Application of Gadolinia Credit to Cask Transportation of BWR-STEP3 SFAs

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Instead of the fresh-fuel assumption, the application of gadolinia credit to cask transportation of BWR SFAs is studied. Its efficacy for BWR-STEP2 SFAs had already been estimated. This paper reports on the application of gadolinia credit to cask transportation of BWR-STEP3 SFAs.

KEYWORDS: gadolinia credit, cask transportation, BWR-STEP3 SFAs model bundle, fuel design code, KENO-Va code

1. Introduction

In the design for the cask transportation of spent-fuel assemblies (SFAs), it is assumed that the SFAs, which include the maximum reactivity supposed, will be loaded in the cask. In the conventional design, the effects of burn-up and burnable neutron poison are not considered, and only the initial content of fissile material is considered (fresh-fuel assumption). Based on this assumption, highly enriched fuel assemblies designed for high burn-up have been used to provide a wide margin for criticality management. In the design of BWR fuel assemblies, the initial reactivity excess has been restrained by using gadolinia (Gd_2O_3), which is a burnable neutron poison. Therefore, the approach using the restraining effect of gadolinia (Gadolinia Credit) is also available for criticality management of BWR SFAs. "Gadolinia Credit" means taking the negative reactivity of gadolinia in fuels into account during the criticality analysis. Its efficacy for BWR-STEP2 SFAs had already been estimated1). After that, BWR-STEP3 fuel assembly whose rod arrangement is 9x9 lattice had been developed. In this paper, the application of gadolinia credit to cask transportation of BWR-STEP3 (A type) SFAs is reported.

The transuranium (TRU) and fission products (FP) are accumulated in the SFAs and their effects restrain the reactivity of SFAs are significant. So, it is necessary to consider these effects of TRU and FP in the criticality management. In this application, the contributions of TRU and FP are considered.

Furthermore, the accumulated amounts of TRU and FP depend on the specific power. So, the change of specific power is also considered in this application.

2. Application Procedure

Firstly, the maximum value of the infinite multiplication factor in the cold stand-by system is determined for actual fuel assemblies. Next, the infinite multiplication factor in the basket (stainless steel containing 1.0 wt%-boron) system is estimated for the selected assembly.

From the viewpoint of criticality management, some TRU and FP nuclides, which are effective in restraining the reactivity of the SFAs, must be selected. For this selection, nuclides with the following attributes are rejected: (i) small effect of neutron capture, (ii) short half-life, (iii) gaseous or volatile and (iv) comparatively volatile. Accordingly, 12 TRU and 14 FP nuclides are selected. They are listed in **Table 1** and **Table 2** 2), 3), 4).

Table 1 Selected 12 TRU nuclides to be considered in the gadolinia credit

U-234, U-235, U-236, U-238
Pu-238, Pu239, Pu-240, Pu-241, Pu-242
Np-237
Am-241, Am-243

Table 2 Selected 14 FP nuclides to be considered in the gadolinia credit

Mo-95
Tc-99
Ru-101
Rh-103
Cs-133
Nd-143, Nd-145
Sm-147, Sm-149, Sm-150, Sm-151, Sm-152
Eu-153
Gd-155

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In comparison to the value for all nuclides, the fractions of neutron capture are more than 99% for the 12 TRU nuclides and about 70% for the 14 FP nuclides. In this application, the 12 TRU nuclides are always considered. The FP nuclides are considered under the following conditions: (i) all FP nuclides are considered, (ii) 14 FP nuclides are considered and (iii) no FP nuclide is considered. From the viewpoint of criticality safety design, the conservatism is large for the condition that no FP nuclide is considered, but the merit of comparison with the fresh-fuel assumption is small in this case.

Furthermore, the accumulated amounts of TRU and FP depend on the specific power. In this application, the estimation was performed under two specific power condition, namely, the standard and maximum power conditions. The specific power and burn-up calculation condition are shown in **Table 3**.

Table 3 Specific power in standard and maximum power condition and burn-up calculation condition

	Specific Power (MW/t)
Standard Power Condition	25
Maximum Power Condition	about 1.5 times of standard

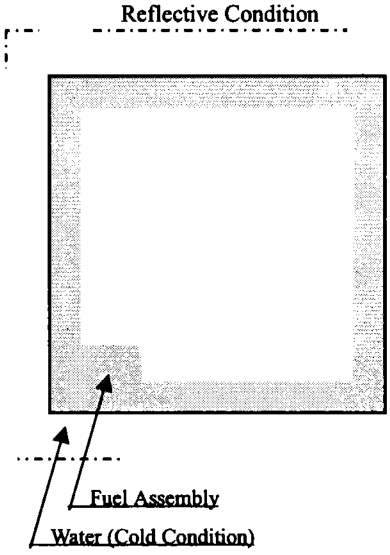
	Void Fraction (%)
Burn-up Calculation Condition	0, 40, 70

Based on the above estimation of the infinite multiplication factor, the model bundle, whose infinite multiplication factor is larger than that of the whole actual fuel assemblies is designed, from the viewpoint of criticality safety. And the criticality safety is estimated in the actual cask system storing this model bundle.

3. Design of Model Bundle

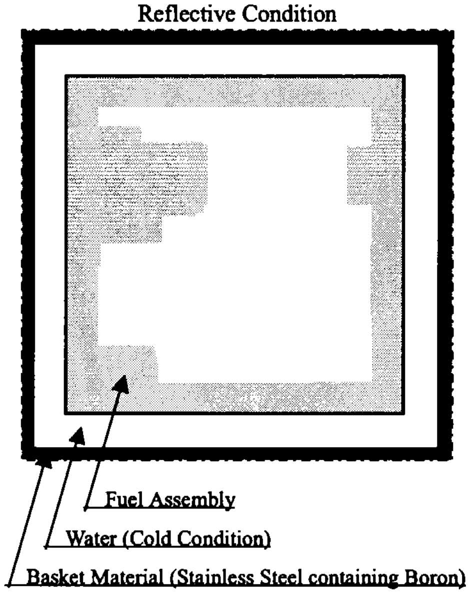
3.1 Maximum Reactivity for Actual SFAs

One of the typical designs for BWR-STEP3 (A type), which is considered in this application, is the adoption of partial length rods (PLRs). Therefore, there are 66 active fuel rods in the upper region and there are 74 active fuel rods in the lower region. The reload fuel assembly for which the infinite multiplication factor is the largest in the BWR-STEP3 (A type) conventional design was selected for the estimations, and the estimations were performed separately for the cross sections of the upper and lower regions.



* Assembly Pitch: 15.24cm

Fig.1 Calculation model of the cold stand-by system, using the nuclear design code of BWR fuel



* Inner Width of Basket: 15.3cm
* Thickness of Basket Material: 1.0cm
* Boron Concentration: 1.0wt% (natural composition)

assembly

Fig.2 Calculation model of the basket system, using the nuclear design code of BWR fuel assembly

Considering the change of fuel composition with burn-up, the infinite multiplication factors in the cold stand-by system and the basket system were estimated. In the calculation of these infinite multiplication factors, the nuclear design code of BWR fuel assembly[5] is used. This calculation performed in two dimensional XY systems. The estimation procedure is as follows: (i) the burn-up calculation for the selected reload assembly is performed and (ii) the infinite multiplication factors in the cold stand-by system and the basket system are calculated by using the fuel composition of each burn-up calculation point. The calculation models for the cold stand-by system and the basket system, using the nuclear design code of BWR fuel assembly, are shown in **Fig.1** and **Fig.2**, respectively.

The burn-up calculation using the nuclear design code of BWR fuel assembly was performed for the void fraction of 0%, 40% and 70%. The infinite multiplication factors in the cold stand-by system were estimated by using the fuel composition of each burn- up calculation point. The behavior of the infinite multiplication factor with burn-up is as follows: the initial reactivity is restrained by the burnable neutron poison, gadolinia, and the reactivity increase by burn-up. Their maximum values appear at around the burn-up ranging from 10 to 15GWd/t. After that, the infinite multiplication factor decreases due to burn-up. As for the infinite multiplication factor, the maximum value in the entire burn-up term appeared at around 10 GWd/t for the cross section of the upper region and at around 15 GWd/t for that of the lower region. The maximum values of infinite multiplication factor for each FP consideration condition are shown in **Table 4 (a)**. As shown in this table, the difference between the condition that all FPs are considered and the condition that no FP is considered is 5%, and the difference between the condition that 14 FPs are considered and the condition that no FP is considered is 3.5%. Therefore, the reactivity restraining effect of the 14 FP nuclides is 70% of that of all FP nuclides.

Table 4 Estimation results on maximum infinite multiplication factors

(a) Cold stand-by system

	Maximum K_∞	Remarks
All FPs Condition	1.269	Upper Cross Section, Void Fraction 40%, and Standard Power
14 FPs Condition	1.284	Upper Cross Section, Void Fraction 40%, and Maximum Power
No FP Condition	1.319	Upper Cross Section, Void Fraction 40%, and Maximum Power

(b) Basket system

	Maximum K_∞	Remarks
All FPs Condition	0.844	Upper Cross Section, Void Fraction 40%, and Standard Power
14 FPs Condition	0.853	Upper Cross Section, Void Fraction 40%, and Maximum Power
No FP Condition	0.873	Upper Cross Section, Void Fraction 40% & 70%, and Maximum Power

NB: The power condition which appears maximum reactivity depends on the FP consideration condition.

Next, for the assembly whose maximum value of infinite multiplication factor in the cold stand-by system was indicated, the infinite multiplication factor in the basket system was estimated under the condition of being filled water. As for the infinite multiplication factor, the maximum value in the entire burn-up term appears at around the same burn-up in the cold stand-by system. The maximum values of the infinite multiplication factor for each FP consideration condition are shown in **Table 4 (b)**. By storing SFAs in the basket system, the infinite multiplication factors become 0.4 to 0.45 smaller than those in the cold stand-by system.

3.2 Definition of Model Bundle

An example of criticality safety design adopting the gadolinia credit is the management of in-site storage pool for SFAs in a nuclear power plant. In this procedure of criticality safety design, the value of the multiplication factor in the cold stand-by system is firstly set up, including a margin, and the model bundle is designed such that the infinite multiplication factor in the cold stand-by system is the value set up. Conventionally, this value set up, including a margin, is 1.3. However, in the conventional design adopting the gadolinia credit, the consideration condition for FP nuclides is that all FP nuclides are considered. From the viewpoint of criticality safety, the most reasonable condition is that the 14 FPs are considered and it is conservatively reasonable to adopt the condition that no FP is considered.

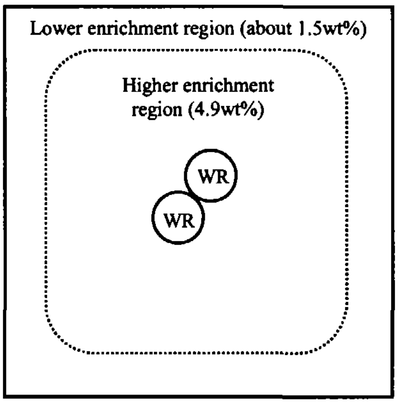
The maximum value of the infinite multiplication factor in the cold stand-by system, estimated in **section 3.1**, has a margin of about 3% with respect to the set-up value, 1.3, in the case of the condition that all FPs are considered. However, the margin decreases to half that value, 1.5%, for the case that the 14 FPs are considered. Furthermore, the maximum value of the infinite multiplication for the case that no FP is considered exceeds the value, 1.3.

Further, regarding the requirement for the model bundle, it is necessary to exceed the maximum value of the infinite multiplication factor of actual SFAs in the basket system. Based on the above, the set-up value of the infinite multiplication factor in the cold stand-by system and the target value of the infinite multiplication factor in the basket system required for the model bundle are decided. For example, **Table 5** shows the required infinite multiplication factor in the cold stand-by system. The infinite multiplication factors in the cold stand-by system were set with a margin of about 3%. And the infinite multiplication factors in the basket system should be given as exceeding the maximum value of actual SFAs.

The model bundle for the condition that all FPs are considered was made of two kinds of fresh fuel rods: the fuel rod of the maximum enrichment used in conventional BWR (4.9 wt%-U235) and the fuel rod of lower enrichment. In the condition that the infinite multiplication factor in the cold stand-by system is set up to 1.30 and the enrichment of higher fuel rod is fixed to 4.9 wt%, simulating the actual distribution of enrichment. The concept of fuel rod arrangement for the model bundle, summary of design and the infinite multiplication factor in the cold stand-by system and the basket system are shown in **Fig.3**. The infinite multiplication factor in the cold stand-by system is 1.30, and the infinite multiplication factor in the basket system is 0.856, which exceeds the target value mentioned in **section 3.1**.

Table 5 Required infinite multiplication factors for model bundle in cold stand-by system

All FPs Condition	1.300
14 FPs Condition	1.320
No FP Condition	1.360

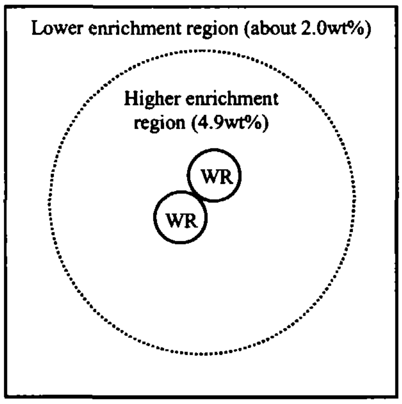


- fraction of higher and lower enrichment fuel rod is about 1 by 1,
- higher enrichment fuel rods are located at inner position, and
- enrichment of lower fuel rods is about 1.5wt%.

	K-infinity
Cold Stand-by System	1.301
Basket System	0.856

Fig.3 Fuel rod arrangement and k_∞ of model bundle for the condition that all FPs are considered

The model bundle for the condition that the 14 FPs are considered was also made of two kinds of fresh fuel rods: the fuel rod of maximum enrichment used in conventional BWR (4.9 wt%-U235) and the fuel rod of lower enrichment. In the condition that the infinite multiplication factor in the cold stand-by system is set up at 1.32 and the enrichment of higher fuel rod is fixed to 4.9 wt%, simulating the actual distribution of enrichment. The concept of fuel rod arrangement for the model bundle, summary of design and the infinite multiplication factors in the cold stand-by system and the basket system are shown in **Fig.4**. The infinite multiplication factor in the cold stand-by system is 1.32, and the infinite multiplication factor in the basket system is 0.862, which exceeds the target value mentioned in **section 3.1**.



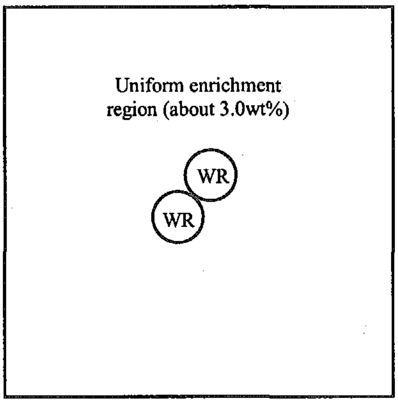
- fraction of higher and lower enrichment fuel rod is about 5 by 2,
- higher enrichment fuel rods are located at inner position, and
- enrichment of lower fuel rods is about 2.0wt%.

	K-infinity
Cold Stand-by System	1.320
Basket System	0.862

Fig.4 Fuel rod arrangement and k_∞ of model bundle for the condition that 14 FPs are considered

The model bundle for the condition that no FP is considered was made by adjusting the enrichment of fuel rods, so that the infinite multiplication factor in the cold stand-by system should be 1.36. The set-up condition is only the infinite multiplication factor, 1.36. The concept of fuel rod arrangement for the model bundle, summary of design and the infinite multiplication factors in the cold stand-by system and the basket system are shown in **Fig.5**. The infinite multiplication factor in the cold stand-by system is 1.36, and the infinite multiplication factor in the basket system is 0.889, which exceeds the target value mentioned in **section 3.1**.

As mentioned above, three kinds of model bundle were designed for each FP consideration condition. The estimation of storage in the cask system is performed for the model bundle for the condition that all FPs are considered (the infinite multiplication factor in the cold stand-by system is 1.30), which is the conventional estimation condition, and the model bundle for the condition that no FP is considered (the infinite multiplication factor in the cold stand-by is 1.36), which is the most conservative.



- use of one kind of fresh fuel rods, and,
- enrichment of fuel rods is about 3.0wt%.

	K-infinity
Cold Stand-by System	1.360
Basket System	0.889

Fig.5 Fuel rod arrangement and k_∞ of model bundle for the condition that no FP is considered

4. Estimation of Criticality Safety

The criticality safety in the NFT-38B cask system, which is used in the actual cask transportation, storing the model bundles is estimated by calculating the effective multiplication factor, using the KENO-Va code6). The calculation of the KENO-Va code was performed for the homogenized assembly model, using 238-group cross-section library in the SCALE system7). The calculation flow of the KENO-Va code, using the SCALE system, is shown in **Fig.6**.

The estimation of criticality safety is performed for the NFT-38B cask system storing the model bundles whose selection is described in the previous chapter, i.e. the model bundle for the condition that all FPs are considered and the model bundle for the condition that no FP is considered. The calculation model for the horizontal cross section of the NFT-38B cask system is shown in **Fig.7**.

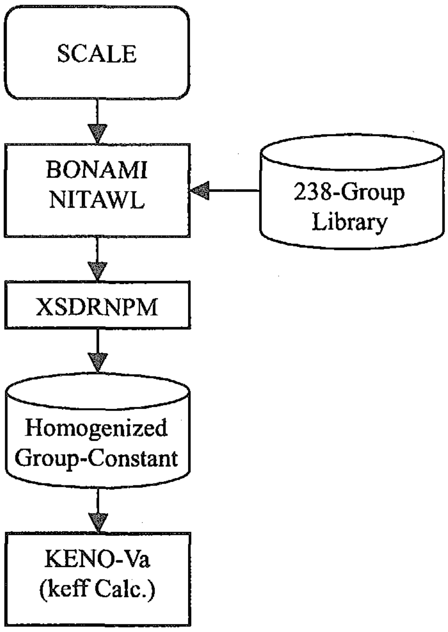


Fig.6 Calculation flow of k_{eff} by using the KENO-Va code

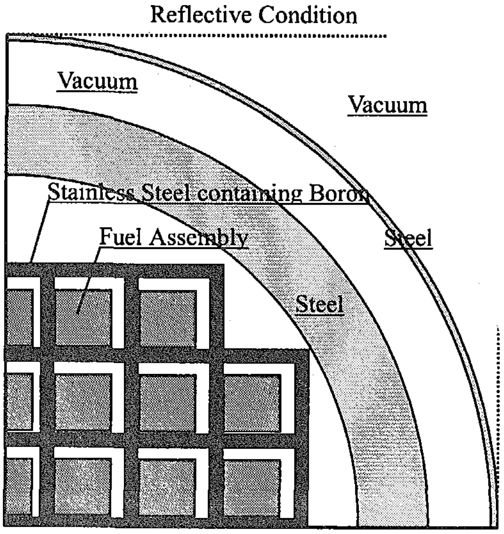


Fig.7 Analysis condition for the NFT-38B cask system

The calculated results of the effective multiplication factors in the NFT-38B cask system, using the KENO-Va code, are shown in **Table 6**. The calculated effective multiplication factor, k_{eff}s, the standard deviation of Monte Carlo calculation, σ s, and the values of (k_{eff}+3 σ)s are shown in this table. The value in the case that three times the standard deviation is added to the effective multiplication factor is about 0.82 in the cask system storing the model bundles for the condition that all FPs are considered, and about 0.85 in the cask system storing the model bundles for the condition that no FP is considered. These values are sufficiently lower than 0.95, and so it is clear that the cask system storing these model bundles is sub-critical.

Table 6 k_{eff} of the NFT-38B cask system estimated by the KENO-Va code

Model Bundle	$k_{eff} \pm \sigma$	$k_{eff}+3\sigma$
for the condition that all FPs are considered	0.8099±0.0040	0.8219
for the condition that no FP is considered	0.8424±0.0038	0.8538

5. Conclusion

In this paper, instead of the fresh-fuel assumption adopted in the conventional SFA cask transportation, application of gadolinia credit to cask transportation of BWR-STEP3 (A type) SFAs was studied. The following three kinds of model bundle are investigated: (i) the condition that all FPs are considered, which is adopted in the management of in-site storage pool for SFAs in nuclear power plants, (ii) the condition that 14 FPs are considered, which reject gaseous volatile elements, and (iii) the condition that no FP is considered, which is the most conservative condition.

From the above model bundles, the condition that all FPs are considered and the condition that no FP is considered were selected for the estimation of storage safety. The storage safety was estimated for the NFT-38B cask system, which was used in the actual SFA cask transportation, storing the model bundles. As for the estimation, the effective multiplication factors were calculated for the NFT-38B cask system, using the KENO-Va code. The obtained effective multiplication factors were sufficiently lower than 0.95.

According to the results of this study, it is available to apply gadolinia credit to cask transportation of BWR-STEP3 (A type) SFAs.

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References

1) K. Kawakami, et al., “The Use of Gadolinia Credit for Criticality Evaluation of a Spent-Fuel Cask,” PATRAM’95, Session VII-3.1 (1995).
2) “Topical Report on Actinide-Only Burnup Credit for PWR Spent Nuclear Fuel Packages,” DOE/ RW-0472 Rev.0, 1995.
3) M.D. DeHart et al., OECD/NEA Burnup Credit Calculational Criticality Benchmark Phase I-B Results, NEA/NSC/DOC(96)-06 ORNL-6901, 1996.
4) Working Group on Nuclear Criticality Safety, “Nuclear Criticality Safety Handbook Version 2,” JAERI 1340 (1999).
5) M. Yamamoto, et al., “Development and Validation of TGBLA Lattice Physics Methods,” Proc. ANS Topical Mtg. on Reactor and Shielding, Chicago, Illinois, Sep. 17-19, 1984 Vol.I, p.364 (1984).
6) L. M. Petrie et al., “KENO Va: An Improved Monte Carlo Criticality Program with Supergrouping,” NUREG/CR-0200 Rev.6 Vol.2 Sec.F11 (1998).
7) ORNL-RSIC, “SCALE 4: A Modular Code Systems for Performing Standardized Computer Analysis for Licensing Evaluation,” CCC-545 (1990).