A Study on the Construction of Experimental System to Verify Criticality Control Performance of Neutron Absorber based on Artificial Rare Earth Compound

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1. Introduction

For the design of dense spent fuel storages, the neutron absorber is essentially used. In the previous study [1], a neutron absorber was proposed using artificial rare earth compound, which is one of the radioactive wastes, to increase the disposal efficiency and economic benefit. To design a new neutron absorber for practical use in spent fuel storages, various performance tests are required. According to ASTM C1761-07 [2], one of the main requirements is that the uniformity of the neutron absorber distribution should be experimentally measured and verified. The requirement is optimized for the metal based neutron absorber. However, it is not a valid method for the neutron absorber based on the artificial rare earth compound because of the absolutely different shapes (cylinder) and chemical compositions. To establish the experimental verification procedure on the neutron absorption ability, an experimental system and method were proposed in this study.

2. Methods and Results

The newly developed neutron absorber based on artificial rare earth compound has lower boron effective density than those of commercial neutron absorbers such as BORAL™ [3]. To control the criticality in the spent fuel storages, the neutron absorber should be inserted in the guide tubes in fuel assemblies. Thus, the shape of the neutron absorber is cylindrically designed as shown in Figure 1-2 and Table I [1]. The neutron absorber has absolutely different shape and chemical composition; therefore, the verifying procedure of the criticality control ability should be newly established.

There are significant problems in testing the criticality control ability of them with existing neutron induced experimental facilities [4]. First, the artificial rare earth compound cannot be used for the experiment because it is strong radioactive material extracted from the pyro-processing. Second, the neutron absorber is too small to test the criticality control ability with the given neutron induced experiment facility. In this study, two methods to verify the neutron absorption ability were proposed. One is a method to develop a substitution material of the artificial rare earth compounds, another is to set an experimental system for estimating the criticality control ability.

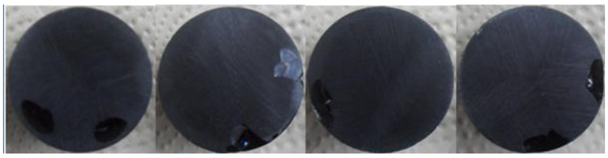
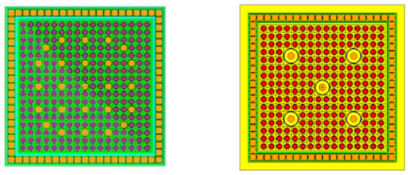


Fig. 1. Neutron Absorber Based on the Artificial Rare Earth Compound



(a) Rack for WH 17x17 (b) Rack for PLUS7
Fig. 2. Conceptual Design of Spent Fuel Storage Racks

Table I. Specification of the Neutron Absorber

Type: Cylindrical [radius (r) = 0.55 cm]		
Classification	With Burnable Poison	Without Burnable Poison
Density	3.813 g/cm^3	4.044 g/cm^3
Material	Mass fraction [w/o]	
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	

2.1 Development of Substitute Material

During the operation of nuclear power reactor, various artificial rare earth isotopes are generated from fission reactions. The artificial rare earth compounds can be extracted by the pyro-processing which is one of the spent fuel reprocessing methods. The isotope compositions of the artificial rare earth are significantly different than those of natural rare earth compounds. The differences of the isotope abundances cause the change of the neutron absorption ability because each isotope has difference neutron absorption cross section.

In this study, two materials are selected as a substitution of the artificial rare earth compounds, which are the praseodymium (Pr) and gadolinium (Gd). Praseodymium exists as single isotope ($^{59}Pr^{141}$ 100%) and it has low neutron absorption cross section (~ 11.5 barns at thermal energy range). And, gadolinium is a strong neutron absorption material having ~ 49,000 barns cross section at thermal energy range. The compositions of the substitution material are decided with the following procedure:

(i) A spent fuel is selected;
(ii) Burn-up analysis is pursued with the given burn-up condition;
(iii) The composition of the artificial rare earth compound was extracted from the results of the burn-up calculation;
(iv) Multiplication factor in a spent fuel storage designed in previous study with inserting the neutron absorber, which is included of the artificial rare earth compound, is estimated;
(v) Composition is decided by criticality sensitivity study by substituting the artificial rare earth compound to the Pr and Gd compounds.

For the preliminary study, two cases of the spent fuels were selected as shown in Table II. Then, the weight composition of the substitution materials were decided with criticality sensitivity study. MCNP5 code [5] is used by criticality calculation with ENDF/B-VI cross section and SAB2002 thermal cross section libraries. The results of the compositions and criticality control ability of the substitution materials are given in Table III.

Table II. Conditions of Spent Fuels to Extract the Artificial Rare Earth Compound

Type	Enrichment [w/o]	Burn-up [MWD/MTU]	Burnable Poison [w/o]
1	4.5	58,000	0
2	4.5	58,000	0.22*

Table III. Compositions and Criticality Control Ability of Substitution Materials

Type	WH 17x17			PLUS7		
	Composition of Substitution Material		Δk_{eff}*	Composition of Substitution Material		Δk_{eff}*
	Pr_2O_3	Gd_2O_3		Pr_2O_3	Gd_2O_3	
1	47.67 w /o	2.33 w/o	0.104 %	46.5 w/o	3.5 w/o	0.051 %
2	47.1 w/o	2.9 w/o	0.062 %	46.4 w/o	3.6 w/o	0.011 %

* Δk_{eff} is the % relative difference of k_{eff} inserting the neutron absorbers based on the artificial rare earth compound and substitute material

2.2 Construction of Experiment System

For the experiment, a neutron induced experiment facility possessed in Korea Atomic Energy Research Institute will be used as shown in Figure 3[4]. The neutron source is Cf-252 having 2.3 x 10^9 Bq. The neutron detector is Berthold LB6411. To check the criticality control ability, low energy neutron is required; therefore, D_2O moderator sphere is used as a moderator. As the results, the thermal neutrons are widely distributed in the D_2O moderator and induced to the detector. And thus, the radius of the neutron absorber should be bigger than 16.2 cm, which is the radius of the D_2O sphere. In this study, a polyethylene block as shown in Figure 4 is introduced and used to lead neutrons toward the neutron absorber in the experiment. The block is cylinder and a hole is located at the center of the block to insert the neutron absorber. The geometrical feature of the polyethylene block and neutron absorber is described in Table IV. Using the polyethylene block, the neutron distributions were evaluated by MCNP5 code as shown in Figure 5. As intended in this study, the results show that the neutron flux densities are properly increased in the hole.

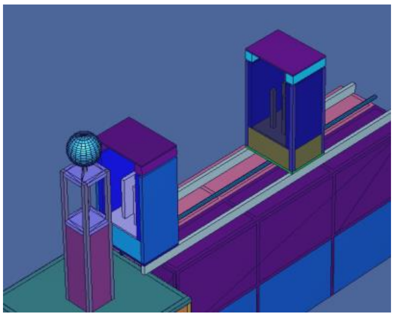


Fig. 3. Overview of Experimental Facility

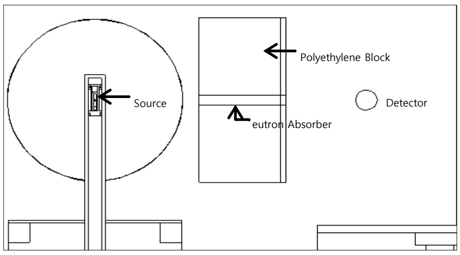


Fig. 4. MCNP Modeling of Experimental System

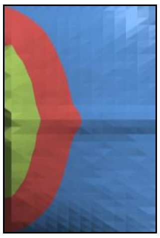


Fig. 5. Results of Neutron Distribution in the Polyethylene Block

Table IV. Geometrical Specifications of the Block and Absorber

Material	Shape	Radius	Height
Absorber (pellet)	Cylinder	1cm	5cm
Polyethylene	Cylinder	16.5cm	15cm
Moderator	Sphere	16.125cm	

The neutron absorption ability with the experimental system is estimated by the fraction of the neutron detection rate. At first, the neutron detection is performed with polyethylene block without any neutron absorber. After that, 5 cm and 15 cm height neutron absorbers are respectively inserted in the hole, and the neutrons are detected for each case. Using the detection fraction of them, the neutron absorption ability is estimated. Table V is the results of the fraction of detector responses. Analysis shows that the experimental system can effective estimate the neutron absorption ability for the cases.

Table V. Results of Detector Response Fraction with Inserting Each Type of Neutron Absorber

Type	Density (g/cm^3)	Fraction of Detector Response	
		5 cm	15 cm
1	3.813	83.50 %	71.70 %
2	4.044	82.94 %	71.45 %

3. Conclusions

In this study, an experimental system was constructed to test the neutron absorption ability of a neutron absorber which was developed with the artificial rare earth compound. At first, a substitution material was decided by the criticality sensitivity study. And then, a polyethylene block was designed for the test of the neutron irradiation experiments using D_2O moderator. Analysis shows that the experimental system can effectively estimate the neutron absorption ability using neutron absorbers that have a small size.

Acknowledgments

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REFERENCES

[1] Song Hyun KIM et al., A Study on the Design of Novel Neutron Absorber Using Artificial Rare Earth Compound, Transaction of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 24-25, 2013.

[2] American Society Testing and Material (ASTM), Standard Practice for Qualification and Acceptance of Boron Based Metallic Neutron Absorbers for Nuclear Criticality Control for Dry Cask Storage Systems and Transportation Packaging, C1671-07, 2013.

[3] A. Machiels and R. Lambert, Handbook on Neutron Absorber Materials for Spent Nuclear Fuel Applications, 1011818, EPRI Final Report, 2005.

[4] Sang In KIM et al., Investigation of Response of Several Neutron Surveymeters by a DT Neutron Generator, Journal of Radiation Protection, Vol37, No.1, March 2012.

[5] X-5 MONTE CARLO TEAM, “MCNP—A General Monte Carlo N-Particle Transport Code, Version 5, Volume II: User’s Guide,” LA-CP-03-0245, Los Alamos National Laboratory, 2003.