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Nuclear Criticality Analyses of Two Different Disposal Canisters for Deep Geological Repository Considering Burnup Credit

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The nuclear criticality analyses considering burnup credit were performed for a spent nuclear fuel (SNF) disposal cell consisting of bentonite buffer and two different types of SNF disposal canister: the KBS-3 canister and small standardized transportation, aging and disposal (STAD) canister. Firstly, the KBS-3 & STAD canister containing four SNFs of the initial enrichment of 4.0wt% ^{235}U and discharge burnup of 45,000 MWD/MTU were modelled. The k_{eff} values for the cooling times of 40, 50, and 60 years of SNFs were calculated to be 0.79108, 0.78803, and 0.78484 & 0.76149, 0.75683, and 0.75444, respectively. Secondly, the KBS-3 & STAD canister with four SNFs of 4.5wt% and 55,000 MWD/MTU were modelled. The k_{eff} values for the cooling times of 40, 50, and 60 years were 0.78067, 0.77581, and 0.77335 & 0.75024, 0.74647, and 0.74420, respectively. Therefore, all cases met the performance criterion with respect to the k_{eff} value, 0.95. The STAD canister had the lower k_{eff} values than KBS-3. The neutron absorber plates in the STAD canister significantly affected the reduction in k_{eff} values although the distance among the SNFs in the STAD canister was considerably shorter than that in the KBS-3 canister.

Keywords: Nuclear criticality analysis, Burnup credit, Disposal cell, KBS-3 disposal canister, STAD disposal canister, Spent nuclear fuel

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1. Introduction

A deep geological disposal has been recognized and adopted as an effective and efficient management solution of high-level radioactive wastes and spent nuclear fuels (SNFs). In general, a deep geological disposal system consists of a surface and an underground facility. A surface facility includes an encapsulation plant, a ventilation building, and other buildings. An underground disposal facility that refers to as a "deep geological repository (DGR) system" is composed of an engineered and a natural barrier system. An engineered barrier system contains a lot of deposition holes, tunnels, and other openings. One long horizontal deposition tunnel is connected with many vertical deposition holes. One vertical deposition hole allows emplacement of one disposal canister and surrounding buffer. One disposal canister stores four pressurized water reactor (PWR) type SNFs. A natural barrier includes a near-field and a far-field geological formation [1-2].

The design of a disposal system requires an accurate nuclear criticality analysis (NCA) considering burnup credit (BUC). The consideration of BUC to an NCA has an effect on the decrease of the effective neutron multiplication factor (k_{eff}) of a disposal system. Because the reactivity of the SNFs in the system decreases due to the depletion of fissile nuclides and the production of neutron-absorbing fission products in nuclear fuels. In general, an NCA considering BUC of a disposal system is carried out according to the following steps:

(1) A calculation of the isotopic compositions in SNFs using a computational tool of fuel depletion, and
(2) An assessment of the k_{eff} value for a DGR system using a computational tool of nuclear criticality.

The performance criterion for an NCA of a DGR system is that the k_{eff} value of the system should not exceed 0.95 including uncertainties under all credible normal and abnormal operating conditions. In addition, credit for burnup of nuclear fuels may be taken [3-11].

In Finland, the design of the Posiva's DGR system in the construction license application is the Kärnbränslesäkerhet 3-Vertikal (KBS-3V) system that is based on vertical emplacement of disposal canisters. In Sweden, that of SKB's DGR system is also KBS-3V [1-2]. The conceptual design of the Posiva and SKB disposal canister is that four PWR-type SNFs are placed into a cast iron insert which is enclosed in a copper shell and lid [12-13]. This type of disposal canister refers to as a "KBS-3 canister" in this paper. On the other hand, in United States of America, the conceptual design of the disposal canister of Department of Energy is that four PWR-type SNFs are placed into an internal basket assembly which is located in the inside cavity of a copper and steel shell and lid [14-15]. This type of disposal canister refers to as a small capacity "Standardized Transportation, Aging and Disposal (STAD) canister". A vertical deposition hole consisting of one disposal canister with four PWR-type SNFs and the surrounding buffer and the host rock near the deposition hole refers to as a "disposal cell".

The main objectives of this paper are

(1) to perform the NCAs considering BUC for the disposal cells in which one KBS-3 or STAD canister is emplaced,
(2) to determine whether the k_{eff} values for the analysis cases meet the performance criterion, $k_{eff} < 0.95$, and
(3) to compare the analysis results and then evaluate which system of two different canisters is more subcritical.

In addition, the fuel type of the SNFs in the KBS-3 or STAD canister is the PLUS7 16×16 nuclear fuel which has been irradiated in the most PWRs in South Korea. The discharge burnups of the SNFs are categorized into two groups: the lower and higher burnup group. For the lower burnup group, the initial enrichment and discharge burnup of the SNFs are 4.0wt% ^{235}U and 45,000 MWD/MTU, respectively. For the higher burnup group, the enrichment and burnup are 4.5wt% ^{235}U and 55,000 MWD/MTU, respectively.

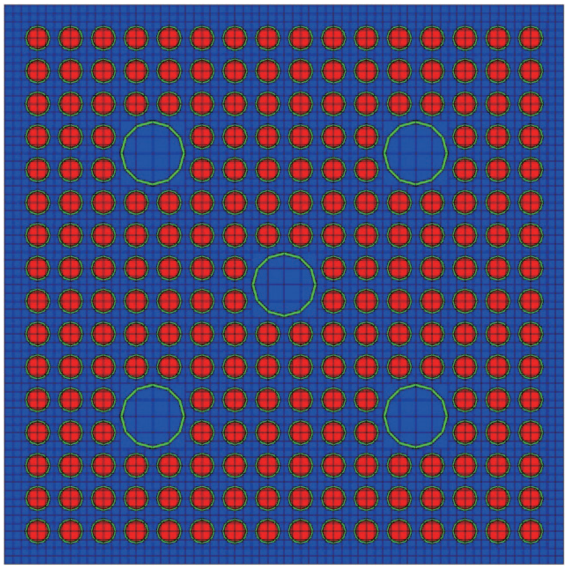


Fig. 1. Geometry of PLUS7 nuclear fuel.

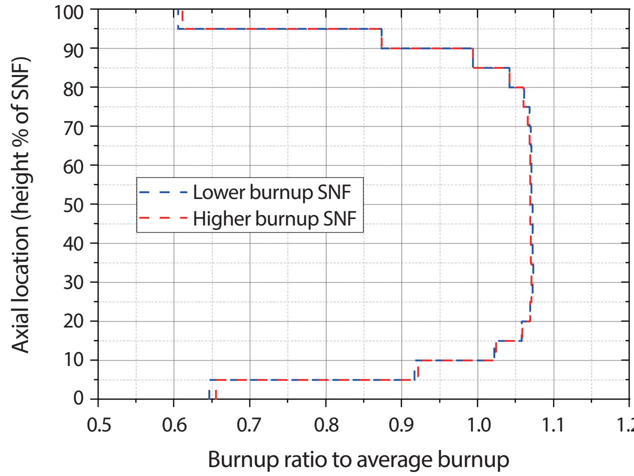


Fig. 2. Axial burnup profiles of lower and higher burnup SNF.

The computational softwares to use for NCAs considering BUC are

(1) the SCALE-TRITON code to generate the nuclear reaction cross-section (XS) libraries required for a depletion calculation of a nuclear fuel and
(2) the SCALE-STARBUCS code to assess the k_{eff} value for a disposal cell system after a calculation of a fuel depletion.

2. Analysis Processes

2.1 Generation of Nuclear Reaction XS Libraries

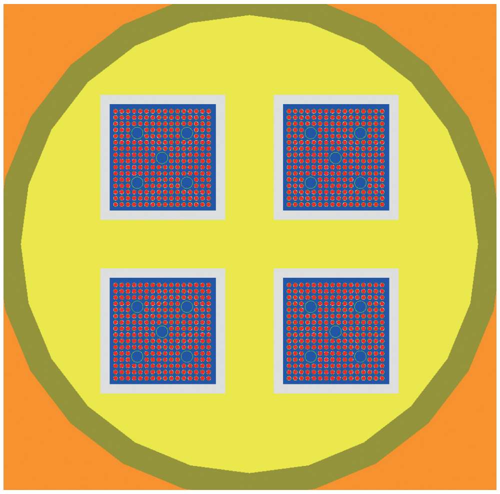
A lot of the nuclear reaction XS libraries for the PLUS7 16×16 nuclear fuel were newly produced in order to apply XS libraries for the fuel depletion calculation. In detail, using the TRITON code, new fourteen XS libraries were produced with fourteen initial enrichments of 0.5 to 6.0wt% ^{235}U and forty-one burnups of 0 to 69,200 MWD/MTU. Fig. 1 shows the geometry of one nuclear fuel modelled by the TRITON code. The red, green and blue regions represent the UO_2 rod of the PLUS7 fuel, the zircaloy-4 cladding tube, and H_2O water, respectively.

New nuclear reaction XS libraries were applied to the SCALE-ORIGEN-S code which calculates the isotopic compositions in SNFs due to the fuel depletion. The ORIGEN-S code is one of two codes of which the STARBUCS code is composed [16].

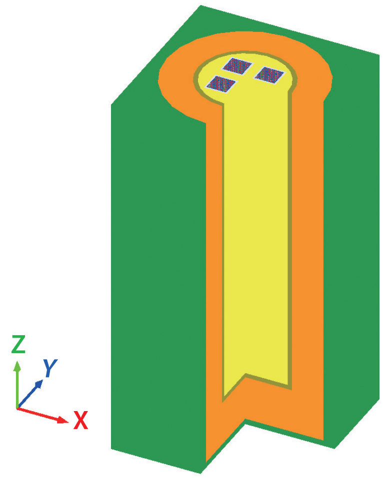
The Evaluated Nuclear Data Files, Part B (ENDF/B)-VII 238-group XS library for the nuclear criticality assessments was applied to the STARBUCS code.

2.2 Selection of Axial Burnup Profile

In Ref. 9, the PLUS7 16×16 nuclear fuels were assumed to be discharged at the Hanbit PWR Unit 3. Then, the normalized axial burnup profiles of twenty SNFs were predicted with twenty axial regions. However, in this work, the only two groups of the PLUS7 SNFs were applied to perform the NCAs. One axial burnup profile was suitably selected based on the lower burnup SNF with the initial enrichment of 4.0wt% ^{235}U and discharge burnup of 45,000 MWD/MTU. The other was selected based on the higher burnup SNF with the initial enrichment of 4.5wt% ^{235}U and discharge burnup of 55,000 MWD/MTU. Fig. 2 shows the



(a) x-y cross-sectional view



(b) 3D sliced view

Fig. 3. Design modelling of KBS-3 canister.

axial burnup profiles of the lower and higher burnup SNF. As the vertical axis stands for the percentage of the height of the PLUS7 SNF, "0%" means the bottom of the SNF height and "100%" the top. The horizontal axis indicates the ratio of the height-dependent discharge burnup to the average discharge burnup. The blue and red dash line represent the axial burnup profiles of the lower and higher burnup SNF, respectively.

The region from 10% to 90% of the SNF height was greater than the average discharge burnup, while the other region was lesser. These axial burnup profiles were set to the STARBUCS code.

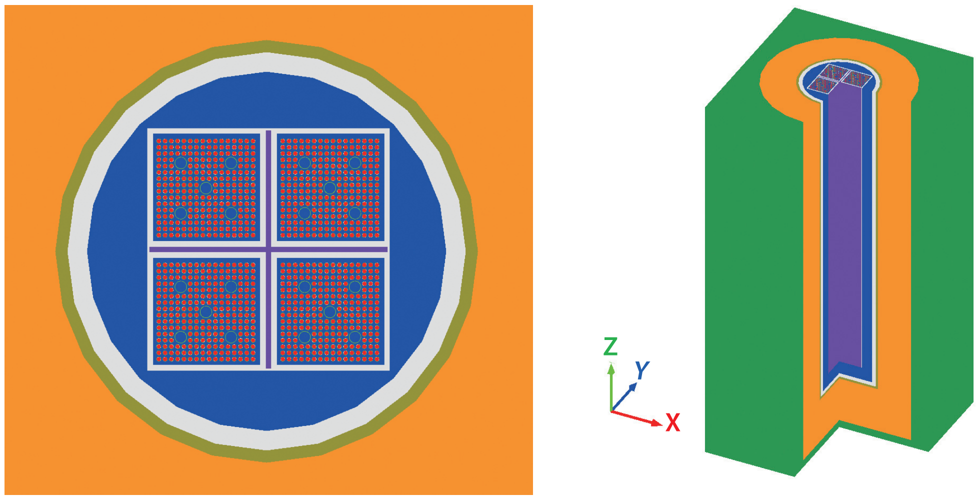
The selected nuclides to consider BUC were only nine major actinides: ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am. Because the concentrations of these nuclides calculated using a computational tool of the fuel depletion have been validated enough in comparison with those measured using a lot of destructive radiochemical and non-destructive experiments. Thus, the uncertainty generated by the calculation considering these nuclides was small sufficiently. However, several neutron-absorbing fission products were not considered in this paper. Because those of these nuclides have not been validated enough yet, the uncertainty considering these nuclides was quite large [8-10].

2.3 Modelling of Disposal Cell System

Two different disposal cell systems in which one KBS-3 or STAD canister was emplaced were modelled in full scale. The vertical deposition hole consisting of one disposal canister with four PWR-type SNFs and the surrounding buffer was modelled. Moreover, the host rock around the outside of the deposition hole was modelled. Finally, the three-dimensional (3D) geometries of two different systems were completed. The chemical composition ratios and volumetric mass densities of all constituent materials were applied to the SCALE-KENO V.a code. The KENO V.a code is one of two codes of which the STARBUCS code is composed [16]. In particular, the detailed design informations on the KBS-3 and STAD canister were explained in the following subsections.

2.3.1 Design of KBS-3 Disposal Canister

Based on Refs. 12 and 13, the KBS-3 disposal canister was composed of four compartments for the storage of four



(a) x-y cross-sectional view (b) 3D sliced view

Fig. 4. Design modelling of STAD canister.

SNFs, the cast iron insert, and the copper shell and lid. The thickness and the height of the compartment with square-formed steel tube were set to 1.25 cm and 4.9 m, respectively. The diameter and the height of the cast iron insert with the safety functions of mechanical strength and radiation shielding were set to 94.9 cm and about 5.04 m, respectively. The thickness and the height of the copper shell and lid with the safety functions of corrosion resistance in a reducing environment were set to 4.9 cm and about 5.22 m, respectively. The outer diameter of the disposal canister was set to 1.05 m. Fig. 3 shows (a) the x-y cross-sectional and (b) the 3D sliced view of the design modelling of the KBS-3 disposal canister with four PLUS7 SNFs using the STARBUCS code, respectively. The red, blue, light gray, light yellow, dark yellow, orange, and green regions indicate the UO_2 rod of the SNF, H_2O water, the steel tube, the cast iron insert, the copper shell, the buffer, and the host rock, respectively.

2.3.2 Design of STAD Disposal Canister

Based on Refs. 14 and 15, the STAD disposal canister was composed of the basket assembly for the storage of four SNFs, the internal steel shell and lid, and the external copper shell and lid. The diameter and the height of the basket assembly with three neutron absorber plates were set to 73.7 cm and 4.9 m, respectively. The inner diameter and the thickness of the internal steel shell and lid were set to 74.7 cm and 4 cm, respectively. The thickness and the height of the external copper shell and lid were set to 2.5 cm and 5.13 m, respectively. The outer diameter of the disposal canister was set to 87.7 cm. Fig. 4 shows (a) the x-y cross-sectional and (b) the 3D sliced view of the design modelling of the STAD disposal canister with four PLUS7 SNFs using the STARBUCS code, respectively. The red, blue, light gray, violet, dark yellow, orange, and green regions indicate the UO_2 rod of the SNF, H_2O water, the steel structure, the neutron absorber plate, the copper shell, the buffer, and the host rock, respectively.

2.3.3 Design of Buffer and Host Rock

Based on Refs. 17 and 18, the buffer surrounding one KBS-3 or STAD canister was filled with a lot of compacted bentonite blocks and pellets. The thickness of the bentonite buffer in which one KBS-3 canister was emplaced was set to 38.65 cm, while that in which one STAD canister was emplaced was set to 30 cm. Because the space of the

Table 1. Design specifications of disposal cell system with KBS-3 canister

Component	Parameter	Size	Chemical compositions
Steel compartment	Thickness	1.25 cm	Fe (97.57%), C (0.22%), Si (0.55%), Mn (1.6%), P (0.03%), S (0.03%)
	Height	4.9 m	
Cast iron insert	Diameter	94.9 cm	Fe (90.02%), C (4%), Si (2.8%), Mn (1%), P (0.08%), S (0.02%), Ni (2%), Mg (0.08%)
	Height	about 5.04 m	
Copper shell and lid	Thickness	4.9 cm	Cu (100%)
	Height	about 5.22 m	
Bentonite buffer	Thickness	38.65 cm	Al (8.91%), Fe (1.86%), Mg (0.97%), Si (24.99%), O (57.89%), H (2.56%), Na (0.95%), Ca (0.58%), K (0.79%), C (0.45%), S (0.05%)
	Outer diameter	1.65 m	
	Height	8.25 m	

Table 2. Design specifications of disposal cell system with STAD canister

Component	Parameter	Size	Chemical compositions
Steel basket assembly	Diameter	73.7 cm	Fe (62.77%), C (0.07%), Si (1%), Mn (2%), P (0.045%), S (0.015%), N (0.1%), Cr (18.5%), Mo (2.5%), Ni (13%)
	Height	4.9 m	
Internal steel shell and lid	Inner diameter	74.7 cm	Fe (98.43%), C (0.29%), Mn (1%), Si (0.28%)
	Thickness	4 cm	
External copper shell and lid	Thickness	2.5 cm	Cu (100%)
	Height	5.13 m	
Bentonite buffer	Thickness	30 cm	Al (8.91%), Fe (1.86%), Mg (0.97%), Si (24.99%), O (57.89%), H (2.56%), Na (0.95%), Ca (0.58%), K (0.79%), C (0.45%), S (0.05%)
	Outer diameter	1.65 m	
	Height	8.25 m	

deposition hole had one size but the sizes of the KBS-3 and STAD canister were different. The outer diameter and the height of the bentonite buffer were set to 1.65 m and 8.25 m, respectively. The host rock around the outside of the deposition hole was composed of crystalline or granitic rock. The design modelling of the bentonite buffer and crystalline host rock is shown in Figs. 3 and 4, respectively.

The design specifications about the major components of the disposal cell system with each of the KBS-3 and STAD canister described in Section 2.3 were summarized in Tables 1 and 2, respectively. In addition, the chemical compositions of the materials composed of the disposal cell system were described in Tables 1 and 2 [3].

3. Analysis Results

The NCAs considering BUC were performed for two different disposal cell systems in which one KBS-3 or STAD canister was emplaced using the STARBUCS code. Two different discharge burnup groups, the lower and higher burnup group, were applied to the PLUS7 SNFs which were stored in the disposal canisters. Three cooling times of the SNFs were assumed to be 40, 50, and 60 years. In other words, two different disposal canister, two different discharge burnup groups of the SNFs, and three different cooling times of the SNFs were considered. Thus, the NCAs for a total of twelve cases were conducted to assess

Table 3. Calculated and final k_{eff} values including the total uncertainty for lower burnup SNFs

Cooling time of SNF	Calculated k_{eff} value (by STARBUCS)		Final k_{eff} value (including uncertainty)	
	KBS-3 disposal	STAD disposal	KBS-3 disposal	STAD disposal
40	0.74407	0.71448	0.79108	0.76149
50	0.74102	0.70982	0.78803	0.75683
60	0.73783	0.70743	0.78484	0.75444

the k_{eff} values for the disposal cell systems. In each case, the number of generations was set to 510, the number of neutrons per generation 10,000, and the number of skipped generations 10.

In addition, the uncertainties generated from the fuel depletion calculations and the nuclear criticality assessments were considered on the results of the NCAs considering BUC. When the PLUS7 SNF with the discharge burnups of 45,000 and 55,000 MWD/MTU and only nine major actinides on the fuel depletion calculations were applied, the uncertainty in k_{eff} for the fuel depletion calculations was 0.03081 in Ref. 8 and the uncertainty in k_{eff} for the nuclear criticality assessments was 0.0162 in Ref. 9. Thus, the total uncertainty in k_{eff} was 0.04701 in this work.

For the lower burnup SNFs, the initial enrichment and the discharge burnup were set to 4.0wt% ^{235}U and 45,000 MWD/MTU, respectively. And then the NCAs for the disposal cell system in which one KBS-3 or STAD canister was emplaced were performed. As a result, the calculated k_{eff} values and the final k_{eff} values including the total uncertainty for the cooling times of 40, 50, and 60 years of the SNFs were tabulated in Table 3.

Fig. 5 shows the final k_{eff} values including the total uncertainty with the cooling time for lower burnup SNFs. The horizontal axis indicates the cooling times of the PLUS7 SNFs and the vertical axis stands for the final k_{eff} values including the total uncertainty. The red and blue dash line represent the k_{eff} values for the disposal cell system in which one KBS-3 and STAD canister was emplaced, respectively. The yellow solid line indicates the maximum value of the performance criterion, 0.95.

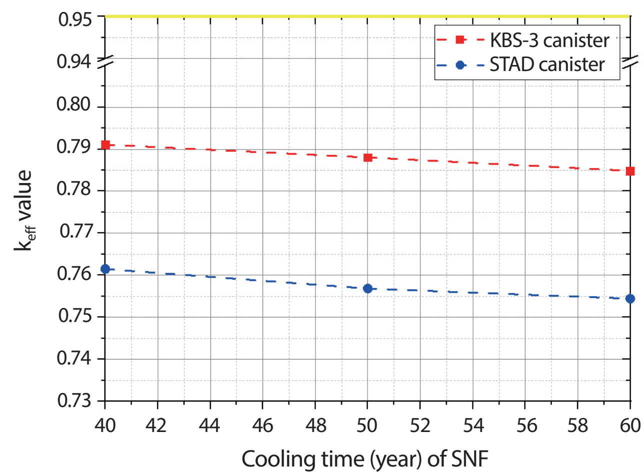


Fig. 5. Final k_{eff} values including the total uncertainty for lower burnup SNFs.

For the higher burnup SNFs, the initial enrichment and the discharge burnup were set to 4.5wt% ^{235}U and 55,000 MWD/MTU, respectively. And then the NCAs for the disposal cell system in which one KBS-3 or STAD canister was emplaced were performed. As a result, the calculated k_{eff} values and the final k_{eff} values including the total uncertainty for the cooling times of 40, 50, and 60 years of the SNFs were tabulated in Table 4.

Fig. 6 shows the final k_{eff} values including the total uncertainty with the cooling time for higher burnup SNFs. The horizontal axis indicates the cooling times of the PLUS7 SNFs and the vertical axis stands for the final k_{eff} values including the total uncertainty. The red and blue dash line represent the k_{eff} values for the disposal cell

Table 4. Calculated and final k_{eff} values including the total uncertainty for higher burnup SNFs

Cooling time of SNF	Calculated k_{eff} value (by STARBUCS)		Final k_{eff} value (including uncertainty)	
	KBS-3 disposal	STAD disposal	KBS-3 disposal	STAD disposal
40	0.73366	0.70323	0.78067	0.75024
50	0.72880	0.69946	0.77581	0.74647
60	0.72634	0.69719	0.77335	0.74420

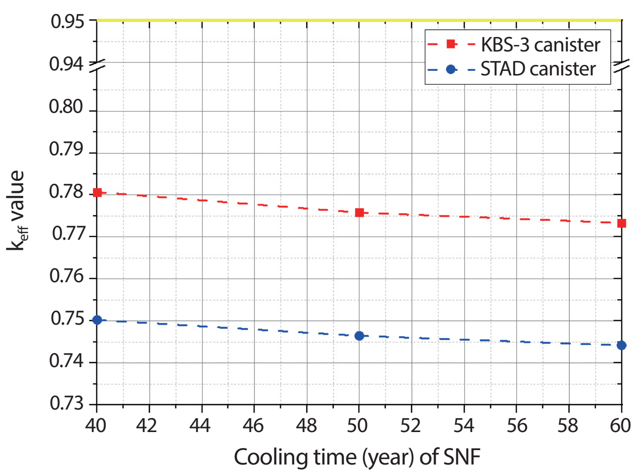


Fig. 6. Final k_{eff} values including the total uncertainty for higher burnup SNFs.

system in which one KBS-3 and STAD canister was emplaced, respectively. The yellow solid line indicates the maximum value of the performance criterion, 0.95.

From the above analysis results, the final k_{eff} values including the total uncertainty for all of twelve cases met the performance criterion, $k_{eff} < 0.95$. All k_{eff} values for the disposal cell system in which the higher burnup SNFs were stored were lower than those in the lower burnup SNFs. Because the inventories of the fissile nuclides, ^{235}U, ^{239}Pu, and ^{241}Pu, in the higher burnup SNFs were smaller than those in the lower burnup SNFs. The final k_{eff} value decreased due to the decay of ^{241}Pu as the cooling time of the SNFs increased [9]. In addition, all of the k_{eff} values for the disposal cell system in which one STAD canister was emplaced were lower than those in the KBS-3 canister. In other words, the disposal cell system in which one STAD canister was emplaced were more subcritical than that in the KBS-3 canister. The neutron absorber plates in the STAD canister significantly affected the reduction in k_{eff} values although the distance among the SNFs in the STAD canister was considerably shorter than that in the KBS-3 canister.

4. Conclusion

The NCAs considering BUC were performed for the disposal cells consisting of the bentonite buffer and two different types of PWR SNF disposal canister: the KBS-3 canister and the STAD canister. The nuclear reaction XS libraries for the nuclear fuel were newly produced using the TRITON code. The NCAs considering BUC were carried out for twelve cases using the STARBUCS code as follows: (1) the calculation of the isotopic compositions in SNFs using the computational tool of fuel depletion and (2) the assessment of the k_{eff} value for the DGR system using the computational tool of nuclear criticality. From the analysis results, the following conclusions were drawn:

- The KBS-3 and STAD canister containing four lower burnup SNFs of the initial enrichment of 4.0wt% ^{235}U and the discharge burnup of 45,000 MWD/MTU were modelled. The final k_{eff} values including the total uncertainty of the cooling times of 40, 50, and 60 years were calculated to be 0.79108, 0.78803, and 0.78484 for the disposal system of the KBS-3 canister, respectively. And thoes were estimated to be 0.76149, 0.75683, and

0.75444 for the disposal system of the STAD canister, respectively.

- The KBS-3 and STAD canister containing four higher burnup SNFs of the initial enrichment of 4.5wt% ^{235}U and the discharge burnup of 55,000 MWD/MTU were modelled. The final k_{eff} values including the total uncertainty for the cooling times of 40, 50, and 60 years were calculated to be 0.78067, 0.77581, and 0.77335 for the disposal system of the KBS-3 canister, respectively. And thoes were estimated to be 0.75024, 0.74647, and 0.74420, respectively.
- Therefore, the final k_{eff} values including the total uncertainty for all cases met the performance criterion, $k_{eff} < 0.95$. In other words, the disposal cell systems for twelve cases remained subcritical.
- All k_{eff} values for the disposal cell system in which the higher burnup SNFs were stored were lower than those in the lower burnup SNFs. Because the inventories of the fissile nuclides, ^{235}U, ^{239}Pu, and ^{241}Pu, in the higher burnup SNFs were smaller than those in the lower burnup SNFs. The final k_{eff} value decreased due to the decay of ^{241}Pu as the cooling time of the SNFs increased.
- All of the k_{eff} values for the disposal cell system in which one STAD canister was emplaced were lower than those for the KBS-3 canister. The neutron absorber plates in the STAD canister significantly affected the reduction in k_{eff} values although the distance among the SNFs in the STAD canister was considerably shorter than that in the KBS-3 canister.

Conflicts of interest

All contributing authors declare no conflicts of interest.

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