A Study on the Design of Novel Neutron Absorber Using Artificial Rare Earth Compound

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1. Introduction

As a countermeasure of the existing fuel depletion and spent nuclear fuel disposal problems, pyro-processing, which is one of the spent fuel reprocessing methods, has received attention in Korea. The artificial rare earth compounds (RE_2O_3) generated by the result of the pyro-processing are radioactive wastes which have many long-live radionuclides. Due to the high and long-lived radioactivity of the article RE_2O_3, specific radiation shielding and disposal techniques are required. In this study, a simultaneous disposal method of the RE_2O_3 with the spent fuels is proposed by reusing them for the neutron absorber.

2. Methods and Results

The spent fuels which include fissionable materials generated high intensity radiations as well as the decay heat. Hence, for the design of the spent fuel storages, the safety analyses of the radiation shielding, durability, and criticality must be performed. Because of the economical aspect, dense fuel storage has been required for their design. As the results, the neutron absorbers to prevent the criticality accident have been installed in the spent fuel storages. In this study, a neutron absorber based on artificial RE_2O_3 compound is proposed and designed for the storages of the spent fuel assemblies.

2.1 Evaluation of RE_2O_3 Composition

The artificial rare earth materials are generated by the nuclear fission reactions; therefore, various parameters such as the burn-up and the enrichment affect the production rate of RE_2O_3. For the calculation of the RE_2O_3 composition, the burn-up conditions of the spent fuels stored in Korea [1] are grouped and representative conditions in each group are decided as shown in Table I. The burn-up evaluations of the CE 16x16 assembly were pursued by ORIGEN-S code [2] with the conditions given in Table I. For the calculations, 10 MW_{th} specific power was used for all cases. From the burn-up results, the rare earth nuclides were extracted. The total amount at each condition was calculated as shown in Table II. The results show that the production amounts are strongly dependent on the fuel burn-up.

Table I. 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

Table II. RE Production Amount for Each Condition

Group	Mass of RE [Gram/Assembly]	Group	Mass of RE [Gram/Assembly]
1-1	1206.74	2-1	1759.76
1-2	1218.11	2-2	1783.16
1-3	5534.23	2-3	5621.86
1-4	5578.80	2-4	5701.82
3-1	1800.21	4-1	2905.94
3-2	1813.09	4-2	2921.98
3-3	7114.57	4-3	7629.00
3-4	7191.69	4-4	7693.57

2.2 Design of Neutron Absorber Based on RE_2O_3

For the design of the neutron absorber with RE_2O_3 compounds, the following aspects are considered:

(a) Neutron Absorption Ability
(b) Applicability into PLUS7 and WH 17x17 Racks
(c) Chemical and Mechanical Durability

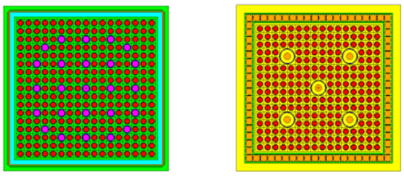
From the experimental studies, the composition and geometrical details of the neutron absorber were determined as shown in Table III. To install the neutron absorber into the guide tubes of both WH 17x17 and PLUS7 assemblies, the radius of the cylindrical neutron absorber was decided to 0.55 cm.

Table III. Design Properties of the Neutron Absorber

Neutron Absorber [ρ =3.543 g/cc]	
Type: Cylindrical [radius (*r*) = 0.55 cm]	
Material	Mass Fraction [w/o]
RE_2O_3	50 w/o
Others	50 w/o

2.3 Rack Design and Criticality Assessment with the Proposed Neutron Absorber

For the design and criticality analysis of the spent fuel storage rack, the following conservative assumptions were used: (1) fresh fuel without burn-up, (2) 5 w/o enrichment, (3) no burnable poison, and (4) the pure water filled in void. In the criticality safety guideline, the criticality in fuel storage must not be exceeded to 0.95 with considering all calculation biases and accident scenarios. Hence, the design purpose of the criticality is set to under 0.91 to give them enough criticality margins. Figure 1 shows the design results of the WH 17x17 and PLUS7 fuel storage racks [3, 4]. For the WH 17x17 storage rack, the neutron absorbers were installed into the guide tubes only. In case of the PLUS7 storage rack, the neutron absorbers are located around of the fuel assembly as well as the guide tubes. For the criticality calculation, the RE_2O_3 material compositions in the neutron absorber were extracted from the 45,000 MWD/MTU spent fuel assembly. The criticality calculations were performed by MCNP5 code [5] with ENDF/B-VI cross section and SAB2002 thermal cross section libraries.



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

Fig. 1. MCNP Modeling Results of Spent Fuel Storage Racks

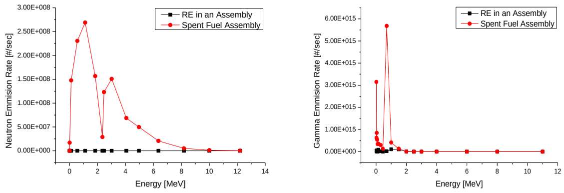
The results of the multiplication factors with the insertion of the neutron absorber were 0.89850 ± 0.00113 and 0.84896 ± 0.00091 for the WH 17x17 and PLUS7 assemblies, respectively. For the analysis of the criticality reduction ability from the composition changes of RE_2O_3, the criticalities in the WH 17x17 storage rack were evaluated by applying the compositions of the nuclides calculated in Table II. Analysis shows that the neutron absorber can control the criticality under the design criterion although the RE_2O_3 compositions are changed by various burn-up conditions.

Table IV. Criticalities in WH 17x17 Fuel Storage with Applying the RE Compositions from Table II

Group	k_{eff}	Group	k_{eff}
1-1	0.89882 ± 0.00106	2-1	0.90054 ± 0.00103
1-2	0.90171 ± 0.00106	2-2	0.90073 ± 0.00110
1-3	0.90321 ± 0.00111	2-3	0.90208 ± 0.00105
1-4	0.90285 ± 0.00105	2-4	0.90311 ± 0.00111
3-1	0.90172 ± 0.00102	4-1	0.90027 ± 0.00105
3-2	0.90105 ± 0.00099	4-2	0.89994 ± 0.00100
3-3	0.90380 ± 0.00107	4-3	0.90284 ± 0.00106
3-4	0.90290 ± 0.00110	4-4	0.90388 ± 0.00102

2.4 Radioactivity and Irradiation Analysis

In this section, the radioactivity of the absorber and the neutrons irradiation analyses were performed in the storage. Figure 2 is the radioactivity results of the Group 4-4 fuel assembly and of the RE_2O_3 extracted from the spent fuel assembly. To compare with the spent fuel assembly, the gamma radio activities were under 1/400 in total. Analysis shows that the radioactivity of the RE_2O_3 can be ignorable in the using the neutron absorber for the spent fuel storage. Also, the irradiation analysis of the absorber was evaluated by using the neutron radioactivity of the spent fuel assembly. The irradiation calculation with FISPACT code [6] was pursed with the conditions of $1.270x10^9$ neutrons/sec-assembly intensity and 100 year irradiation period. The results show that the stable nuclides in the neutron absorber have extremely small changes due to the low neutron radioactivity; however, some unstable nuclides such as Y-90, Y-91, La-140, Ce-140, and etc. are decayed and changed to the other nuclides. To confirm the criticality control ability of the absorber in this case, the criticality calculation with the irradiated absorber was evaluated using the MCNP5 code. The multiplication factor was 0.87911 ± 0.00091, which is decreased about 0.025 than that of the non-irradiated neutron absorber. It is analyzed that the decrease is caused by the high absorption cross sections of the produced nuclides after decays of the unstable nuclides.



(a) Neutron Activity (b) Gamma Activity

Fig. 2. Radiation Emission Rates of Spent Fuel Assembly and RE_2O_3

3. Conclusions

In this study, the neutron absorber based on artificial RE_2O_3 compound was designed for the use in the spent fuel storage. The design of the storage racks for the WH 17x17 and PLUS7 spent fuel assemblies were designed and the criticalities were evaluated with the various RE_2O_3 compositions. Also, the radioactivity and irradiation calculations were performed for the applicability and stability analyses of the neutron absorber into the spent fuel storage. The results show that the neutron absorber can sufficiently reduce the criticality under the regulation guideline. It is expected that the neutron absorber can contribute minimizing the disposal area of the radioactive wastes as well as the reducing the costs and resources for the using the other types of the neutron absorbers.

Acknowledgments

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