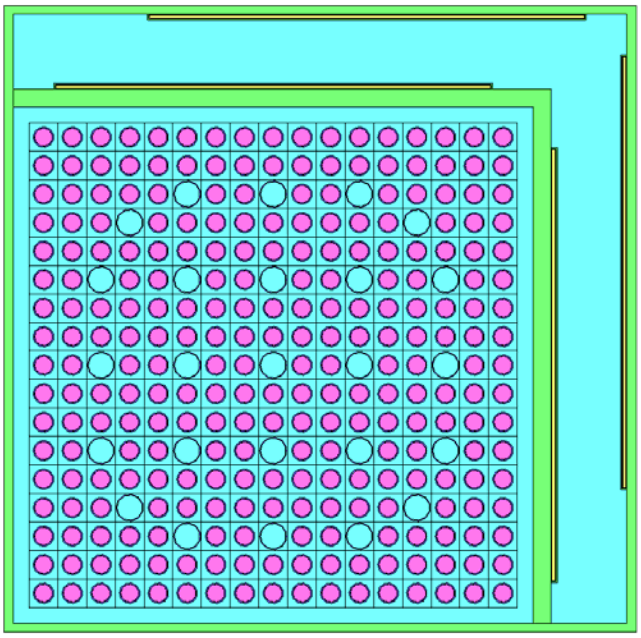

Fig. 2. Configuration of the basket cell of MPC-24

Table 1. HI-STORM 100 cask system specification

Parameter	**Value**
Over-pack thickness (cm)	68.04
Over-pack inner shell (cm)	4.98
Canister outer shell (cm)	1.2663
Neutron absorber material	Boral
Neutron absorber thickness (cm)	0.1397
Neutron absorber length (cm)	19.05
Neutron absorber Al cladding (cm)	0.0254
Neutron absorber clearance gap (cm)	0.0089
Neutron absorber SS sheathing (cm)	0.0597
Flux trap width (cm)	2.7686
Basket cell thickness (cm)	0.79375

Table 2. WH 17x17 OFA specification

Parameter	**Value**
Fuel material	UO_2
U-235 enrichment (w/o)	4.0
Fuel density (g/cm^3)	10.522
Number of fuel rods	264
Fuel pin radius (cm)	0.3922
Cladding inner radius (cm)	0.40005
Cladding outer radius (cm)	0.4572
Pin pitch (cm)	0.6299
Guide tube inner radius (cm)	0.56135
Guide tube outer radius (cm)	0.602
Active fuel length (cm)	365.76
Assembly pitch (cm)	22.8092

Also, the criticality calculation with burnup credit was performed by applying the bounding axial burnup profiles shown in Fig. 3[2]. It has been known that bounding axial burnup profiles produce the largest end effect (i.e., the difference in k_{eff} between a calculation with the axial-burnup distribution and a calculation that assumes uniform axial burnup)[2]. As shown in Fig. 3, the bounding axial burnup profile is given for each of twelve burnup groups.

2.2. Computational method

The STARBUCS sequence of SCALE 6.1 is used for the criticality calculations with the 238 group ENDF/B-VII.r0 nuclear cross section library and with burnup credit. We considered the bounding axial profiles given in Fig. 3. In this work, we used 500 cycles and 10000 particles for each cycle which gave the small standard deviation of ~ 40pcm.

The reference SNF assembly is the Westinghouse OFA type spent fuel assembly of 40 MWD/kg burnup. We considered the burnup credit using two different sets of nuclides given in Table 3. The nuclides were suggested for the burnup credit using SCALE code system in NUREG/CR-6801[2].

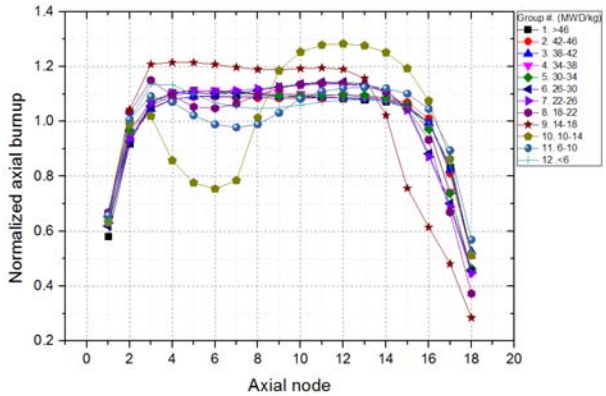

Fig. 3. Bounding axial profiles by burnup group

Table 3. Nuclide classifications used for the analyses

Set 1 : Actinide-only nuclides (10 total)				
U-234	U-235	U-238	Pu-238	Pu-239
Pu-240	Pu-241	Pu-242	Am-241	O*
Set 2 : Actinide and fission-product nuclides (29 total)				
U-234	U-235	U-236	U-238	Pu-238
Pu-239	Pu-240	Pu-241	Pu-242	Am-241
Am-243	Np-237	Mo-95	Tc-99	Ru-101
Rh-103	Ag-109	Cs-133	Sm-147	Sm-149
Sm-150	Sm-151	Sm-152	Nd-143	Nd-145
Eu-151	Eu-153	Gd-155	O*	

*Oxygen is neither an actinide nor a fission product, but included because it is an integral part of fuel.

All the cases were analyzed for fully flooded conditions for conservatism. The USL (Upper Subcritical Limit)s were set based on the isotopic uncertainties[3] and k_{eff} uncertainties including biases related to the cross section uncertainties[4] versus burnup that are suggested in NUREG/CR-7108 and 7109, respectively. Also, we considered the administrative margin of 0.05 Δk in determining USL. The determined USLs are shown in Table 4.

Table 4. USLs determined based on the isotopic and k_{eff} bias and bias uncertainties by burnup

Burnup (MWD/kg)	**Isotopic k_{eff}**		**k_{eff}**				**USL[d]**	
	Bias uncertainty[a]		**Bias[b]**		**Bias uncertainty[c]**			
	Set 1	**Set 2**	**Set 1**	**Set 2**	**Set 1**	**Set 2**	**Set 1**	**Set 2**
0-15	0.01430	0.01480	-0.00160	-0.00158			0.91950	0.91902
15-30	0.01500	0.01540	-0.00160	-0.00158	0.0146		0.91880	0.91842
30-45	0.01700	0.01630	-0.00162	-0.00157			0.91678	0.91753

[a] Bias is not considered at isotopic k_{eff} because it is a positive value.
[d] USL(Upper Subcritical Limit) = 0.95 – (a) + (b) – (c)

3. Results

3.1. Selection of axial burnup profile

To select a bounding axial burnup profile as conservative as possible, we used the following two steps : 1) Evaluation of the end effects of the reference SNF assembly (40MWD/kg) with the bounding axial burnup profiles given in Fig. 3. 2) Evaluation of the end effects of the SNF assemblies having average burnups of burnup groups and their corresponding bounding profiles given in Fig. 3.

The result of the first step is given in Fig. 4, which shows that the bounding axial burnup profile for the 9th burnup group gives the largest end effects for two sets of nuclides for burnup credit. Fig. 5 compares the end effects of the second step. As shown in Fig. 5, the end effects for the 9th burnup group with its bounding burnup profile are very large in spite of its low burnup for two sets of nuclides for burnup credit.

Therefore, we selected the bounding burnup profile for 9th burnup group as the conservative boundary burnup profile.

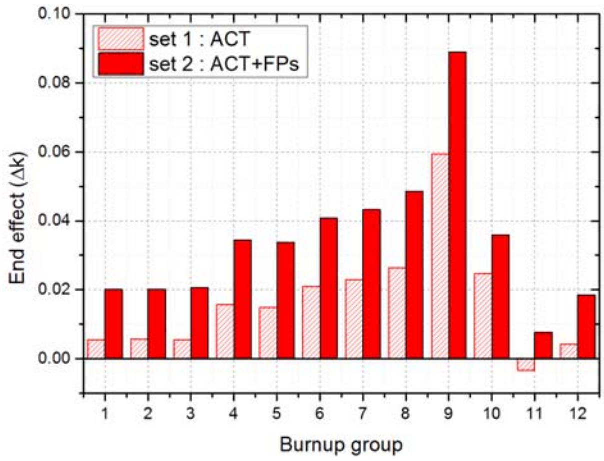

Fig. 4. End effect by applying the bounding axial profiles corresponding a fixed burnup of 40 MWD/kg

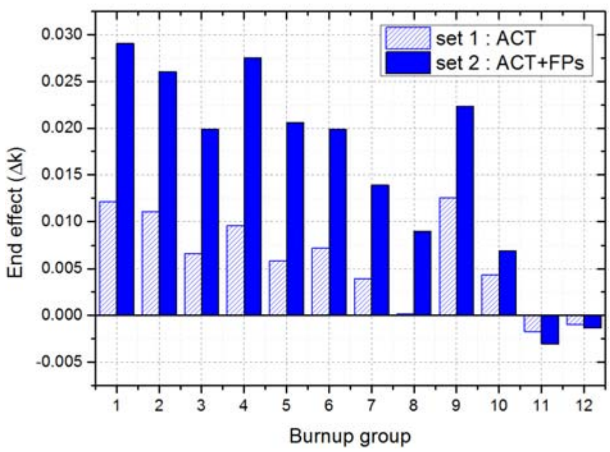

Fig. 5. End effect by applying the bounding axial profiles corresponding burnup group

3.2. Misloading analyses

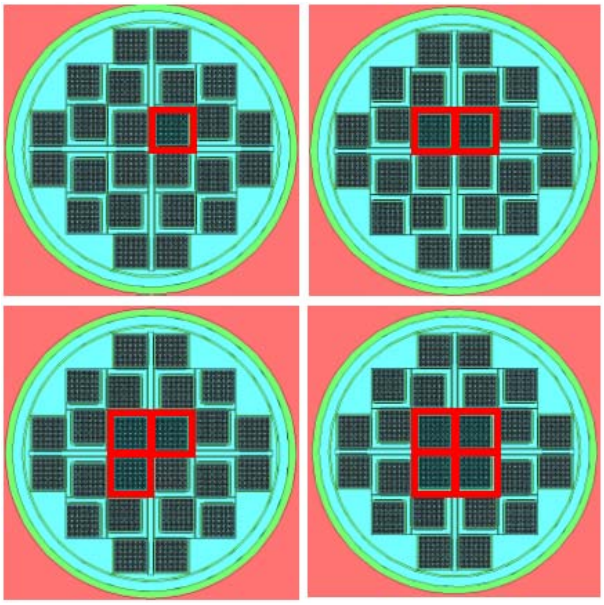

Fig. 6. Configuration of the misloading cases

The postulated misloading of fresh or low burnup fuel assemblies should be considered in the criticality safety analysis. In this work, we considered the misloading accidents in which 1~4 fuel assemblies of low burnup of 16 MWD/kg are misloaded in the central region of the canister filled with high burnup of 40 MWD/kg assemblies with application of the bounding axial burnup distribution for 9th burnup group by reflecting the results of sec. 3.1. Fig. 6 shows the considered configurations of the misloadings. Table 5 shows the k_{eff}'s estimated with the different numbers of misloaded assemblies. All the cases give lower k_{eff} values than USL (i.e.,0.91678 and 0.91753 for the nuclide sets 1 and 2, respectively).

Table 5. The estimated k_{eff} for the considered misloadings

Number of misloaded assemblies	k_{eff}	
	Set 1	Set 2
1	0.81066(41)*	0.76951(40)
2	0.82472(44)	0.78720(41)
3	0.83380(37)	0.79717(40)
4	0.84276(40)	0.80885(36)

* Standard deviation (pcm) of the k_{eff} from the SCALE 6.1.

3.3. Loading Curve

In this section, we evaluated the loading curves which specify the acceptable loading region in the initial uranium enrichment and burnup space based on the USL give in the Table 4. The STARBUCS sequence of SCALE 6.1 has a function to automatically search the initial enrichment that corresponds to the USL values with a given burnup and a cooling time. In this work, we didn't consider cooling time and used the bounding axial burnup profile for the burnup group 9. The obtained loading curves are plotted in Fig. 7. In Fig. 7, the points correspond to all the fuel assemblies discharged from Kori Unit 3 and 4. From the loading curves, it was shown that all the fuel assemblies can be loaded regardless of the set of nuclides.

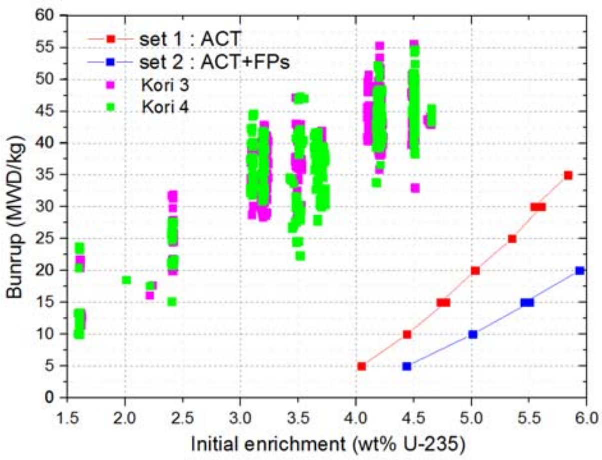

Fig. 7. Initial enrichment loading curve according to the burnup

4. Conclusion

In this work, we performed criticality analysis of MPC-24 of HI-STORM 100 cask system considering burnup credit with STARBUCS sequence of scale 6.1. For the conservative analysis, 100% submerged condition was assumed in the cask with a bounding axial profile that gives the most positive value end effect.

The end effect analysis for searching bounding axial burnup profile showed that the end effects are all positive for the actinides only and for actinides and fission products sets except for very low burnup. (i.e., < 10 MWD/kg), the end effects with actinides and fission products sets range from 0.006 Δk to 0.029 Δk, and the bounding axial burnup profile for the low burnup group (14~18 MWD/kg) gives the conservatively large end effect.

From the misloading analysis with the conservative axial burnup profile, it is shown that misloading of four low burnup SNF assemblies of 16 MWD/kg are acceptable in terms of criticality in the MPC-24 loaded with reference SNF assemblies of 40 MWD/kg.

Finally, the loading curve analysis showed that the SNF assemblies discharged from Kori unit 3 and 4 are acceptable for loading with burnup credit application in the MPC-24.

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