공학석사 학위논문

Nuclear Heating Analysis for the HANARO Cold Neutron Source by McCARD Burnup Calculations

McCARD 연소계산을 이용한 하나로 냉중성자 장치 발열량 분석

2021년 8월

서울대학교 대학원

에너지시스템공학부

황성재

Nuclear Heating Analysis for the HANARO Cold Neutron Source by McCARD Burnup Calculations

McCARD 연소계산을 이용한 하나로 냉중성자 장치 발열량 분석

지도 교수 심 형 진

이 논문을 공학석사 학위논문으로 제출함
2021년 8월

서울대학교 대학원
에너지시스템공학부
황 성 재

황성재의 공학석사 학위논문을 인준함
2021년 8월

위 원 장 김 기 현

부위원장 심 형 진

위　　원 서 철 교

Abstract

The cold neutrons are used for research purposes such as cell observation and, the cold neutron source (CNS) has been operated in the HANARO reactor at KAERI since 2010. The CNS should be utilized at a low temperature. However, the nuclear heating in the CNS increases due to the fission neutrons and the gamma rays from the core. Thus, it is important to analyze accurately the nuclear heating in the CNS.

The objectives of this study are to establish a nuclear heating analysis methodology in McCARD, and to analyze accurately the nuclear heating in the CNS during the cycle operation of 28 days by McCARD.

The nuclear heating in the CNS is categorized into four types. These are neutron heating by fission neutrons, gamma heating from prompt gamma rays from fission reactions, gamma heating from delayed gamma rays by fission product decays, and beta heating produced by beta decays of Al-28 in the CNS tank.

The flux conversion factor is used to convert a Monte Carlo output to one in real-scale. The flux conversion factor in McCARD changes with burnup steps, and it is the key factor to obtain the value of the nuclear heating in the CNS. McCARD burnup calculations are performed with constant power and constant flux maintaining criticality.

The nuclear heating in the CNS increased by 6.54% from BOC to EOC in the constant power condition while that in the constant flux condition by 5.35%. The result of the constant flux condition is a more appropriate final result in this research because the HANARO reactor is a research reactor to maintain the constant flux.

The flux conversion factor is consistent within the confidence interval (2σ) from BOC to EOC in the constant power condition while that in the constant flux condition decreases by 2.69%. From these results, it is demonstrated that the nuclear heating in the CNS did not increase due to the flux conversion factor.

However, the flux in the CNS increased from BOC to EOC in both the constant power and the constant flux condition. To maintain criticality, the control rod between the core and the CNS was withdrawn from BOC to EOC. Therefore, it can be concluded that the nuclear heating in the CNS increased due to the increase of the neutron flux and the gamma flux from the core.

Keyword: HANARO reactor, Cold Neutron Source, Nuclear Heating, McCARD, Flux Conversion Factor, Burnup Calculations, Neutron Flux, Gamma Flux

Student Number: 2019-22929

Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1. Research Background

The HANARO reactor at KAERI is a research reactor and it has been used for many types of research using neutron since 1995. The cold neutron source (CNS) in the HANARO reactor produces the cold neutrons using the fission neutrons from the HANARO reactor core and it is a very important facility in the HANARO reactor. The nuclear heating is generated when the fission neutrons and the gamma rays from the HANARO reactor core collide with the CNS. The nuclear heating can be a serious problem to the CNS because the cold neutrons are produced at a temperature of 20K.

The helium refrigerator cools the CNS to maintain helium as liquid hydrogen. In addition, the helium refrigerator removes the heating of the CNS and the helium refrigerator itself. From the result of the review of the helium refrigerator system cooling capacity in KAERI, the total heating which the helium refrigerator should remove increased by 34% [1] during one cycle operation of 28 days.

To estimate the portion of the nuclear heating from the total heating increase, the nuclear heating analysis of the CNS has been conducted using MCNP [2] and HELIOS [3] by KAERI. The result of the previous study was the 5.8% [4] increase due to the CNS nuclear heating during one cycle operation of 28 days at equilibrium core.

1.2. Research Objectives

The objectives of this study are to establish a nuclear heating analysis methodology in McCARD [5], and to analyze accurately the nuclear heating contributions for the HANARO CNS during the cycle operation of 28 days by McCARD based on the recent study [6].

Chapter 2. Introduction to the HANARO Cold Neutron Source (CNS)

2.1. HANARO Core

Figure 2-1 shows that the HANARO core is next to the CNS. The total thermal power of the HANARO reactor is 29.3MWth. From the figure, one can see that the fission neutrons and the gamma rays from the HANARO reactor core are the sources of the nuclear heating in the CNS.

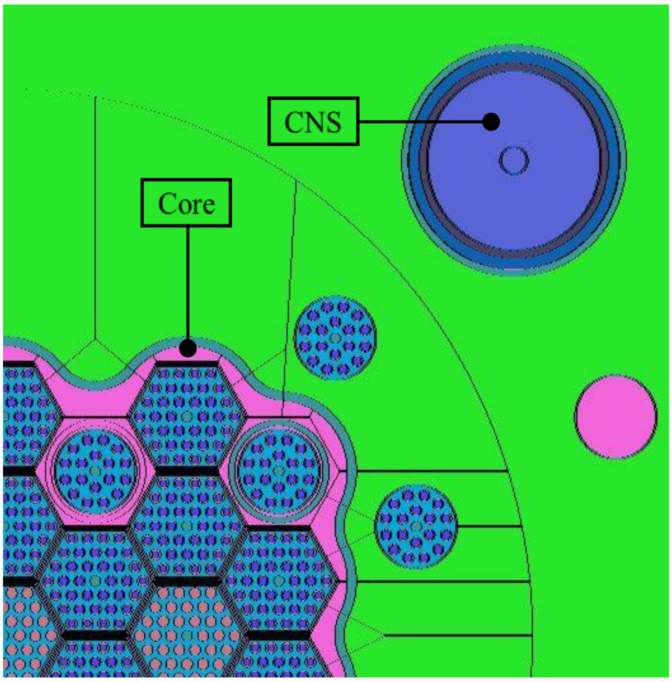

Fig. 2-1 Horizontal cross section of the HANARO Core and the CNS

2.2. HANARO CNS

Figure 2-2 shows the HANARO CNS and its inside. The CNS is a double cylinder that has an open cavity. The thickness of the wall is 1mm and the height of the inner cylinder is 15cm. The material of the tube, tank, cavity, and case is aluminum alloy. The helium is in the inner cylinder and the outer cylinder is full of liquid hydrogen which is a moderator of the fission neutrons. The fission neutrons from the core are transformed into the cold neutrons by the liquid hydrogen in the CNS.

When the cold neutrons are produced, there is the nuclear heating in the CNS. The nuclear heating is also generated when the gamma rays from the core collide with the CNS.

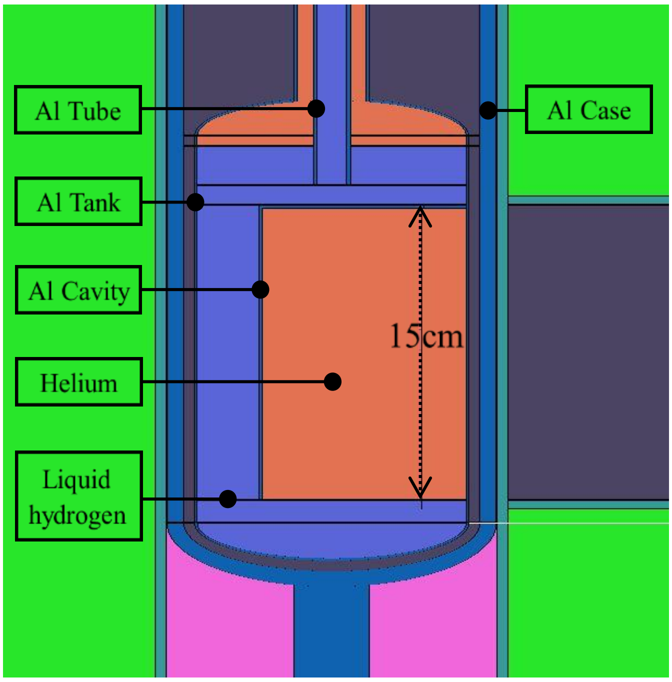

Fig. 2-2 Vertical cross section of the HANARO CNS

Chapter 3. Monte Carlo (MC) Nuclear Heating Analysis Methodology

3.1 CNS Heatings by Radiations

The nuclear heating of the HANARO CNS means that the CNS heatings are generated by radiations. The source of the nuclear heating in the CNS has already been analyzed [7] in the previous study. Figure 3-1 shows that there are four types of the nuclear heating in the CNS. McCARD has a power tally function to obtain the MeV/cm^3/neutron. The MeV/cm^3/neutron from the neutron heating and the gamma heating can be converted into J/neutron by multiplying volume and J/MeV. The beta heating is obtained by multiplying the neutron capture rate of Al-27 in the CNS tank and the kinetic energy of beta from the Al-28 decay. The keV/cm^3/neutron can be converted into J/neutron by multiplying volume and J/keV.

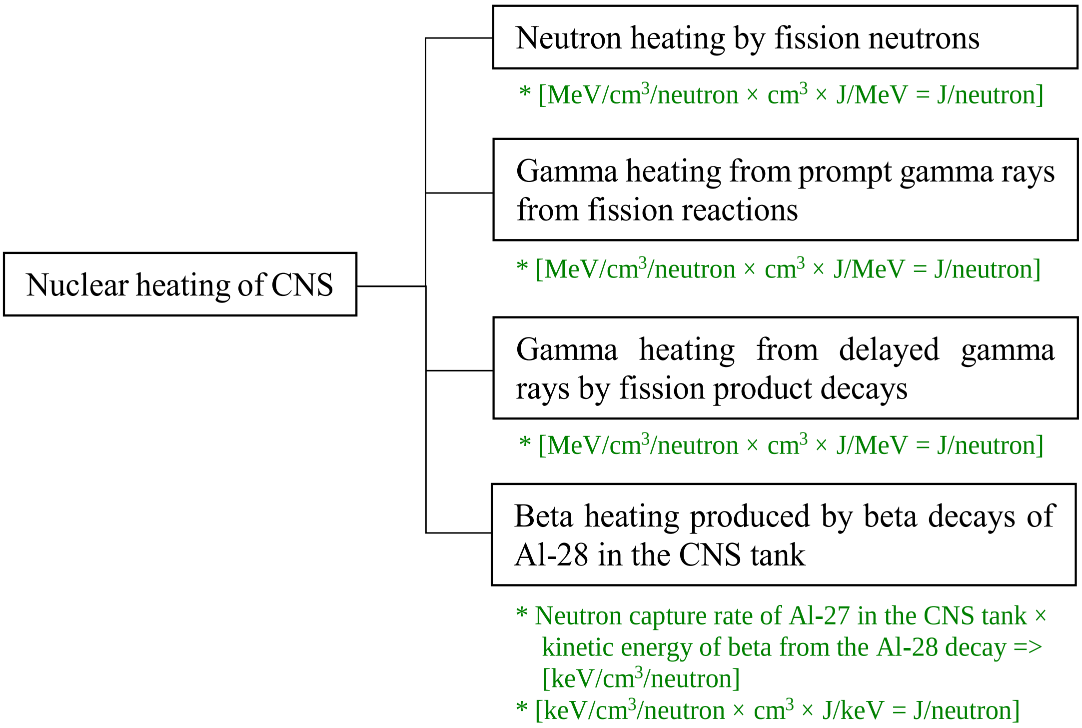

Fig. 3-1 Nuclear heating of the HANARO CNS

3.2 Flux Conversion Factor in MC Eigenvalue Calculations

3.2.1 Flux Conversion Factor in Previous Approach

The flux conversion factor is introduced to convert a MC output normalized by a unit source neutron to one in real-scale. Previously, the constant values of energy per fission (κ) and fission nu (ν) are used to obtain the flux conversion factor making the fission power *Q* as

$$C.F.=\frac{1}{k}\cdot\frac{Q}{\kappa}\cdot\nu \tag{3.1}$$

where *k* is the effective multiplication factor.

The physical meaning of the flux conversion factor becomes the actual number of the current-generation fission neutrons, i.e., the source neutrons. The flux conversion factor is treated as a constant value but, in reality, the flux conversion factor can be varied with burnup steps.

3.2.2 Flux Conversion Factor in McCARD

In McCARD, the flux conversion factor is calculated using region-wise tallied fission power as

$$C.F.=\frac{Q}{\sum_{m=1}^{M}\left(\kappa\Sigma_f\phi\right)_m \mathrm{V}_m} \tag{3.2}$$

The physical meaning of the flux conversion factor becomes the actual number of the current-generation fission neutrons, i.e., the source neutrons. The flux conversion factor changes with burnup steps by considering region-wise tallied fission power. The flux conversion factor is the key factor of the change in the CNS nuclear heating.

3.2.3 Comparison of Flux Conversion Factor Calculation Methods

Table 3-1 shows that the comparison of the flux conversion factors between the previous study and McCARD. In the previous study, the number of fissions per fission neutron is included in k which is a constant value in the calculation. However, the number of fissions per fission neutron in the previous study is not directly used in the flux conversion factor. On the other hand, the number of fissions per fission neutron is directly used in the flux conversion factor in McCARD.

The physical meaning of the flux conversion factors in the two methods is the actual number of current-generation fission neutrons. However, the actual values of the flux conversion factors in the two methods are not the same. The flux conversion factor in the previous study is a constant value, but the flux conversion factor in McCARD changes with burnup steps.

Table 3-1 Comparison of flux conversion factor calculation methods

Category		Previous study	McCARD method
Flux conversion factor		$\frac{1}{k}\cdot\frac{Q}{\kappa}\cdot\nu$	$\frac{Q}{\sum_{m=1}^{M}\left(\kappa\Sigma_f\phi\right)_m \mathrm{V}_m}$
Power (Q)		29.3 MWth	29.3 MWth
Energy per fission (κ)	U-235	200 MeV	202.3415 MeV
	U-238	200 MeV	212.6019 MeV
Number of fissions per fission source neutron ($\sum_{m=1}^{M}\left(\Sigma_f\phi\right)_m \mathrm{V}_m$)		Energy dependent	Energy dependent
Number of fission neutrons per fission (ν)		2.354	Energy dependent
Physical meaning		Actual number of current-generation fission neutrons	Actual number of current-generation fission neutrons

Chapter 4. McCARD Nuclear Heating Analyses for the HANARO CNS

4.1 Heating Analysis by Constant Power Operation Condition

4.1.1 Burnup Calculation Option in Constant Power Operation Condition

Table 4-1 shows that the burnup calculation is performed to maintain constant power which is the way that the power reactor is operated. The critical search is used to maintain criticality during the calculation. The cycle length is the same period as that of the actual cycle operation of the HANARO reactor and the constant value is the real total power of the HANARO reactor.

Table 4-1 Burnup calculation option with constant power

Category	Burnup calculation
Option	Constant power and criticality search
Calculation option	1,000,000 histories per cycle on 50 inactive and 100 active cycles
Cross section library	ENDF/B-VII.0
Cycle length (Burnup step)	28 days (16 Steps)
Constant value	29.3 MWth
Core	Equilibrium core

4.1.2 Burnup Calculation Results in Constant Power Operation Condition

Figure 4-1 shows that the nuclear heating in the CNS increased by 6.54% while the flux conversion factor is consistent within the confidence interval (2σ) during one cycle operation of 28 days at equilibrium core. Table 4-2 and Table 4-3 show the detailed results. It is shown that the neutron flux and the gamma flux in the CNS increased when all types of nuclear heating increased.

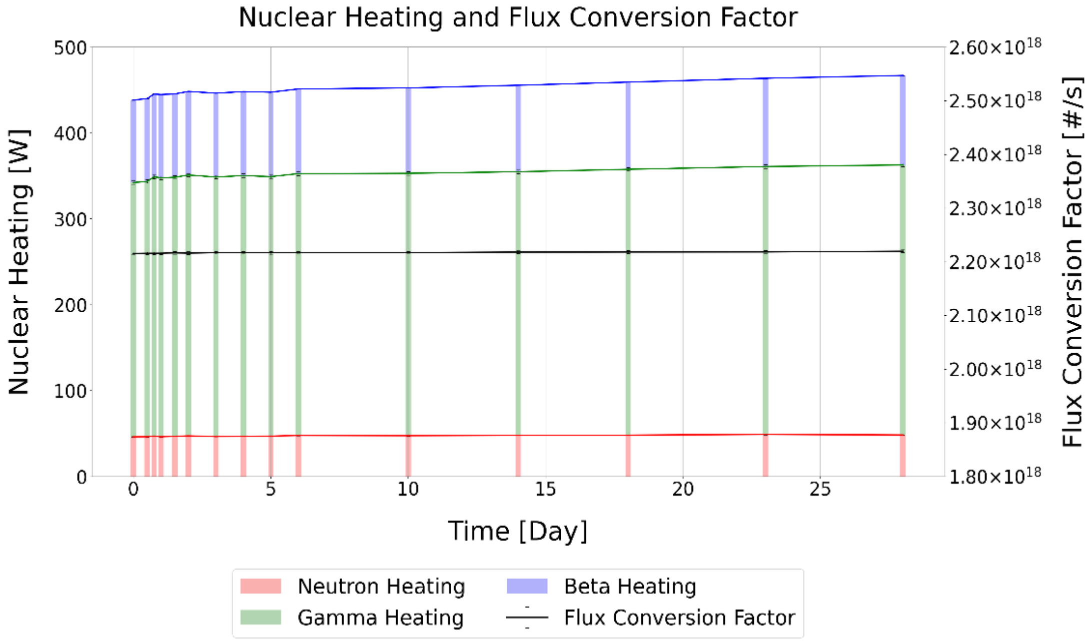

Fig. 4-1 Nuclear heating and flux conversion factor with constant power

Table 4-2 Nuclear heating and flux with constant power

Category	Nuclear heating [W]				Flux [$cm^{-2} \cdot s^{-1}$]	
	Neutron (SD)	Gamma (SD)	Beta (SD)	Total (SD)	Neutron (SD)	Gamma (SD)
BOC	46.2 (0.34)	296.1 (1.90)	96.0 (0.14)	438.3 (1.94)	0.167 (0.0002)	0.091 (0.0002)
EOC	48.4 (0.35)	314.4 (2.10)	104.2 (0.14)	467.0 (2.13)	0.178 (0.0002)	0.098 (0.0002)
Rel. Diff.	4.72% (1.06)	6.18% (0.96)	8.55% (0.21)	6.54% (0.66)	5.99% (0.16)	6.82% (0.24)

Table 4-3 Flux conversion factor with constant power

BOC (SD)	EOC (SD)	Relative Difference (SD)
2.216×10^{18} (2.46×10^{15})	2.220×10^{18} (2.46×10^{15})	0.18% (0.16)

4.2 Heating Analysis by Constant Flux Operation Condition

4.2.1 Burnup Calculation Option in Constant Flux Operation Condition

Table 4-4 shows that the burnup calculation is performed to maintain constant flux which is the way that the HANARO reactor is operated. Except for the constant value, the other options are the same as the previous calculation. The constant value is the constant average flux that is obtained from the BOC state of the previous calculation.

Table 4-4 Burnup calculation option with constant flux

Category	Burnup calculation
Option	Constant flux and criticality search
Calculation option	1,000,000 histories per cycle on 50 inactive and 100 active cycles
Cross section library	ENDF/B-VII.0
Cycle length (Burnup step)	28 days (16 Steps)
Constant value	$5.02\times10^{14}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$
Core	Equilibrium core

4.2.2 Burnup Calculation Results in Constant Flux Operation Condition

Figure 4-2 shows that the nuclear heating in the CNS increased by 5.35% while the flux conversion factor decreases by 2.69% during one cycle operation of 28 days at equilibrium core. Table 4-5 and Table 4-6 show the detailed results. It is shown that the neutron flux and the gamma flux in the CNS increased when all types of nuclear heating increased.

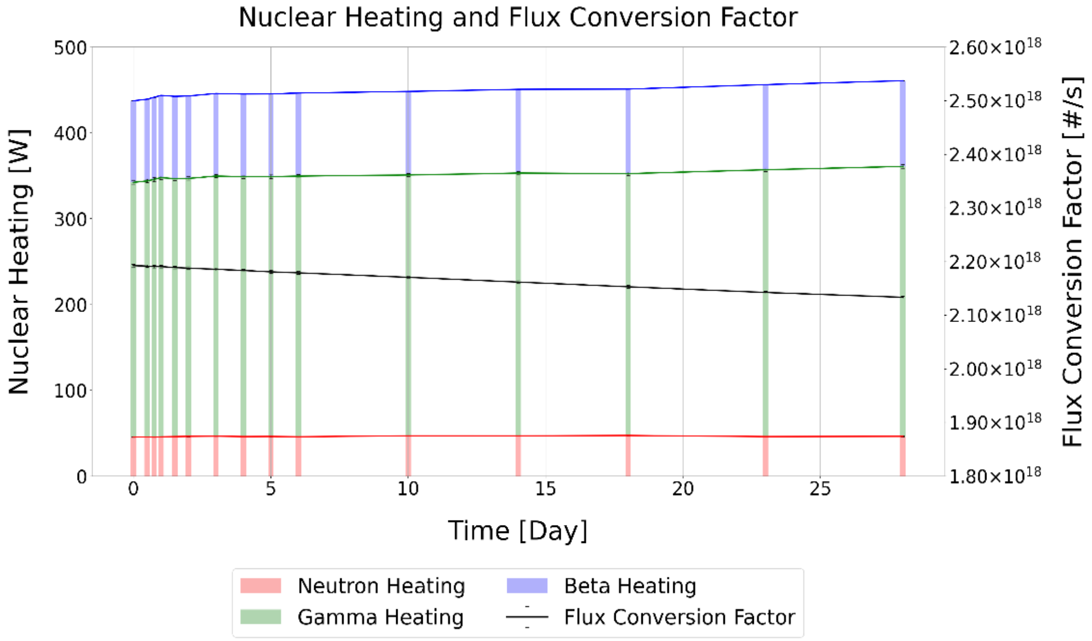

Fig. 4-2 Nuclear heating and flux conversion factor with constant flux

Table 4-5 Nuclear heating and flux with constant flux

Category	Nuclear heating [W]				Flux $[\mathrm{cm}^{-2}\cdot \mathrm{s}^{-1}]$	
	Neutron (SD)	Gamma (SD)	Beta (SD)	Total (SD)	Neutron (SD)	Gamma (SD)
BOC	45.6 (0.34)	296.8 (1.91)	95.0 (0.14)	437.4 (1.95)	0.167 (0.0002)	0.091 (0.0002)
EOC	46.4 (0.34)	314.6 (2.15)	99.9 (0.14)	460.8 (2.19)	0.178 (0.0002)	0.098 (0.0002)
Rel. Diff.	1.77% (1.05)	5.98% (0.97)	5.11% (0.21)	5.35% (0.67)	6.17% (0.16)	7.02% (0.24)

Table 4-6 Flux conversion factor with constant flux

BOC (SD)	EOC (SD)	Relative Difference (SD)
2.19×10^{18} (2.46×10^{15})	2.13×10^{18} (2.46×10^{15})	- 2.69% (0.16)

Chapter 5. Conclusion

In this research, the nuclear heating analysis methodology has been established by McCARD starting from identifying the nuclear heating sources as fission neutrons, prompt gamma rays from fission reactions, delayed gamma rays by fission product decays, and the betas produced by beta decays of Al-28 in the CNS tank.

The flux conversion factor is the key factor in this study to obtain the value of the nuclear heating in the CNS like as it was in the previous study. The physical meaning of the flux conversion factor in this study is the same as the previous study. However, the flux conversion factor in McCARD changes with burnup steps by considering region-wise tallied fission power while that in the previous study is a constant value. It is shown that the flux conversion factor in McCARD can exactly reflect its variations according to the fuel burnup.

The nuclear heating amounts in the CNS are evaluated by the established McCARD procedure with changing the burnup calculation options; the constant options of power and flux. The nuclear heating in the CNS increased by 6.54% from BOC to EOC in the constant power condition while that in the constant flux condition by 5.35%. The result of the constant flux condition is a more appropriate final result in this research because the HANARO is a research reactor to maintain the constant average flux. Therefore, it is observed that the nuclear heating in the CNS did not notably increase like the result of the previous study.

The flux conversion factor is consistent within the confidence interval (2σ) from BOC to EOC in the constant power condition while that in the constant flux condition decreases by 2.69%. From these results, it is demonstrated that the nuclear heating in the CNS did not increase due to the flux conversion factor which is the actual number of current-generation fission neutrons.

Instead, it is notable that the flux in the CNS increased in both the constant power and the constant flux condition. In order to maintain criticality, the control rod between the core and the CNS was withdrawn from BOC to EOC. From that effect, the neutron and the gamma flux in the CNS increased from BOC to EOC. Thus, it can be concluded that the nuclear heating in the CNS increased due to the increase of the neutron flux and the gamma flux from the core.

References

1. C. G. Seo, “Nuclear Heating Analysis for Operation of the HANARO CNS Facility,” KAERI Internal Memo, pp. 4 (2020).

2. G. Mckinney, “MCNP6 User’s Manual – Version 1.0,” LA-CP-13-00634, Los Alamos National Laboratory (2013).

3. R. J. J. Stamm’ler, “HELIOS Methods,” Studsvik Scanpower (2002).

4. C. G. Seo, “Nuclear Heating Analysis for Operation of the HANARO CNS Facility,” KAERI Internal Memo, pp. 5 (2020).

5. H. J. Shim, B. S. Han, J. S. Jung, H. J. Park, and C. H. Kim, “McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis,” *Nuclear Engineering and Technology*, 44(2), pp. 161-176 (2012).

6. S. J. Hwang, Y. I. Kim, H. J. Shim, and C. G. Seo, “Nuclear Heating Analysis for HANARO Cold Neutron Source by McCARD Burnup Calculations,” KNS, pp. 1-3 (2021).

7. C. G. Seo, Y. J. You, D. G. Hwang, and K. H. Lee, “Nuclear Heating Analysis for HANARO Cold Neuron Source,” KNS, pp. 1-2 (2005).

초 록

냉중성자는 세포 관측 등의 연구 목적으로 사용되고, 그리고 냉중성자 장치는 한국원자력연구원의 하나로 원자로에서 2010년부터 운영하고 있다. 냉중성자 장치는 저온상태에서 운영해야 한다. 그러나, 노심에서 발생하는 핵분열 중성자와 감마선에 의해 냉중성자 장치의 발열량이 증가하게 된다. 따라서, 냉중성자 장치의 발열량을 정확하게 분석하는 것이 중요하다.

본 연구의 목표는 McCARD를 이용하여 발열량 분석 방법론을 구축하고, 그리고 이를 통하여 McCARD를 이용하여 원자로 한 주기 28일 동안 냉중성자 장치의 발열량을 정확하게 분석하는 것이다.

냉중성자 장치의 발열량은 네 가지로 분류하여 분석하였다. 핵분열 중성자에 의한 Neutron Heating, 핵분열 반응의 즉발 감마선에 의한 Gamma Heating, 핵분열 생성물 붕괴의 지발 감마선에 의한 Gamma Heating, 그리고 CNS Tank에서 Al-28의 베타 붕괴에 의한 Beta Heating으로 분류하였다.

Flux Conversion Factor는 몬테칼로 코드의 아웃풋을 실제 스케일로 바꿔주기 위해 사용된다. McCARD의 Flux Conversion Factor는 연소단계에 따라 달라지고, 냉중성자 장치의 발열량을 계산하는 핵심 요소이다. McCARD 연소계산은 임계를 유지하는 상태에서 Power 일정 계산과 Flux 일정 계산으로 수행하였다.

McCARD 연소계산 결과 냉중성자 장치의 발열량은 BOC 대비 EOC에서 Power 일정일 경우 6.54% 증가하였고 Flux 일정일 경우 5.35% 증가하였다. Flux 일정 결과가 최종결과에 더 적합한 결과인데 왜냐하면 하나로 원자로는 연구용 원자로이기 때문에 실제로 Flux 일정 방식으로 운전하기 때문이다.

Fux Conversion Factor는 BOC 대비 EOC에서 Power 일정일 경우 신뢰구간 (2σ) 내에서 일정하고 Flux 일정일 경우 2.69% 감소한다. 이러한 결과로부터, 냉중성자 장치의 발열량은 Flux Conversion Factor 때문에 증가하지 않았다는 것을 알 수 있다.

그러나, 냉중성자 장치의 Flux는 BOC 대비 EOC에서 Power 일정 및 Flux 일정일 경우 모두 증가하였다. 임계를 유지하기 위해, 노심과 냉중성자 장치 사이의 제어봉이 BOC 대비 EOC에서 인출되었다. 따라서, 냉중성자 장치의 발열량은 노심에서 오는 Neutron Flux와 Gamma Flux의 증가 때문에 증가했다는 것을 알 수 있다.

주요어: 하나로 원자로, 냉중성자 장치, 발열량, McCARD, Flux Conversion Factor, 연소계산, Neutron Flux, Gamma Flux

학번: 2019-22929