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An Evaluation on the Criticality Control Ability of a Neutron Absorber based on Artificial Rare Earth Compounds in PLUS7 and WH17x17 Spent Fuel Storage

Jae Hyun KIM [a], Che Wook Yim [a], Chang Ho SHIN [a], Song Hyun KIM [a,*], Jung Hun CHOE [b], In Hak CHO [b], Jong Kyung KIM [b], Hwan Seo PARK [b], Hyun Seo PARK [c], Jung Ho KIM [c], and Yoon Ho KIM [c]
[a]*Department of Nuclear Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul, 133-791, Korea*
[b]*Korea Atomic Energy Research Institute, 150, Deokjin-dong, Yuseong-gu, Daejeon, 305-353, Korea*
[c]*Korea Research Institute of Standards and Science, 267, Gajeong-ro, Yuseong-gu, Daejeon, 305-353, Korea*
[*]*Corresponding author: nucleon@hanyang.ac.kr*

1. Introduction

In Korea, it has been discussed about that the intermediate storage of the spent nuclear fuels is one of the main management plans for the spent fuel problems. These storages have been designed to minimize space due to increasing storage efficiency. Therefore, the neutron absorbers are generally used for the design of dense spent fuel storages. In a previous study [1], a neutron absorber based on artificial rare earth compounds with a conceptual design was proposed for efficient and economic disposal of spent nuclear fuel. In this study, the design criteria of the neutron absorber are established by performance evaluations of the neutron absorber.

2. Methods and Results

The spent fuel storage should keep sub-criticality with considering lots of uncertainty variables. The criticality control ability of the neutron absorber is affected by the following parameters:

- Density of the neutron absorber
- Material composition of neutron absorber
- Shape of neutron absorber
- Geometrical structure of neutron absorber
- Position of neutron absorber in spent fuel storage

To analyze the criticality control ability, a reference model of the neutron absorber based on the conceptual design of is first determined. Then, the sensitivity analysis of criticality is performed from change of design parameters of the neutron absorber. Finally, the design requirements are established.

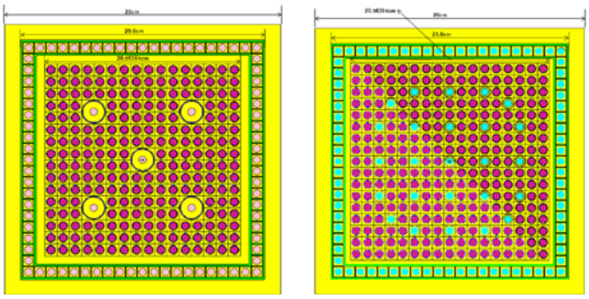
2.1 Overview of Conceptual Storage Rack Design

The conceptual design of the neutron absorber and spent fuel storage was proposed in a previous study [1]. The standard composition of the neutron absorber is given in Table I. The density of the neutron absorber can be changed by the composition of the artificial rare earth compound; therefore, the minimum density is used for conservative evaluation.

Table I: Density and Composition of the Neutron Absorber

Density	> 3.6 g/cm^3
Material	Mass Fraction
RE_2O_3 SiO_2 Al_2O_3 B_2O_3	50 w/o 25 w/o 16.67 w/o 8.33 w/o
Sum	100 w/o

The shape of the neutron absorber is cylindrically designed to use it in guide tubes. Fig. 1 show that the arrangement of PLUS7 [2] and WH17x17 [3] spent nuclear fuel storage racks with the neutron absorbers.



(a) Rack for PLUS7 (b) Rack for WH17x17

Fig. 1. Spent Fuel Storage Rack and Disposition of the Neutron Absorber

The artificial rare earth isotopes used in the neutron absorber are extracted from the spent fuels. The composition of the artificial rare earth isotopes is different from burn-up condition and initial properties of the spent nuclear fuel. In the previous study [1], it is classified to thirty cases for the burn-up condition and initial fuel conditions as shown in Table II. In this study, ORIGEN-ARP code [4] is used for the composition evaluation.

Table II: Grouped Spent Fuels for RE Composition Evaluation

Group	Enrichment [w/o]	Burn-up [MWD/MTU]	Group	Enrichment [w/o]	Burn-up [MWD/MTU]
1-1	1.5	9,000	2-1	2	13,000
1-2	1.75	9,000	2-2	2.5	13,000
1-3	1.5	44,000	2-3	2	44,000
1-4	1.75	44,000	2-4	2.5	44,000
3-1	3	13,000	4-1	4	21,000
3-2	3.5	13,000	4-2	4.5	21,000
3-3	3	55,000	4-3	4	58,000
3-4	3.5	55,000	4-4	4.5	58,000

2.2 Criticality Sensitivity Estimation

To obtain minimum requirements and design guidelines of the absorber, the parameters which affect the criticality control ability, are selected as follows:

- Material composition of neutron absorber
- Diameter and height of cylindrical neutron absorber
- Inserting position of neutron absorber
- Interval spent nuclear fuel and neutron absorber
- Circumstance of neutron absorber which has inhomogeneous distribution

The evaluations of criticality control ability on change design parameters were performed with the absorber which is described in Table III. The details of the PLUS7 and WH17x17 spent fuel storages are given in Tables IV and V. MCNP5 code [5] is used for criticality calculation with ENDF/B-VI cross section and SAB2002 thermal cross section libraries.

Table III: Standard Design Value of Neutron Absorber for Criticality Control Ability Evaluation

Classification	Value
Density	3.6 g/cm^3
Type	Cylinder
Diameter	0.8 cm
Height	Effective Height of Nuclear Fuel
Composition of RE	Mass Fraction Emitted from Group 4-4 Spent Fuel Condition
Material	Mass Fraction
RE_2O_3	50 w/o
SiO_2	25 w/o
Al_2O_3	16.67 w/o
B_2O_3	8.33 w/o
Sum	100 w/o

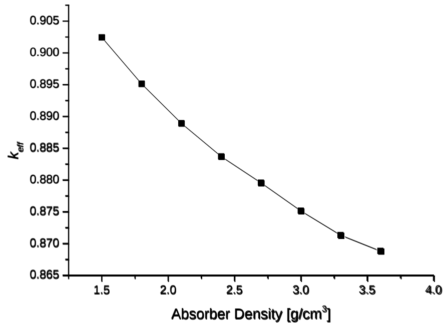
Table IV: Property of the PLUS7 Spent Fuel Assembly and Storage

Classification	Value
Fuel Radius	0.409575 cm
Fuel Density	10.313 g/cm^3
Cladding Material	ZIR-4
Cladding Density	6.563 g/cm^3
Outer Radius of Fuel Cladding	0.47498 cm
Inner Radius of Guide Tube	1.143 cm
Outer Radius of Guide Tube	1.2446 cm
Width of Fuel Assembly	20.56384 cm
Active Height of Fuel Assembly	381 cm
Thickness of Inner Fuel Rack	0.2 cm
Material of Inner Fuel Rack	SS-316
Density of Inner Fuel Rack	7.94 g/cm^3
Thickness of Outer Fuel Rack	0.2 cm
Material of Outer Fuel Rack	SS-316
Density of Outer Fuel Rack	7.94 g/cm^3

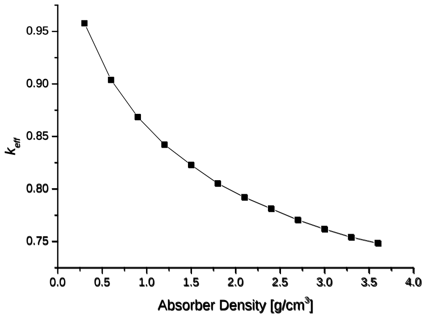
Table V: Property of the WH17x17 Spent Fuel Assembly and Storage

Classification	Value
Fuel Radius	0.41 cm
Fuel Density	10.412 g/cm^3
Cladding Material	ZIR-4
Cladding Density	6.55 g/cm^3
Outer Radius of Fuel Cladding	0.47493 cm
Inner Radius of Guide Tube	0.56134 cm
Outer Radius of Guide Tube	0.60198 cm
Width of Fuel Assembly	21.41728 cm
Active Height of Fuel Assembly	365.76 cm
Thickness of Inner Fuel Rack	0.7 cm
Material of Inner Fuel Rack	SS-316
Density of Inner Fuel Rack	7.92 g/cm^3
Thickness of Outer Fuel Rack	0.2 cm
Material of Outer Fuel Rack	SS-316
Density of Outer Fuel Rack	7.82 g/cm^3

First, the evaluation of criticality control ability about material composition of neutron absorber was analyzed. Main materials influencing on criticality control in the neutron absorber are B_2O_3 and RE_2O_3 (artificial Rare Earth Oxide). To estimate the criticality control effect of reducing these absorbing materials, criticality was evaluated as by change of the neutron absorber density. The result of effective multiplication factor is given as shown in Fig. 2. Result shows that criticality control ability is satisfied when the absorbing materials for PLUS7 and WH17x17 spent fuel storages are included above 44.4 % and 13.9 %, respectively.



(a) Rack for PLUS7



(b) Rack for WH17x17

Fig. 2. Result of Criticality Evaluation as the Change of Neutron Absorber Density

The diameter of the cylindrical neutron absorber can be changed by manufacturing procedure. Thus, the minimum diameter to control the criticality should be established by sensitivity analysis on diameter of neutron absorber. Fig. 3 is criticality evaluation result on the diameter change of the neutron absorber given condition. Result shows that criticality can be controlled when the diameters of the absorber are above 0.6 cm and 0.4 cm for PLUS7 and WH17x17 spent fuel storages, respectively.

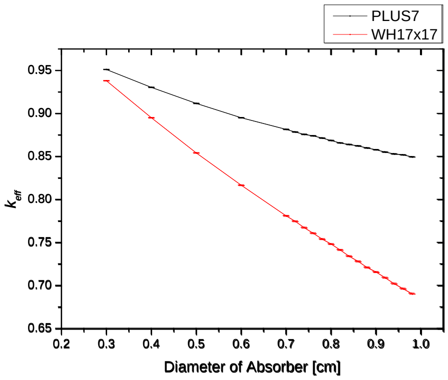


Fig. 3. Result of Criticality Evaluation Depending on Diameter of Neutron Absorber

To confirm the use of the various neutron absorbers for the condition that are heterogeneously composed, an extremely condition was assumed. Each absorbing material (RE_2O_3 and B_2O_3) is located at the one-side of the neutron absorber on the axial direction; then, the others are located at the other side. Fig. 4 shows the overview of this calculation. The unit heights of each neutron absorber are 1 cm, 5 cm, 10 cm, and 20 cm, respectively. Table VI shows the result of the heterogeneous cases. Analysis shows that if the unit height of the neutron absorber is manufactured below 1 cm, the absorber can control the criticality even though the absorber has a heterogeneous condition.

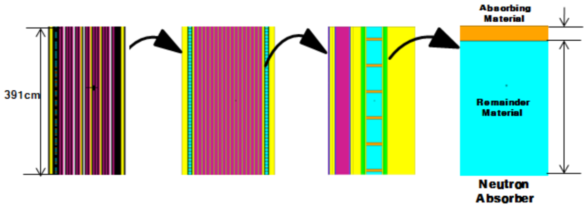
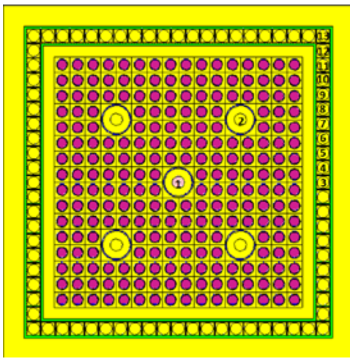


Fig. 4. Criticality Evaluation Overview with Heterogeneity Assumption

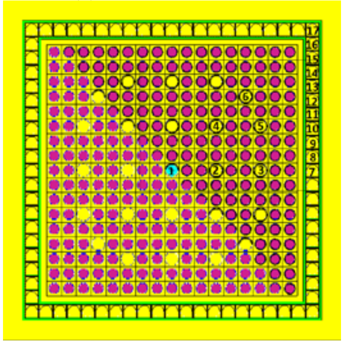
Table VI: Result of Criticality Calculation with Heterogeneity Assumptions

Inhomogeneous Material	Effective Height	Effective Multiplication Factor	
		PLUS7	WH 17x17
RE_2O_3	1 cm	0.87297 (±0.00037)	0.75565 (±0.00034)
	5 cm	0.88235 (±0.00036)	0.77361 (±0.00035)
	10 cm	0.88410 (±0.00036)	0.77948 (±0.00035)
	20 cm	0.88843 (±0.00035)	0.78587 (±0.00035)
B_2O_3	1 cm	0.89635 (±0.00036)	0.80555 (±0.00035)
	5 cm	0.91891 (±0.00036)	0.85210 (±0.00035)
	10 cm	0.92468 (±0.00035)	0.86373 (±0.00035)
	20 cm	0.92987 (±0.00035)	0.87280 (±0.00035)

Arrangement of the absorbers in storage has also large influence on criticality control ability. To study the effects, the insertion positions of neutron absorber on each fuel assembly type are selected as shown in Fig. 5. At each position, the neutron absorber was inserted, and the others remain to be void space (all voids are filled by pure water). The difference of effective multiplication factor after inserting the absorber is shown in Fig. 6. Analysis shows that the absorbers located in the guide tubes have high control abilities above 2 times than those located at out of the fuel assemblies.

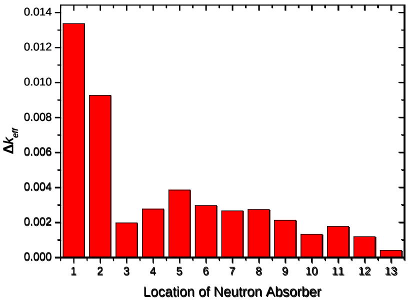


(a) Rack for PLUS7

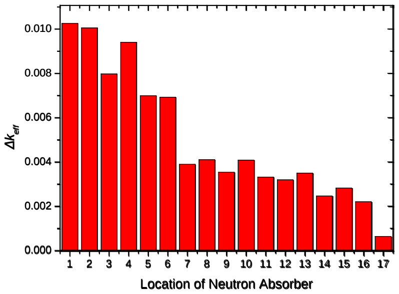


(b) Rack for WH 17x17

Fig. 5. Insertion Position for Criticality Control Ability Evaluation Depending on Disposition of Neutron Absorber



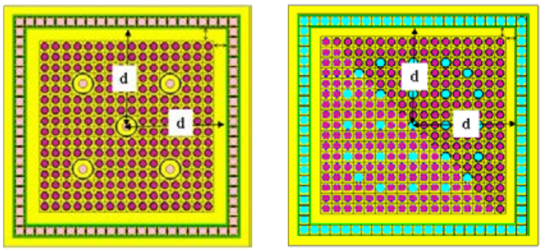
(a) Rack for PLUS7



(b) Rack for WH 17x17

Fig. 6. Evaluation Result of Criticality Control Ability Depending on Insertion Position of Neutron Absorber

Also, the evaluation of the criticality control ability depending on distance of neutron absorber from the spent fuel assembly is performed. Changing the distance, ‘d’ at Fig. 7, criticality control ability was evaluated. The calculation result is given in Fig. 8. It shows that the close distance gives higher criticality control ability for both types of nuclear fuel assembly.



(a) Rack for PLUS7 (b) Rack for WH 17x17

Fig. 7. Evaluation of Criticality Control Ability Depending on Distance of Outside Neutron Absorber ‘d’

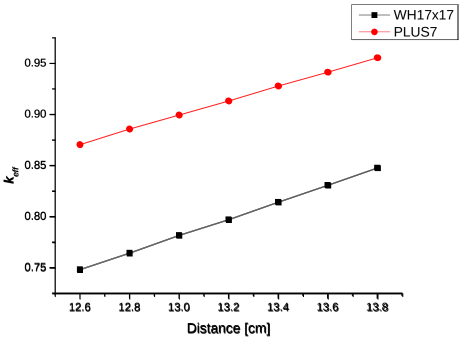


Fig. 8. Evaluation Result of Criticality Control Ability as the Distance ‘d’

2.3 Establishment of the Design Criteria

From the results of the sensitivity analyses on the neutron absorber, a requirement of neutron absorber, which is a minimum value for the utilization as a criticality control materials in the spent fuels, is established. The design requirements of the neutron absorber are given in Table VII. Also, using the requirement, the criticality control ability was evaluated as shown in Table VIII.

Table VII: Minimum Requirements of Neutron Absorber based on Artificial Rare Earth Compound

Classification	Design Parameter	Value
1	Neutron Absorber Radius	> 0.35 cm
2	Mass Fraction of B_2O_3	> 5 wt%
3	Mass Fraction of RE_2O_3	> 30 wt%
4	Neutron Absorber Density	> 3.6 g/cm^3

Table VIII: Evaluation Result of Criticality Control Ability of Neutron Absorber using Minimum Requirements

Classification	Type of Spent Fuel	k_{eff}
1	PLUS7	0.89975 (±0.00036)
2	WH 17x17	0.82107 (±0.00117)

3. Conclusions

In this study, a design criterion of the neutron absorber based on the artificial rare earth compound was established by the sensitivity analysis of the design parameters. The sensitivity estimations were pursued as the material composition, geometrical feature, heterogeneous conditions, and the arrangement of the absorber. The results show that the neutron absorber has an enough margin of the criticality control when the absorber is manufactured by the minimum requirements. Thus, development of neutron absorber based on vitrified material is supposed to be conducted in the future.

Acknowledgments

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