Design of Capsule for Advanced Material Analysis according to Installation of B_4C in a IP5 hole

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1. Introduction

In the meantime, the neutron irradiation tests in the nuclear field have been studied from the viewpoint of nuclear fuel performance and structural material damage. However, the neutron irradiation is a tool that can induce material properties change without change of material composition through nuclear transformation, defect formation, disordering by neutrons. From this viewpoint, it can be efficiently used to study the performance improvement of advanced materials. Therefore, it is intended to analyze on material property change through neutron irradiation for advanced materials (superconductors, microwaves, semiconductors, electronic materials, multi ferroics, etc.) [1].

The mechanism for reaction between materials and neutrons in the irradiation at HANARO is affected by the energy of neutrons. Usually, thermal neutrons cause nuclear transmutation by the capture reaction and fast neutrons create defects by collision with nucleus of material. It is necessary to conduct the irradiation test using the fast neutrons which can cause the property change of the material rather than the thermal neutrons affecting the activation. Therefore, it is necessary to minimize the activation by thermal neutron to easily handle the irradiated materials [2]. Therefore, in this paper, the basic study of the nuclear design of the irradiation test capsule equipped with a thermal neutron shielding material. Based on this, it is intended to analyze and evaluate the effects of fast neutrons, which can cause defects in advanced materials.

2. Selection of irradiation hole and shielding material

2.1. Irradiation hole

There are 32 vertical irradiation holes and 7 horizontal irradiation holes at HANARO as shown in Fig 1. Among them, the horizontal irradiation holes are used for the micro & nano-scale analysis for materials. Therefore, the most of irradiation tests for advanced materials have been conducted using the vertical irradiation holes. Although the vertical irradiation holes such as CT, IR1&2, ORs in-core region have been used for the irradiation performance test of nuclear materials with high neutron flux, it is difficult to handle the irradiated materials.

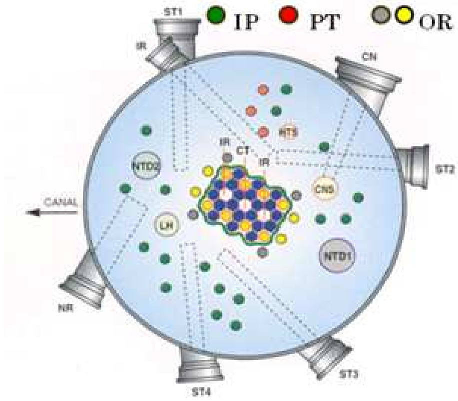

Figure 1. The schematic diagram of irradiation holes in HANARO [3]

Also, NAA (Neutron Activation Analysis) holes are difficult to use because of the strict experimental conditions by PTS (Pneumatic Transfer System). Therefore, IP irradiation holes mainly used for RI production can be used for the irradiation of advanced materials. In this paper, among the 17 IP holes, IP4 and IP5 are mainly used for irradiation materials. Among them, IP5 hole was selected because it does not affect the NTD (Neutron Transmutation Doping) hole [1].

2.2 Shielding material

B_4C has good thermal neutron absorption ability (3,840 barn) and it is thermally and chemically very stable and has good mechanical properties. And it has high advantageous in that sintering is convenient and the content of B_4C can be easily controlled according to the purpose of use. It is widely used for military industry due to its good chemical safety and structural materials requiring corrosion resistance. Also, it is used in spent fuel storage vessels and neutron shielding of nuclear facility. Therefore, in this paper, B_4C was selected as the thermal neutron shielding material.

3. Design of the irradiation test device

3.1. Capsule design

Among the devices used for neutron irradiation test, the irradiation test capsule is used to evaluate the neutron irradiation effects of materials and nuclear fuel. It is a device that reconstruct the operating environment of NPPs, and it is designed according to the user's requirement. The capsule used in the paper is a cylindrical shape made of S.S (outer tube) with a radius of 30mm and a height of 870mm. and it consists of 3 stages. Figure 2 shows the model of the capsule loaded with a IP5 hole by using the MCNP6 code. The specimen (SiC), which is widely used as advanced materials, is present in each stage, and thermal neutron shielding material is fixed in the inside of a capsule (upper, lower, right and left). Also, it consists of a rectangular shape that encloses to the specimen in duplicate. In addition, the thickness of the thermal neutron shielding material was 2mm, and the thermal neutron shielding efficiency according to the thickness was analyzed. Figure 3 shows the component of the capsule. Also, IP5 hole is less affected by neutrons because it is located at the reflector site. Therefore, the angle of the specimen and the shielding material was adjusted to maximize the influence of the neutrons. This angle is 65 degrees, which is the angle between the core and the IP5 hole. This is shown in Figure 4.

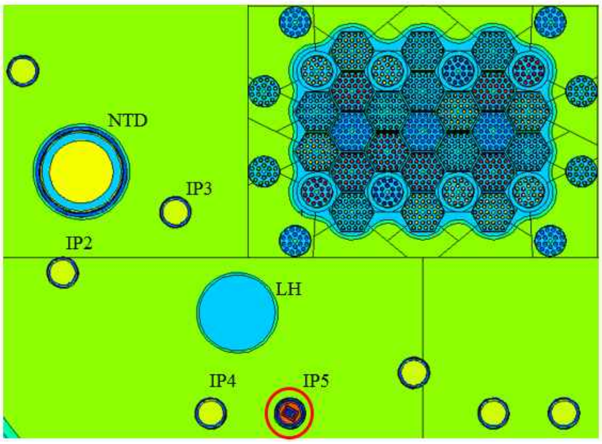

Figure 2. A model of capsule loaded in IP5 hole using the MCNP6 code

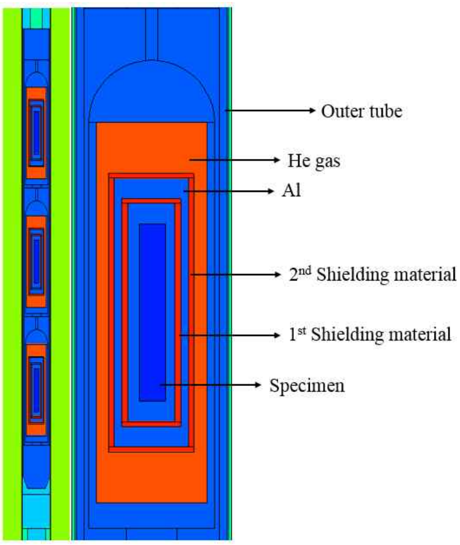

Figure 3. The shape and component of capsule

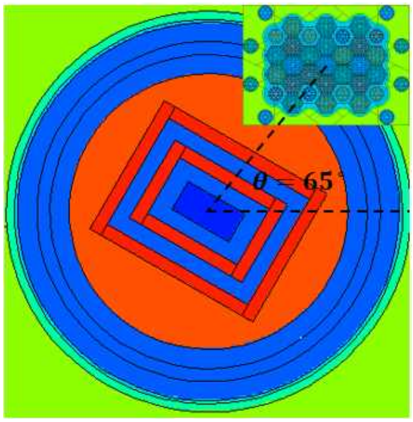

Figure 4. A model of capsule according to angle

4. Neutron flux and Safety analysis

4.1. Neutron flux

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. Table 1 shows the neutron flux according to the shielding material. Also, the energy group is classified into thermal neutron (0 ~ 0.625eV), and fast neutron (0.1 ~ 20MeV).

Table 1. Thermal & Fast neutron flux by application of shielding materials

Stage	Neutron Flux (neutrons/cm^2·sec)			
	Thermal neutron flux		Fast neutron flux	
	No use	Use shielding material	No use	Use shielding material
1	7.899E+13	9.899E+06	2.722E+11	2.355E+11
2	8.719E+13	1.157E+07	2.723E+11	2.376E+11
3	6.905E+13	7.776E+06	1.342E+11	1.039E+11

As a result of the calculation, when thermal neutron shielding material was used, the thermal neutron flux was shielded from 7.84×10^{13} neutrons/cm^2 · sec to 9.74×10^6 neutrons/cm^2 · sec. On the other hand, fast neutron flux was not nearly affected. Figure 3 shows the neutron energy spectrum according to the shielding material.

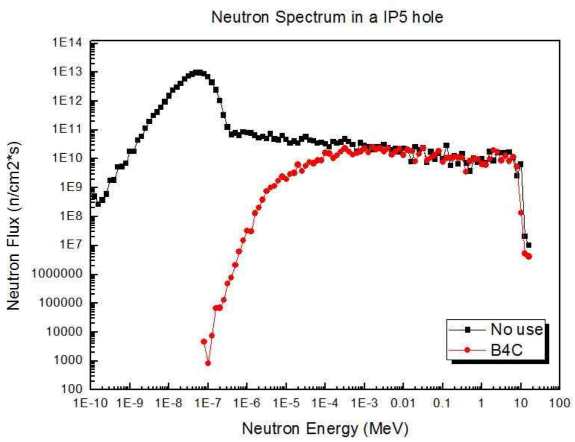

Figure 3. Neutron energy spectrum according to the B_4C

4.2. Safety analysis

The criticality(K_{eff}) represents the degree of variation in number of the neutrons with time and it is expressed as the ratio of the number of neutrons between successive generation. Therefore, the reactivity indicates the degree of variation in the criticality the reactor. The definition of the reactivity indicates that the reactor state is how far from the criticality state, as shown in Equation 1.

$$\rho = 1 - \frac{1}{K_{eff}} \qquad (1)$$

If the state of reactor is changed from K_1 to K_2, the change of reactivity is given by Equation 2.

$$\Delta\rho = \rho_2 - \rho_1 = \frac{1}{k_1} - \frac{1}{k_2} \qquad (2)$$

Therefore, it is essential to calculate the reactivity of the capsule according to the state of reactor core prior to irradiation test in HANARO. The limitation of the reactivity by the experiment is stated in the Technical Specification for Operation of HANARO 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 the 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 capsule was drawn out and filled with water. Table 3 shows the results of the criticality calculation and the reactivity of capsule.

Table 3. Criticality and Reactivity calculation

IP5 Hole	Criticality (K_{eff})	Reaction (mk)
No use	1.03502	-
Withdrawn	1.03467	0.32
B_4C	1.03484	0.15

As a result of the calculation, when B_4C was used as the thermal neutron shielding material, the variation of the reactivity did not exceed the limit of 12.5mk.

5. Conclusion

This paper is a basic study for the nuclear design of irradiation test capsule equipped with a thermal neutron shielding material (B_4C) for analyzing and evaluating the effect of fast neutrons. The MCNP6 code was used to model the shape of the capsule with the shielding materials. Based on this, neutron energy spectrum and safety analysis were calculated. The results of this calculations show the possibility of capsule performance that can shield thermal neutrons and analyze the effect of fast neutrons.

As a result of calculation of the shielding efficiency of the designed capsule, the thermal neutron flux was reduced from about 7.84×10^{13} neutrons/cm$^2 \cdot$ sec to 9.74×10^6 neutrons/cm$^2 \cdot$ sec. On the other hand, the fast neutron flux was not nearly affected. And it is essential to calculate the reactivity of the capsule according to the state of reactor core prior to irradiation test in HANARO. As a result of the calculation, when B_4C was used as the thermal neutron shielding material, the variation of the reactivity did not exceed the reference value. Therefore, the designed capsule will contribute to the minimization of the radioactivity of electronic materials and the irradiation test for the performance improvement using the fast neutrons.

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