Monte Carlo simulation for an irradiation of the single-crystal silicon in HANARO

Tae-Yang Noh *, B.G. Park and M.S. Kim
Korea Atomic Energy Research Institute, Yuseong-gu, Daejeon, 34057, Republic of Korea
**Corresponding author: tynoh@kaeri.re.kr*

1. Introduction

There were neutron irradiation tests of single-crystal silicon five times in HANARO by Konkuk University since 2010. The silicon specimens were located in IP5 and NAA1 horizontal irradiation holes. The specimens were in the top capsule in IP5 and the rabbit connected with pneumatic transport system (PTS) was used in NAA1.

The purpose of experiments was the evaluation of electrical properties. It is needed to know how much irradiate neutron to silicon specimens quantitatively for an accurate analysis of experimental results. In this paper, the quantity of neutron irradiation for the specimens is evaluated at each experimental cycle with Monte Carlo method.

2. Simulation Method

2.1. Core Modeling

The burned-core model in previous study is used as the HANARO core model [1]. It is improved from the conventional model which is loaded fresh fuel in the MCNP code. Burnup information such as burnup, power distribution and fuel composition is reflected to the HANARO model at each time node. The information is extracted from the WIMS/VUNTURE code system.

There are many irradiation holes, not only IP5 and NAA1 which the silicon specimens are loaded. The materials in the core affect the neutron flux distribution to surrounding irradiation hole directly. The irradiation times are categorized as 5 cases and the reactor operating information of each case is corrected. The loading conditions in the irradiation holes are described in table 1.

The CT and IR holes which are inside inner shell are modeled same with table 1. The OR3 and OR4 holes are also modeled same with table 1 because these are located along the route of neutron transportation to the silicon specimens. On the other hand, OR5 and OR6 holes are not able to affect to specimens due to be located opposite. Dummy assemblies are assumed in the OR5 and OR6 holes. Other irradiation holes are modeled same with table 1. The cross sectional area of the HANARO model is shown in figure 1 and some irradiation holes are indicated such as IP5, NAA1 and et cetera.

Table 1. Loading conditions of the horizontal irradiation holes

Location	Case 1 (68 cycle)	Case 2 (69 cycle)	Case 3 (87 cycle)	Case 4 (90 cycle)	Case 5 (95 cycle)
CT	IR rig	IR rig	capsule	capsule	dummy
IR1	dummy	dummy	dummy	dummy	dummy
IR2	IR rig	IR rig	IR rig	IR rig	dummy
OR3	IR rig	IR rig	IR rig	IR rig	mini plate
OR4	PWR fuel	PWR fuel	hyb. UO_2	hyb. UO_2	hyb. UO_2
OR5 *	SFR fuel	SFR fuel	capsule	TRISO	IR rig
OR6 *	IR rig	IR rig	IR rig	IR rig	IR rig
NTD	light water				
HTS	light water				
LH	3 rigs (filled with light water)				
IP	aluminum can (filled with air)				
NAA	Pneumatic Transport System (PTS)				
Control rod position	477.3 mm	559.0 mm	450.0 mm	490.4 mm	478.0 mm

* Dummy assembly is loaded in OR5 and OR6 hole in MCNP model

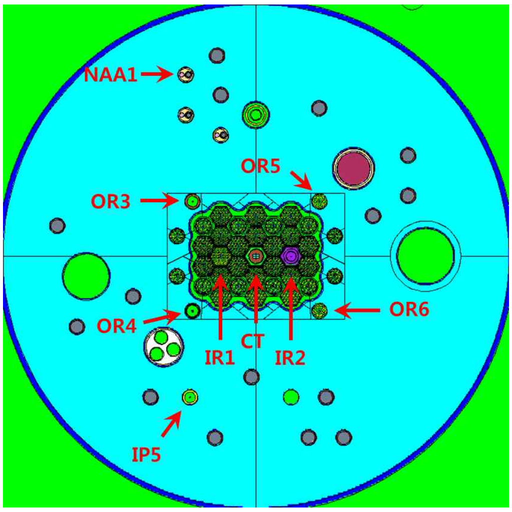


Figure 1. Radial core map of the HANARO

2.2. Modeling of the Specimens

The characteristics of silicon specimens and loaded irradiation hole are indicated in table 2. The specimens in the MCNP model are drawn in figure 2. The specimens are natural and single-crystal silicon. There are two types of silicon specimens, the plate type and the cylindrical type. The cylindrical specimens are wide and flat. These are assumed to be laid down. The plate specimens are squared shaped and very thin. These are assumed to be laid down in NAA1 hole. However these are impossible to be laid down in IP5 hole because of insufficient space. So these are assumed to be stood up in IP5. When the several specimens are irradiated simultaneously such as case 3, 4 and 5, it is assumed to be layered repeatedly in the capsule or rabbit.

In the case of irradiation in IP5, the specimens are located top of the core because the specimens are loaded in the top capsule among several capsules. Meanwhile, the specimens are located center of the core in case of loaded in NAA1. Because the rabbit which is connected with pneumatic transport system is located in center of the core.

Table 2. Characteristics of silicon specimens

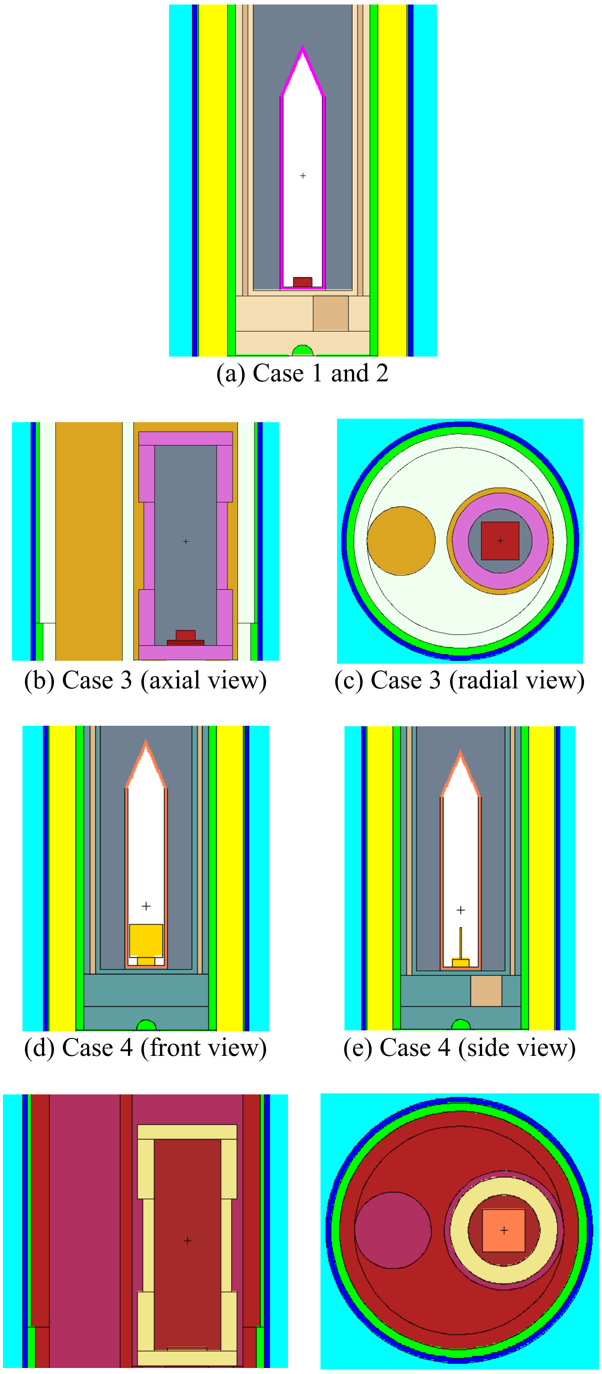
Case	Dimension (mm)	Density (g/cm^3)	Irrd. hole
Case 1 (68 cycle)	Φ 5.26 x 2.53	2.328	IP5
Case 2 (69 cycle)	Φ 5.26 x 2.53	2.328	IP5
Case 3 (87 cycle)	Φ 5.26 x 2.54	2.326	NAA1
	9.97 x 9.98 x 0.49	2.227	
	9.98 x 9.98 x 0.49	2.221	
	9.98 x 9.98 x 0.49	2.209	
Case 4 (90 cycle)	Φ 5.25 x 2.53	2.331	IP5
	9.97 x 9.96 x 0.482	2.303	
Case 5 (95 cycle)	10 x 10 x 0.49	2.280	NAA1
	10 x 10 x 0.49	2.283	

2.3. Calculation Method

The MCNP ver. 6.1 code is used the simulation. The neutron flux at the specimens and the neutron capture reaction rate of Si-30 are calculated. The energy group for the neutron flux calculation is set 97 groups. Meanwhile, for the calculation of reaction rate, the energy group is divide 5 groups which are consisted of 1 group of thermal energy range, 3 groups of intermediate energy range and 1 group of fast energy range. The energy boundary of 5 groups is indicated in table 3.

The relative error of reaction rate depends on the number of neutrons corrected at the specimens. There is large variation according to location, shape of specimen and energy group. The averaged relative errors of the reaction rate in thermal range are followings: 1.76% of the cylindrical specimens and 1.30% of the plate specimens in IP5 and 2.04% of the cylindrical specimens and 1.59% of the plate specimens in NAA1.

The criticality problem mode is used for the calculation. Detailed calculation options are 1,000,000 of histories, 500 of active cycles and 15 of inactive cycles. It is confirmed that the fission source distribution is converged during the preliminary 15 inactive cycles. As a result, the relative error of k-eff value is 0.003%.



(a) Case 1 and 2
(b) Case 3 (axial view)
(c) Case 3 (radial view)
(d) Case 4 (front view)
(e) Case 4 (side view)
(f) Case 5 (axial view)
(g) Case 5 (radial view)

Figure 2. The drawings of the specimens in the MCNP

Table 3. Energy range for calculation of reaction rate (5G)

Group	Energy boundary		
1	0	-	0.625 eV
2	0.625 eV	-	4 eV
3	4 eV	-	9.118 keV
4	9.118 keV	-	0.821 MeV
5	0.821 MeV	-	10 MeV

3. Calculation Results

The energy differential neutron flux distribution is shown at each silicon specimen in figure 3. The averaged thermal neutron flux in IP5 and NAA1 are calculated 6.62E+13 n/cm^2-sec and 4.78E+13 n/cm^2-sec respectively.

In table 4, the neutron capture reaction rate of Si-30 of the silicon specimen is indicated at each case. The averaged reaction rate in thermal range in IP5 and NAA1 are 9.42E+09 reactions/cm^3-sec and 6.83E+09 reactions/cm^3-sec respectively. The difference between IP5 and NAA1 comes from the distance from the core.

The relative error of reaction rate in thermal range for case 3 is 0.7% between maximum and minimum value in spite of the different shape of the specimens shown in figure 2 (b) and (c). In case 4, the relative error is 2.6% which is larger than in case 3. It seems to come from the geometric effect which plate specimen stands on shown in figure 2 (d) and (e). In case 5, there are two plate specimens. The plate specimen is very thin and it can be assumed that two specimens are located same position. It makes same reaction rate.

The 99.8% of neutron capture reaction of Si-30 occurs in thermal energy range by comparing thermal and total energy range in table 4.

Table 4. Neutron capture reaction rate of Si-30 in thermal energy range and total energy range

Case	Irrd. hole	Shape	Capture reaction rate (reactions/cm^2-sec)	
			thermal	Total
Case 1 (68 cycle)	IP5	Cylinder	9.63E+09	9.65E+09
Case 2 (69 cycle)	IP5	Cylinder	9.51E+09	9.53E+09
Case 3 (87 cycle)	NAA1	Cylinder	6.89E+09	6.89E+09
		Plate	6.91E+09	6.92E+09
		Plate	6.93E+09	6.93E+09
		Plate	6.94E+09	6.94E+09
Case 4 (90 cycle)	IP5	Cylinder	9.16E+09	9.17E+09
		Plate	9.40E+09	9.42E+09
Case 5 (95 cycle)	NAA1	Plate	6.66E+09	6.67E+09
		Plate	6.66E+09	6.67E+09

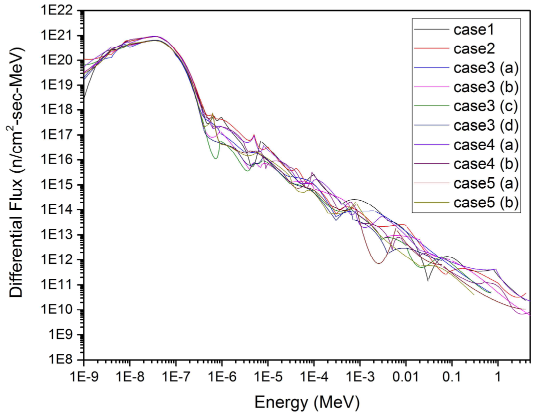


Figure 3. Energy differential neutron flux distribution at the silicon specimens

4. Conclusions

The quantity of irradiated neutron in the HANARO reactor is calculated for the silicon specimen by using the Monte Carlo method. The core is modeled differently for each case based on real experiment and records of HANARO. As a calculation result, the thermal flux at specimens and neutron capture reaction rate of Si-30 in thermal range in IP5 are calculated 6.62E+13 n/cm^2-sec and 9.42E+09 reactions/cm^3-sec respectively. In NAA1, these are calculated 4.78E+13 n/cm^2-sec and 6.83E+09 reactions/cm^3-sec respectively. The thermal flux at NAA1 is 72% of thermal flux at IP5 and the thermal flux is little dependent of operation cycle. The 99.8% of neutron capture reaction rate occurs in thermal energy range which energy is lower than 0.625eV.

REFERENCES

[1] Byung Gun Park, Dong-Keun Cho and Myong-Seop Kim, Development of Automated Burned-core Modeling System of HANARO, Proceedings of the 2015 International HANARO Symposium, May 11-15, 2015, Daejeon.