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Analysis of Tritium-Production Core Model for the 5 MWe Yongbyon Reactor Using McCARD Burnup Calculation

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1. Introduction

The International Atomic Energy Agency (IAEA) published a report on North Korea's 5 MWe reactor at Yongbyon, announcing that the reactor showed signs of a restart that was detected in early July 2021 [1]. There are concerns among experts that the reactor restart could be linked to the production of tritium, a crucial element for lightweight nuclear weapons [2]. The 5 MWe reactor is a graphite-moderated gas-cooled reactor using Magnox fuel, which is known to be capable of producing nuclear materials in North Korea [3]. The reactor is evaluated to have the capability to produce about 6 kg of plutonium per year [3,4], and some experts estimate that it can also produce tritium using a lithium target [5,6].

The aim of this study is to design a tritium-production core model for the 5 MWe reactor and perform a burnup analysis using McCARD (Monte Carlo Code for Advanced Reactor Design), a neutron transport analysis code developed by Seoul National University [7]. The tritium-production core model is designed using Tritium-Producing Burnable Absorber Rod (TPBAR), a lithium target developed by the U.S. government program [8]. As a result of burnup calculation for the tritium-production core model, tritium production, tritium production rate, operating days, TPBAR worth, and radial power distribution are analyzed.

2. Core Modeling by McCARD

2.1 Core characteristics of 5 MWe reactor

Table I shows the core characteristics of the 5 MWe reactor [3,4]. The reactor core is composed of 811 fuel channels and 76 control channels illustrated in Figure 1.

Table I: Core characteristics of 5 MWe reactor

Parameters	Value
Electric power	5 MWe
Thermal power	25 MWt
Number of channels	877
Number of fuel channels	801
Number of control channels	76
Distance between channels	200 mm
Radius of fuel channel	32.5 mm
Radius of control channel	65.0 mm
Core height	6 m
Fuel	Nat U
Clad	Mg
Coolant	CO_2 gas
Moderator and reflector	Graphite

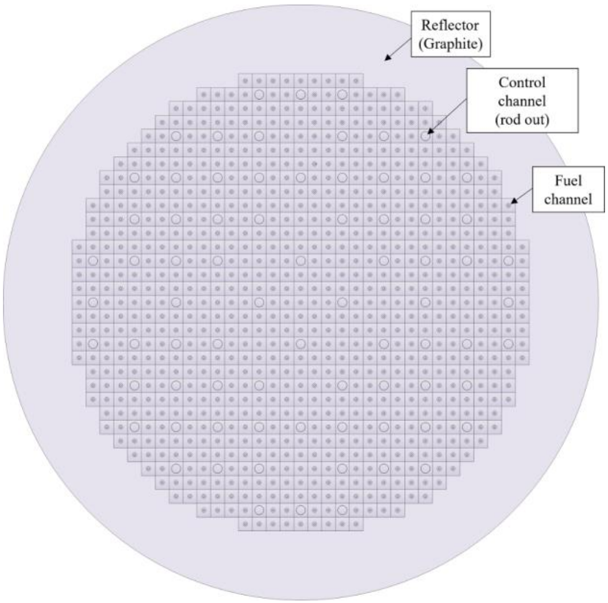

Fig. 1. Radial configuration of 5 MWe reactor core

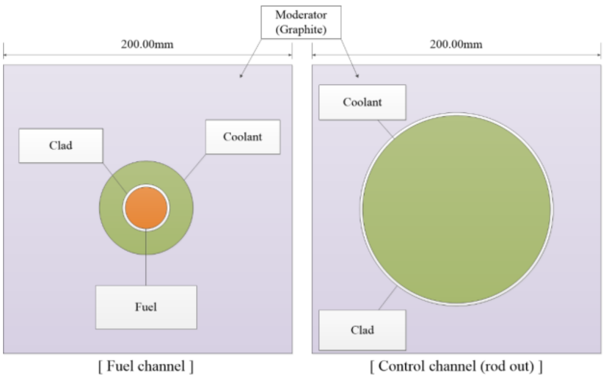

Fig. 2. Radial configuration of fuel and control channels

2.2 Features of TPBAR

Lithium is the main nuclide used as a tritium production material in a nuclear reactor core [5,6]. In this study, a lithium target is utilized as TPBAR, which is used by the U.S. government's Tritium Readiness Program developed to produce tritium in nuclear reactor systems [8]. As shown in Figure 3, the composition of TPBAR is presented in three parts: Zircaloy-4 linear, burnable absorber pellet, and homogenized cladding. Table 2 summarizes the material information for TPBAR [8].

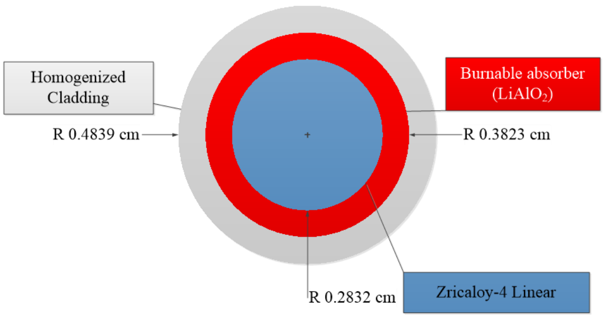

Fig. 3. Radial configuration of TPBAR

Table 2: Material information for TPBAR

Parameters	Nuclide	Value (atoms/barn/cm)
$LiAlO_2$ pellet	Li	2.39254E-02
	Al	2.38892E-02
	O	4.77789E-02
Homogenized cladding	Cr	8.13377E-03
	Fe	2.80987E-02
	Ni	2.68800E-02
	Mo	6.30038E-04
	Mn	6.59759E-04
	Zr	9.66593E-03

2.3 Tritium-production core models using TPBARs

To model the tritium-production core, a TPBAR channel was designed by loading seven TPBARs into the control channel. Figure 4 shows the radial configuration of the TPBAR channel drawn using the McCARD input visualization tool, by McView [9].

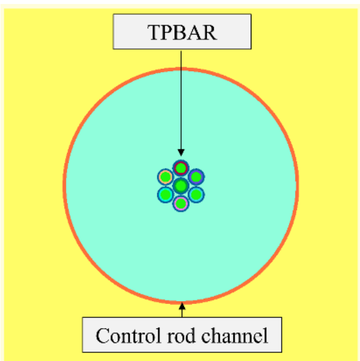

Fig. 4. Radial configuration of TPBAR channel

The tritium-production core consists of 801 fuel channels, 44 control channels, and 32 TPBAR channels. The core modeling in this study was designed with 1/4 core symmetry and reflection boundary conditions, and the upper, lower, and outer radial regions of the core were surrounded by reflectors. Figure 5 shows the radial configuration of the core drawn by McView.

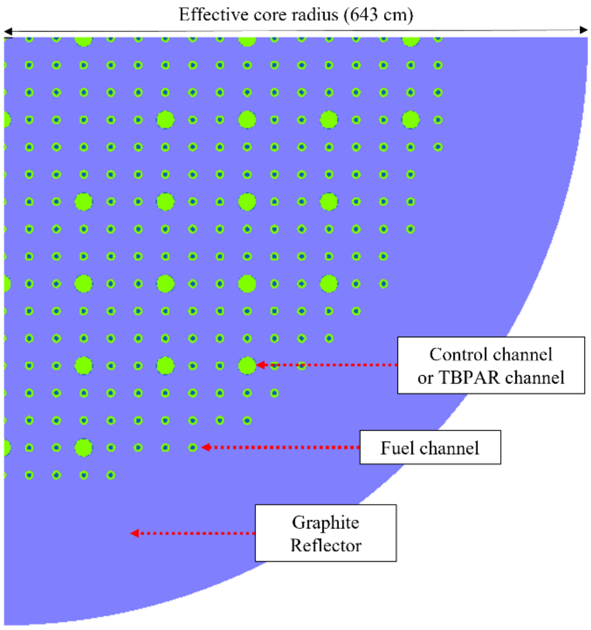

Fig. 5. Radial configuration of core drawn by McView

3. Results of burnup analysis

The McCARD burnup calculations were conducted with 50,000 histories per cycle on 350 active and 150 inactive cycles using the continuous energy cross section libraries produced from ENDF/B-VII.1 [10]. The fuel and cladding temperatures were set to 600 K, and TPBAR and the other material temperatures were set to 293.6 K.

Figure 6 shows the effective multiplication factor ($k_{eff.}$) against the effective full power day (EFPD) of the original and tritium-production cores, and the standard deviation (SD) of $k_{eff.}$ was less than 0.00012. As TPBARs act as burnable absorbers in the core, the initial reactivity and cycle length of the tritium-production core were calculated to be smaller than that of the original core. Table 3 summarizes the calculated burnup results of both cores.

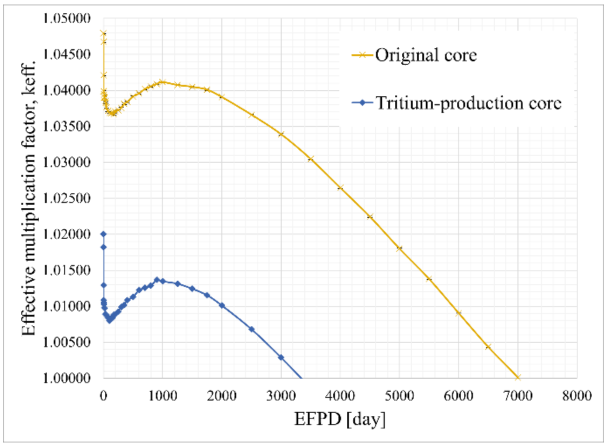

Fig. 6. $k_{eff.}$ vs. EFPD of original and tritium-production cores

Table 3: Calculated burnup results of both cores

Parameters	Original core	TPBAR core
Initial excess reactivity [pcm]	4,576 ± 11	1,963 ± 11
Total TPBARs rod worth [pcm]	-	2,613 ± 15
Single TPBAR rod worth [pcm]	-	11.66 ± 1.00
Max. discharged burnup [MWd/tU]	3,507 ± 0.0031	1,670 ± 0.0001
Max. cycle length [EFPD]	7,008 ± 0.0061	3,337 ± 0.0002

Figure 7 shows tritium production mass against EFPD for the tritium-production core. It was estimated that the tritium-production core could produce 49.26 ± 0.11 g of tritium by operating the core up to 3,337 EFPD.

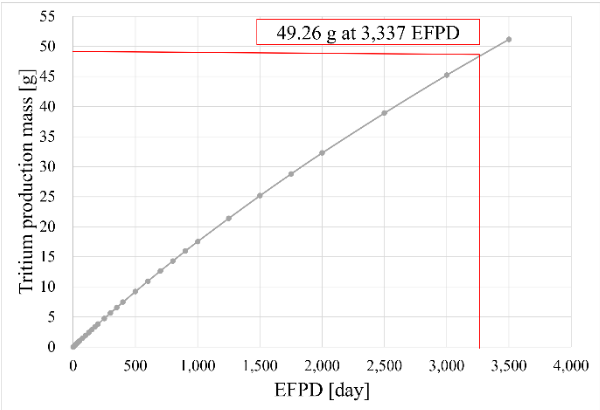

Fig. 7. Tritium production mass vs. EFPD

In order to evaluate the tritium production rate, the tritium production mass per day (g/day) was calculated up to 100 EFPD. As shown in Figure 8, the peak value of the tritium production rate is observed between 10 and 20 EFPD, and the maximum tritium production per rate (g/day) was calculated to be 0.0194 ± 0.0002. Based on the maximum tritium production rate, the tritium-production core was estimated to generate 7.0759 ± 0.0156 g of tritium per year.

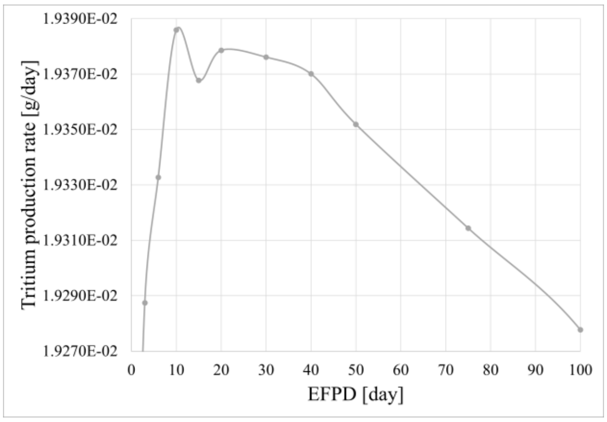

Fig. 8. Tritium production rate (g/day) vs. EFPD

4. Conclusions

This paper presented the tritium-production core model for the 5 MWe reactor using TPBAR as the lithium target and the evaluation of the core's tritium-production capability. The tritium production mass was estimated to be about 49.26 g by operating the core to its maximum cycle length. Calculating the annual tritium production based on the maximum tritium production (g/day), it was estimated that the core could produce about 7.0759 g of tritium per year.

In this work, the number and location of TPBARs are not optimized. Therefore, by locating the TPBAR channel inside the core to take advantage of the high neutron flux and optimizing the number of TPBARs in the core, it is suggested that tritium production might increase.

REFERENCES

[1] IAEA, Application of Safeguards in the Democratic People's Republic of Korea, GOV/2021/40-GC (65)/22, 2021.

[2] Masterson, J. DPRK Strategic Capabilities and Security on the Korean Peninsula: Looking Ahead, Arms Control Today, 52(2), 36-36. 2022.

[3] Braun, C., Hecker, S., Lawrence, C., Papadiamantis, P., North Korean Nuclear Facilities After the Agreed Framework, Center for International Security and Cooperation, Stanford University, 2016.

[4] Park, G. H., & Hong, S. G., An estimation of weapon-grade plutonium production from 5 MWe YongByon reactor through MCNP6 core depletion analysis, Progress in Nuclear Energy, 130, 103533, 2020.

[5] Verification Research, Training and Information Centre (VERTIC), Producing Tritium in North Korea, Issue no. 152, 2016

[6] KIM, M., Lee, S., & Chang, S., DPRK's 4th Nuclear Test and its Tritium Production, Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, 2016

[7] 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, Nucl. Eng. Technol., Vol. 44, No. 2, p. 161, 2012.
[8] Burns, K. A., Love, E. F., Thornhill, C. K., Description of the tritium-producing burnable absorber rod for the commercial light water reactor, TTQP-1-015 Rev 19. Pacific Northwest National Lab. (PNNL), Richland, WA (United States), 2012.
[9] Jeang, S., Shim, H.J., McView: McCARD Input Visualization Tool, Transactions of the Korean Nuclear Society Autumn Meeting Changwon, Korea, 2022
[10] CHADWICK, Mark B., et al. ENDF/B-VII. 1 nuclear data for science and technology: cross sections, covariances, fission product yields and decay data. Nuclear data sheets, 2011, 112.12: 2887-2996.