Comparison of Core Design Parameters for BANDI-60 Using UO_2 and U-Mo Fuels

Dokyun Kim [a], Hyung Jin Shim [a*], Jong Tae Seo [b]
[a] *Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Korea*
[b] *New Technology Business Group, KEPCO E&C 111, 989 Beon-gil, Daeduck-daero, Daejeon 34057*
[*] *Corresponding author: shimhj@snu.ac.kr*

1. Introduction

The small modular reactor (SMR) has several advantages such as power supply to remote locations, seawater desalination, and marine propulsion [1]. Recently, the BANDI-60 [2] SMR of 200 MWth developed by KEPCO E&C is designed as a core with 52 fuel assemblies (FAs) using UO_2 fuel enriched to 4.95% and the Pyrex burnable absorber (BA) for excess reactivity control [3]. In the core, five types of FAs in the same number of BA rods of 24 with different concentrations of Pyrex are loaded to have core characteristics of its cycle length of about 4.9 years and the maximum excess reactivity of around 3800 pcm [4].

In this paper, the core design parameters of Bandi-60 with changing the UO_2 fuels into U-Mo are compared with the existing ones. The main core design target is to extend the cycle length by using the U-Mo fuel. Since the U-Mo fuel has a higher uranium density than UO_2 fuel, U-Mo fuel can make the cycle length longer with the same amount of uranium enrichment [5, 6]. For the comparison of core design parameters, the core burnup calculation is performed by the Monte Carlo particle transport analysis code, McCARD [7]. For the two cores, their neutronics parameters such as the effective multiplication factor ($k_{eff.}$), the power peak factor, and the temperature coefficient are compared.

2. Core Design of SMR

2.1 Fuel materials

Table I shows a comparison of information of UO_2 and U-Mo fuels. U-Mo fuel has a higher thermal conductivity than UO_2 fuel, which leads to a lower maximum fuel temperature, while the melting temperature of U-Mo is lower than UO_2 [5, 6]. Because U-Mo fuel has a high density, using it enables to load more uranium into the core.

Table I: Information for UO_2 and U-Mo fuels

Division		UO_2 fuel	U-Mo fuel
Thermal Conductivity [W/m/K] (@ 377 ℃)		4.78	25.6
Melting Temperature [℃]		2,865	1134
Density [g/cm^3]	Uranium	9.04	17.10
	The others	1.22	0.90
	Total	10.26	18.00
Initial uranium loading in BANDI-60 [kg]		11,894	22,497
Uranium enrichment		4.95 wt%	

2.2 Core design parameters

Table II shows the design parameters of SMR [3, 4]. The thermal power of the core is 200 MW. FA is based on the Westinghouse 17×17 FA. 52 FAs are loaded in the core. The average linear power density is 7.28 kW/m, which is lower than that of commercial PWR and there is no soluble boron in the coolant.

Table II: The design parameters of SMR

Parameters	Value
Reactor type	PWR
Thermal power	200 MW
Average Linear power density	7.28 kW/m
Coolant & Moderator	Light water
Coolant Average Temp.	580.65 K
Number of FAs	52
Active core height	200 cm
FA pitch / Pin pitch	21.50 cm / 1.26 cm
FA type	Westinghouse 17×17
Uranium enrichment	4.95 wt%
Fuel Material	UO_2 or U-Mo
BA material	Pyrex

The core is designed using FA loaded with Pyrex. As shown in Figure 1, BA rods of 24 are loaded instead of fuel pins. The neutron absorption capacity of BA is proportional to the weight percent (w/o) of B_2O_3 contained in Pyrex [3]. Figure 2 shows the cross-sectional view of the fuel pellet and BA.

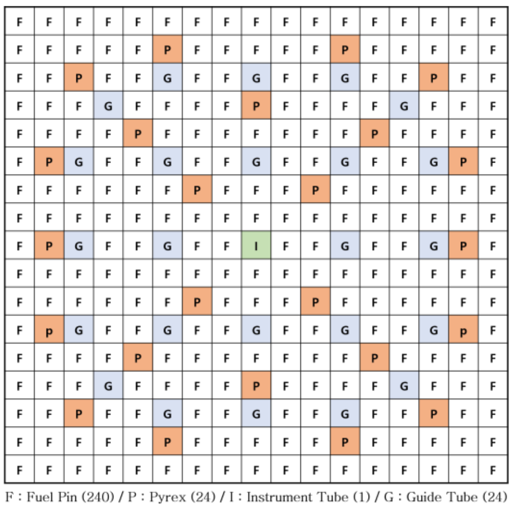
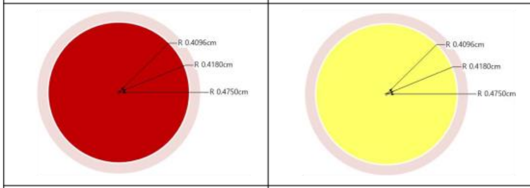


Fig. 1. Fuel assembly configuration

Fuel	BA



Material	Radius [cm]
: UO2 or U-Mo (Fuel)	0.4096
: Pyrex (BA)	0.4096
: He (Gap)	0.4180
: Zircaloy (Cladding)	0.4750

Fig. 2. The cross-sectional view of the fuel and BA.

2.3 Loading Pattern of the Core

Table III shows the information of FA types by the concentration of BA. FAs using a high concentration of B_2O_3 are placed in the center of the core and FAs using a low concentration of B_2O_3 are placed in the periphery to make power distribution smooth in the radial direction [3, 4]. Figure 3 presents the loading pattern of SMR. In the soluble boron-free SMR, the core needs a large amount of the reactivity control mechanism instead of soluble boron, and the reactivity change should be controlled by using the control rods. As shown in Figure 4, there are forty (40) Control Element Assemblies (CEAs) in the core for the reactivity control [2]. The location of CEAs is determined to control for normal operation and provide sufficient control rod worth to overcome the reactivity feedback caused by the core state change [3, 4].

Table III: FA types by the concentration of BA

B_2O_3 w/o in Pyrex	Number of fuel pins	Number of BA pins	Number of FA
5	240	24	8
10	240	24	12
25	240	24	16
35	240	24	12
40	240	24	4
Total	12,480	1,248	52

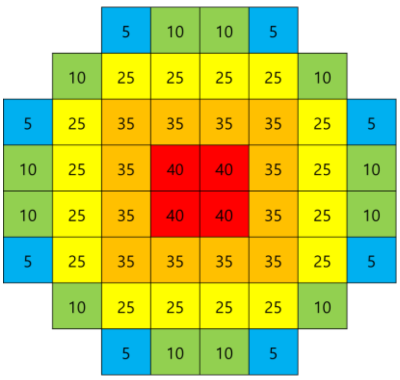
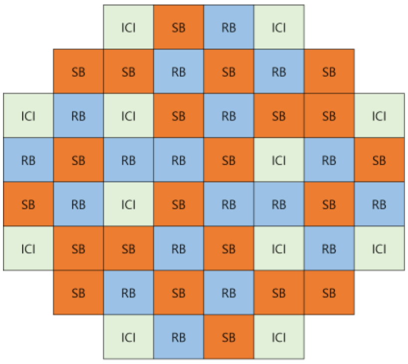


Fig. 3. The loading pattern of SMR



* RB: Regulating Bank (18), SB: Shutdown Bank (22),
ICI : In-Core Instrumentation (12)

Fig. 4. The location of the CEAs

3. Numerical Results

The McCARD burnup calculation is conducted with 50,000 or 100,000 histories per cycle on 150 inactive and 300 active cycles using the continuous-energy cross section libraries produced from ENDF/B-VII.1. Table IV shows the McCARD burnup calculation options.

Table IV: The McCARD burnup calculation options

Division	UO_2 core	U-Mo core
Neutron histories	100,000	50,000
Active/inactive cycle	300 / 150	300 / 150
Fuel Avg. Temp.	700 K	700 K
Moderator Avg. Temp.	580.65 K	580.65 K
Moderator density	0.7105 g/cm^3	0.7105 g/cm^3

3.1 The effective multiplication factor ($k_{eff.}$)

Figure 5 shows $k_{eff.}$ vs. the effective full power day (EFPD) behavior of UO_2 and U-Mo cores. The calculated maximum cycle lengths for UO_2 and U-Mo cores are 1,784 ± 6 and 2,905 ± 10 days, respectively. The excess reactivity for the U-Mo core is calculated as 7,080 ± 15 pcm, which is 3,291 ± 15 pcm more than the UO_2 core. Table V shows the difference in results about EFPD, burnup, and the excess reactivity.

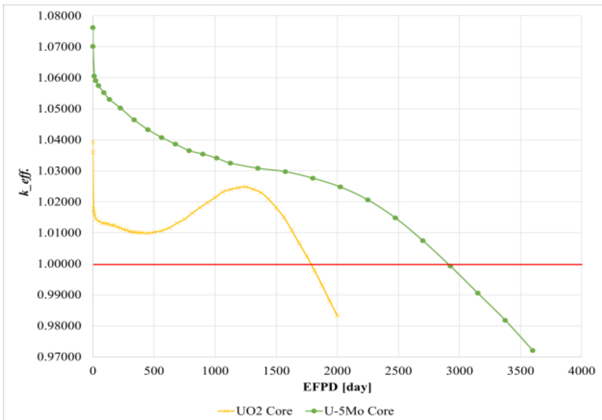


Fig. 5. $k_{eff.}$ vs. EFPD behavior of UO_2 and U-Mo cores

Table IV: The calculation results of UO_2 and U-Mo cores

Division	UO_2 Core	U-Mo Core
Max. EFPD [day]	1,784 ± 6	2,905 ± 10
Max. burnup [MWD/kgU]	29.99 ± 0.09	25.82 ± 0.09
Excess reactivity [pcm]	3,790 ± 10	7,080 ± 18
BOC $k_{eff.}$	1.03939 ± 0.00012	1.07620 ± 0.00017

3.2 The power peaking factor

The assembly power peaking factor (Fr) for both cores are compared in Figure 6. Both graphs decrease from BOC to the middle of the cycle (MOC) and reach their highest value at the end of the cycle (EOC). The maximum Fr values for UO_2 and U-Mo cores are 1.355 ± 0.002 and 1.328 ± 0.003, respectively.

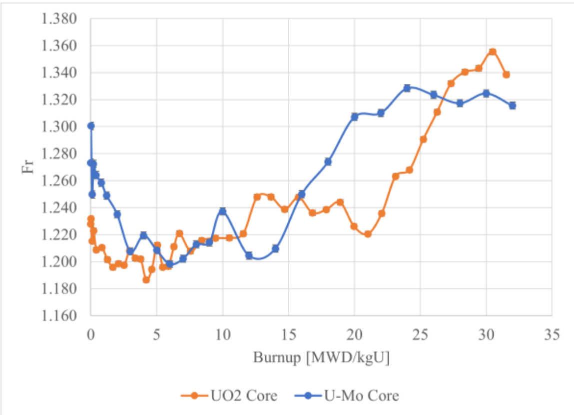


Fig. 6. Fr vs. burnup behavior of UO_2 and U-Mo cores

Figure 7 shows the pin power peaking factor (Fq) vs. burnup of UO_2 and U-Mo cores. Both cores show similar Fq behavior over the cycle, with the U-Mo core maximum peaking factors being slightly higher within the error bars indicating 1σ statistical uncertainty in calculated results. The maximum Fq values for UO_2 and U-Mo cores are 2.33 ± 0.10 and 2.57 ± 0.17, respectively.

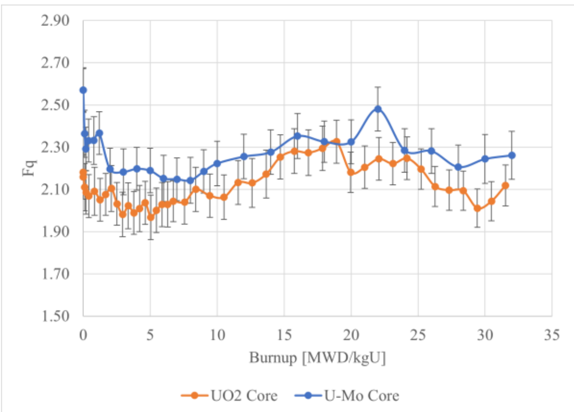


Fig. 7. Fq vs. burnup behavior of UO_2 and U-Mo cores

3.3 The temperature coefficient

Table IV shows the McCARD burnup calculation options for the temperature coefficients of both cores. The fuel temperature coefficients (FTCs) for UO_2 and U-Mo cores are compared in Figure 8. The U-Mo core FTCs are more negative than the UO_2 core FTCs over the cycle.

Table V: The calculation options for FTC & MTC

Division	UO_2 Fuel		U-5Mo Fuel	
	FTC	MTC	FTC	MTC
Delta fuel temp. [K]	200	0	50	0
Delta moderator temp. [K]	0	7.5	0	7.5
Fuel avg. temp. [K]	900	700	650	700
Moderator avg. temp. [K]	580.65	573.15	580.65	573.15
Moderator density [g/cm^3]	0.7105	0.7270	0.7105	0.7270
Neutron histories	100K	50K	50K	25K
Active cycle	300	300	300	300
Inactive cycle	150	150	150	150

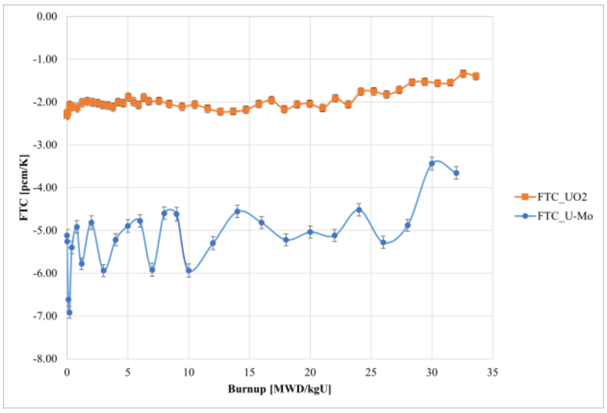


Fig. 8. FTC vs. burnup of UO_2 and U-Mo cores

Figure 9 shows a comparison of the moderator temperature coefficient (MTC) for both cores. In BOC, the UO_2 core MTC is more negative than the U-Mo core FTC, and vice versa in EOC.

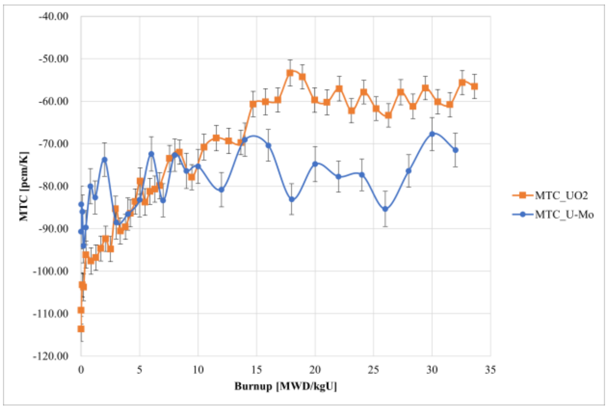


Fig. 9 MTC vs. burnup of UO_2 and U-Mo cores

4. Conclusions

In this paper, the core design parameters of the Bandi-60 SMR using UO_2 and U-Mo fuels enriched to 4.95% are compared. The main design target is to extend the cycle length of the core by using U-Mo fuel. This study presents that the cycle length of the U-Mo core is 2,905 ± 10 days, which is about 1.63 times that of the UO_2 core. Because the U-Mo fuel is a higher density than the UO_2 fuel, the core contains a large amount of uranium, which can extend the cycle length. The maximum excess reactivity for the U-Mo core is 7,080 ± 15 pcm, which is about 3,290 pcm higher than that of the UO_2 core. The maximum Fq values for the UO_2 and U-Mo cores are 2.33 ± 0.10 and 2.57 ± 0.17, respectively. The U-Mo core has more negative FTC than the UO_2 core.

As for future work, the core design adopts a newly proposed BA concept for Gd_2O_3 (gadolinia), the cylindrically inserted and mechanically separated burnable absorber (CIMBA) [8].

REFERENCES

[1] Deployment Indicators for Small Modular Reactors Methodology, Analysis of Key Factors and Case Studies, International Atomic Energy Agency, September 2018. IAEA-TECDOC-1854.

[2] Il Hwan Kim et al., Development of BANDI-60S for a Floating Nuclear Power Plant, Transactions of the Korean Nuclear Society Autumn Meeting, Goyang, Korea, October 24-25, 2019.

[3] Dokyun Kim, et al., Boron-Free Small Modular Reactor Design by McCARD Burnup Calculation with T/H Feedback., Transactions of the Korean Nuclear Society Autumn Meeting, December 17, 2020.

[4] Dokyun Kim, Advanced Core Design of Soluble Boron Free Small Modular Reactor for Marine Applications, Master thesis, Seoul National University, 2021.

[5] REST, Jeffrey, et al. U-Mo fuels handbook. Version 1.0. Argonne National Lab.(ANL), Argonne, IL (United States), 2006.

[6] Kim Seongbae, Nuclear core design of soluble boron free water-cooled reactor for submarines using low enriched uranium alloy fuel, Master thesis, Seoul National University, 2020.

[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] YuGwon Jo, Ho Cheol Shin, Design optimization of cylindrical burnable absorber inserted into annular fuel pellets for soluble-boron-free SMR, Nuclear Engineering and Technology, 2021.