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A Study on Nuclear Design and Safety Analysis of Capsules according to Installation of Thermal Neutron Shielding Materials

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1. Introduction

In HANARO, the neutron irradiation is to investigate the nuclear reaction and the irradiation effect by irradiating the specimens such as materials and nuclear fuel with neutrons. In addition to evaluating the performance and integrity of materials as well as nuclear used in NPPs and core design data, it is important field for securing safety and economic efficiency of domestic NPPs. Among the devices used for neutron irradiation test, an irradiation test capsule is used to evaluate the neutron irradiation effects of a reactor pressure vessel, the core materials, and the nuclear fuel, which are essential for NPPs. And it is a device for reproducing the use environment of NPPs.

Usually thermal neutron (less than 0.625 eV) affect the activation and fission of the material, and fast neutrons (0.821 MeV ~ 20 MeV) affect the material properties. Currently, researches are being conducted in the fourth generation of nuclear reactors such as SFR. However, in Korea, both HANARO and commercial reactors are thermal reactors, and the neutron spectrum is also very different from fast neutrons. Therefore, it is necessary to develop a technology that can simulate the operating conditions of fast reactors in Korea. Also, research is being conducted to improve the performance of electronic materials by using neutron irradiation in advanced materials industries such as semiconductor and electronic materials through irradiation tests. In particular, Electronic materials have a mechanism with neutrons, and it is necessary to conduct the irradiation test using only fast neutrons that can cause defects. And it is necessary to minimize the radioactivity by the thermal neutrons in order to easily handle the irradiated materials.

In this paper, MCNP6 computer code was used to simulate the shielded capsule in the CT hole. And the shielding efficiency was evaluated by calculating the energy spectrum of the neutron according to thermal neutron shielding materials. Also, the safety analysis of the capsule was performed by calculating the reactivity of CT hole. Based on the results of calculations, it would be possible to construct an environment for analyzing and evaluating the effects of only fast neutrons if the irradiation test is performed using the designed capsule [1].

2. Thermal neutron shielding material

It is shielded by using a material containing element such as boron, cadmium, gadolinium, etc. with a large thermal neutron absorption cross-section.

2.1 Cd (Cadmium)

Cd has good mechanical properties and corrosion resistance, and has high thermal expansion coefficient and ductility. Therefore, Cd has high thermal neutron absorption ability and is widely used as a control rod in NPPs. However, due to the low melting point (321℃), it is similar to the reactor operating temperature, so there is a risk of melting, toxicity is strong, and the symptoms of poisoning are prohibited in advanced countries [2].

2.2 Gd (Gadolinium)

Gd is chemically stable material with good ductility and a high melting point (1,311℃) and has a very high thermal neutron absorption cross-section. However, Gd is in the form of powder, and its reactivity with oxygen during dissolution is very strong, so that it rapidly oxidizes during dissolution, so dissolution in the atmosphere is difficult. Therefore, it is mainly used as a composite material by adding to aluminum or stainless steel alloy having good corrosion resistance in order to improve it [2].

2.3 B_4C (Boron Carbide)

B_4C has good thermal neutron absorption ability, and is thermally and chemically very stable and has good mechanical properties. And it has high hardness, strength, fracture toughness and high melting point. It is widely used for military materials of military industry due to its good chemical safety or structural materials requiring corrosion resistance. And it is used in spent fuel storage vessels of NPPs. However, B_4C is a very difficult material to sinter as power. It is added to pure B_4C material such as aluminum or stainless steel alloy and is used as composite material. This is advantageous in that sintering is convenient and the content of B_4C can be easily controlled according to the purpose of use [3].

3. Analysis method

3.1 MCNP6

The MCNP6 code is a transport code for neutrons, photons and electrons, and it is widely used in radiation shielding, radiation dose measurement, and criticality calculation. In addition, geometries can be simulated in three-dimensions of reactor structures. The capsule according to the thermal neutron shielding was modeled using MCNP6 code, and neutron flux calculation was performed by applying them to the HANARO core. Prior to designing the capsule to be used for the irradiation test, the criticality and reactivity calculations were also performed. The neutron flux, criticality, and reactivity calculations were performed according to the core conditions, since it is difficult to make accurate predictions before the capsule irradiation test. [4].

3.2 Operation Condition

The nuclear fuel was loaded at all sites. In IR1 and IR2, bundles consisting of Al rod were loaded and a capsule with a thermal neutron shielding material was loaded in the CT hole. The position of the control rod was assumed to be inserted 450 mm from the lower end of the core. In order to increase the reliability of the MCNP6 code used in this calculation, KCODE, which is a criticality calculation mode, was used with 50,000 particles/cycle and 1,050 cycle. Figure 1 shows the model of the capsule loaded with CT hole by using MCNP6 code.

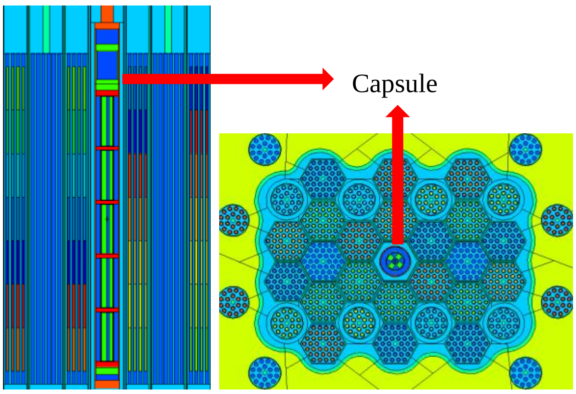

Figure 1. A model of capsule loaded in CT hole using MCNP6

Figure 2 shows an enlarged view of a capsule with a thermal neutron shielding loaded with a CT hole, and is based on a standard material capsule. Inside the capsule, a thermal neutron shielding material is present in a form of 1 mm thick fixed on the capsule inner walls (up, down, left and right). Also, the shielding was cylindrical and focused on completely blocking the thermal neutrons, leaving no space for thermal neutrons to enter [4].

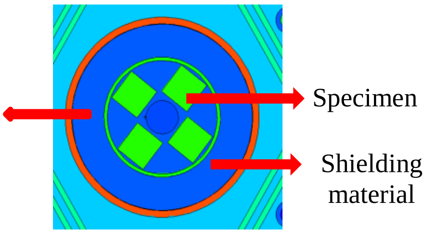

Figure 2. A model of enlarged shielding capsule using MCNP6

4. Neutron flux and safety analysis

4.1 Neutron flux spectrum

The most obvious way to verify the shielding performance of a thermal neutron shielding material is to calculate the energy distribution of neutrons through the shielding material. And the capsule is composed of five stages, and table 1, 2, and 3 show the neutron flux and shielding efficiency depending on whether shielding is used or not. And the energy group is classified into thermal neutron, Epi-thermal neutron, and fast neutron [5].

Table 1. Thermal neutron flux and shielding efficiency by application of shielding materials

Neutron Flux (10^{14} neutrons/cm2-sec)						
	Thermal Neutron flux (0 ~ 0.625 eV)					
Stage	No use	Cd	15% Gd_2O_3-Al	30% Gd_2O_3-Al	15% B_4C-Al	30% B_4C-Al
1	1.123	0.0270 97.6%	0.151 86.5%	0.112 90%	0.265 76.3%	0.108 90.3%
2	1.605	0.0391 97.6%	0.218 86.4%	0.154 90.4%	0.369 77.0%	0.151 90.6%
3	1.688	0.0428 97.5%	0.228 86.5%	0.166 90.1%	0.387 77.0%	0.157 90.7%
4	1.378	0.0347 97.5%	0.190 86.2%	0.136 90.1%	0.318 76.9%	0.128 90.7%
5	0.867	0.0225 97.4%	0.124 85.7%	0.0894 89.7%	0.204 76.4%	0.084 90.3%

Table 2. Epi-thermal neutron flux and shielding efficiency by application of shielding materials

Neutron Flux (10^{14} neutrons/cm2-sec)						
	Epi-thermal Neutron flux (0.625 eV ~ 0.821 MeV)					
Stage	No use	Cd	15% Gd_2O_3-Al	30% Gd_2O_3-Al	15% B_4C-Al	30% B_4C-Al
1	1.407	1.345 4.36%	1.353 3.83%	1.342 4.58%	1.294 8.00%	1.234 12.3%
2	1.982	1.900 4.14%	1.908 3.73%	1.874 5.45%	1.807 8.84%	1.722 13.1%
3	2.097	1.997 4.81%	2.017 3.82%	1.984 5.38%	1.904 9.23%	1.813 13.5%
4	1.746	1.657 5.09%	1.671 4.32%	1.646 5.75%	1.588 9.06%	1.514 13.2%
5	1.148	1.082 5.80%	1.093 4.80%	1.086 5.47%	1.044 9.09%	0.999 12.9%

Table 3. Fast neutron flux and shielding efficiency by application of shielding materials

Neutron Flux (10^{14} neutrons/cm2-sec)						
	Fast thermal Neutron flux (0.821 MeV ~ 20 MeV)					
Stage	No use	Cd	15% Gd_2O_3-Al	30% Gd_2O_3-Al	15% B_4C-Al	30% B_4C-Al
1	1.090	1.045 4.13%	1.053 3.44%	1.043 4.32%	1.043 4.28%	1.028 5.70%
2	1.533	1.476 3.75%	1.466 4.39%	1.453 5.26%	1.454 5.19%	1.431 6.69%
3	1.617	1.535 5.08%	1.546 4.41%	1.540 4.77%	1.532 5.25%	1.520 6.00%
4	1.354	1.280 5.46%	1.299 4.02%	1.276 5.75%	1.280 5.47%	1.260 6.94%
5	0.882	0.838 5.04%	0.847 4.05%	0.842 4.57%	0.841 4.70%	0.837 5.14%

As a result of the calculation, the shielding efficiency of Cd which is not mixed with other metals when using thermal neutron shielding was the highest at about 97%. And when the shielding material is 15%, 30% Gd_2O_3-Al, B_4C-Al shielding efficiency was calculated to be about 86%, 90%, 76%, 90%, respectively. The shielding efficiency of Cd and Gd_2O_3-Al is calculated to be about 3 ~ 5% in the Epi-thermal neutron flux and fast neutron flux. However, B_4C-Al is calculated to have about 8 ~ 13 % in the Epi-thermal neutron flux and about 4 ~ 7% in the fast neutron flux. Also, in the case of Gd_2O_3-Al, B_4C-Al, the higher the content of Gd and B_4C, the higher the shielding efficiency. Figure 3 shows a graph of the neutron spectrum for each neutron energy with or without a shielding. Table 4 shows the shielding ratios using the ratio of Fast/Thermal neutron flux based on the previous tables. When the shielding is not used, the Fast/Thermal ratio is close to 1:1. However, when using the shielding material Cd, about 37 times, 15%, 30% Gd_2O_3-Al about 6.7, 9.2 times, 15%, 30% B_4C-Al about 4, 9.6 times.

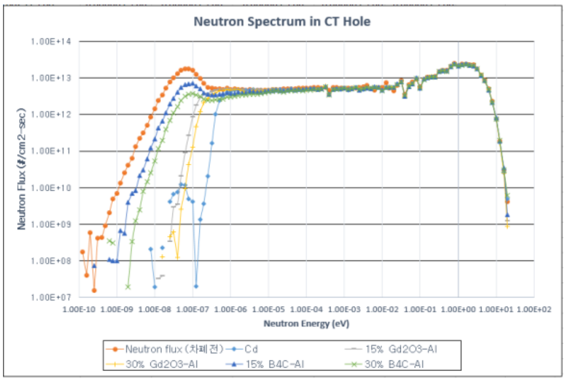

Figure 3. comparison of neutron flux spectrum before/after installation of thermal neutron shielding

Table 4. Fast/Thermal with or without shielding

Stage	No use	Cd	15% Gd_2O_3-Al	30% Gd_2O_3-Al	15% B_4C-Al	30% B_4C-Al
1	0.97	38.68	6.94	9.29	3.93	9.47
2	0.96	37.68	6.71	9.41	3.93	9.46
3	0.96	35.85	6.76	9.24	3.95	9.68
4	0.98	36.83	6.83	9.37	4.02	9.82
5	1.02	37.21	6.80	9.41	4.11	9.96

4.2 Safety Analysis

The limitation of the reactivity by the experiment is stated in the Technical Specification for Operation of HANARO [6] as "The positive reactivity by a single test device due to withdraw, insertion and breakage cannot exceed 12.5mk". Therefore, MCNP6 code was used to calculate the reactivity of core by capsule. Also, the criticality calculation was performed according to the thermal neutron shielding material. In order to confirm the reactivity, the criticality calculation was performed assuming that the shielded capsule was loaded, the Al mockup bundle was loaded instead of capsule, and the capsule was drawn out and filled with water. Table 5 shows the results of the criticality calculation and the reactivity of capsules when Cd, Gd_2O_3-Al and B_4C-Al were used as thermal neutron shielding materials.

Table 5. Criticality and Reactivity calculation

CT Hole	Control Rod Location	Criticality	Reaction (±mk)
Capsule Withdraw	450 mm	1.02025±0.0001	-
Al mockup		1.02743±0.0001	6.84
Cd		1.01025±0.0001	9.70
15% Gd_2O_3-Al		1.01145±0.0001	8.52
30% Gd_2O_3-Al		1.01044±0.0001	9.51
15% B_4C-Al		1.00925±0.0001	10.68
30% B_4C-Al		1.00686±0.0001	13.03

As a result of the analysis, when Cd and Gd_2O_3-Al were used as the thermal neutron shielding material, the variation of the reactivity did not exceed the limit of 12.5mk, which is the limit of the reactivity of the specimen. And 15% Gd_2O_3-Al showed the lowest reactivity. However, when B_4C-Al was used, the reactivity of the specimen was not satisfied because it was over or close to the limit. In addition, the higher the content of Gd_2O_3, B_4C-Al, the higher the reactivity is calculated.

5. Conclusion

Usually thermal neutrons affect the activation and fission of the material, and fast neutrons affect the material properties. Therefore, in this paper is a basic study for the design of irradiation test capsule equipped with a thermal neutron shielding material for analyzing and evaluating the effect of only fast neutrons causing material defects. And the characteristics of Cd, Gd and B_4C with high thermal neutron absorption cross-section were analyzed. The capsule equipped with thermal neutron shielding material is loaded in CT hole. And it is modeled by using MCNP6 code. Based on this, neutron flux spectrum, shielding efficiency and safety analysis were calculated.

The results of this calculation show the possibility of capsule performance (thermal neutron shielding rate, safety) that can shield thermal neutrons and analyze the effect of only fast neutrons. In the case of Cd with the best shielding efficiency, although there is a risk of low melting point and toxicity, it is considered that the small thickness of the shielding material does not have a bad influence to carry out the irradiation test, but it is necessary to discuss with the regulatory agency and HANARO operation room. The next shielding efficiency, Gd_2O_3-Al, showed lower shielding efficiency than Cd, but more stable than Cd in terms of reactivity. Therefore, it can be most effectively used if appropriate Gd_2O_3-Al is added. On the other hand, B_4C-Al showed the most unstable results in terms of reactivity and shielding efficiency was also lowest.

In future, it will be possible to carry out the irradiation test using only fast neutron similar to the fast reactor core in HANARO using the capsule equipped with the optimal shielding material through various analyzes, based on the irradiation test, it can be expected to contribute to the development of fast reactor materials in Korea. In addition, it can contribute to high tech materials such as semiconductors and advanced materials using only fast neutrons, and it is considered that the radioactivity effect of thermal neutrons can be minimized.

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