Nuclear Design Characteristics of Thorium-Plutonium Fueled Soluble Boron-Free Small Modular Reactor

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1. Introduction

Small modular reactor (SMR) is a reactor developed in South Korea and aimed at achieving several goals: relatively long cycle length of more than 3 years, soluble boron-free nuclear design with keeping safety-related nuclear characteristics within design limits. Main SMR requirements are stated in [1]. Excess reactivity control in SMR is intended to be performed by using a combination of initially loaded burnable absorbers (BA) and control rods. Therefore, it is desired to reach relatively flat reactivity distribution that could be fully suppressed by control rods. However, there are also designs with adding small amounts of soluble boron [2]. The main advantage of this nuclear design is longer achieved cycle length compared to soluble boron-free design. However, using soluble boron for excess reactivity control of SMR contradicts to the original idea of this reactor.

On the moment of writing this article, in all reviewed publications on SMR nuclear design, only enriched UO_2 fuel is used. Due to small size of SMR, fuel is supposed to be enriched up to 4.95 wt% of ^{235}U, as shown in [1] and [2]. This limitation can be avoided by using thorium-plutonium (Th-Pu) fuel as it is discussed in [3]. However, main challenges in case of using Th-Pu fuel are reaching required design criteria such as cycle length, maximum excess reactivity and maximum pin peaking power, as well as having acceptable safety-related nuclear design characteristics such as values of moderator temperature coefficient (MTC), fuel temperature coefficient (FTC), control rod worth (CRW) and shutdown margin (SDM). Therefore, the main goal of this research is to find a loading pattern (LP) for SMR with Th-Pu fuel, which would satisfy all given criteria.

2. Nuclear design of thorium-plutonium loading pattern for SMR

Pu-based fuel has several main disadvantages that make design of new LP problematic. Firstly, as it is stated in [3], Pu-based fuel loaded into standard Westinghouse PWR introduces epithermal neutron spectrum due to neutron resonance absorption in ^{240}Pu and ^{242}Pu. As a result, more fissile material is required to reach desired cycle length compared to UO_2 fuel.

Secondly, epithermal neutron spectrum reduces both efficiency of BAs and CRW in Pu-based cores. As it is shown in [3], use of conventional BAs such as Gadolinia (Gd) could introduce positive MTC due to its' decreased absorption ability in epithermal spectrum. At the same time, efficiency of Gd as well as other types of BA is lower in Th-Pu fuel due to competing neutron absorption in Th and Pu, which is higher compared to components of UO_2 fuel. However, concerns regarding BA influence on MTC raised in [3] could be reactor type-dependent (large Westinghouse type PWR that is using soluble boron for excess reactivity control was studied in that article).

Thirdly, high load of fissile Pu into the core required for achieving long cycle length together with hardened neutron spectrum could affect reaching acceptable value of maximum pin peaking power due to thermal neutron migration between fuel assemblies (FA) loaded into the core.

To overcome given problems, an advanced design of a FA was used. Figure 1 shows a quarter of 17*17 Westinghouse type FA where all fuel rods (FR) are coated with Integral Fuel Burnable Absorber (IFBA).

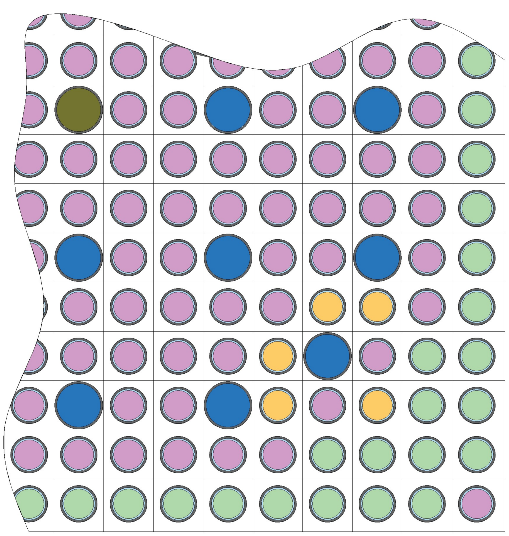
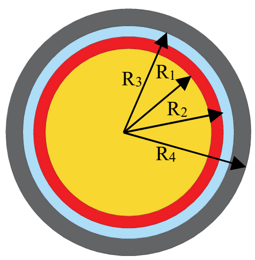


Fig. 1. FA design for Th-Pu SMR.

The idea of using IFBA coating for all FRs in Th-Pu fuel was discussed in [3]. However, several important improvements were introduced in given design. Firstly, BA zoning was used. In particular, yellow colored FRs shown on Figure 1 have highest load of boron, while pink and green colored FRs have medium and low load of boron, correspondingly. Secondly, the thickness of used coating was increased from 0.004 cm given in [3] up to 0.009 cm with slight reduction of fuel pellet radius and keeping a standard air gap thickness in all FRs. Thirdly, due to increase of IFBA thickness and lower load of fissile material, the required concentration of boron in IFBA was reduced compared to the design presented in [3].

As shown on Figure 1, corners of FA are loaded with higher amount of BA. This design mitigates possible negative impact of thermal neutrons migrating from neighboring FAs. As it was stated earlier, these neutrons could cause an increase of maximum pin peaking power in FRs close to corners or borders of FA. In more details, the structure of used IFBA coated FR is shown on Figure 2, while the main parameters of used FAs are listed in Table 1.



Radius	Value, cm
R_1	0.40058
R_2	0.40958
R_3	0.41783
R_4	0.47498

Fig. 2. Design of IFBA-coated FR.

Table 1: Types of FAs used in design

FA type	IFBA type	Boron wt% in IFBA
T1	High (Yellow)	2.4
	Medium (Pink)	1.85
	Low (Green)	0.4
T2	High (Yellow)	1.9
	Medium (Pink)	1.4
	Low (Green)	0.2

Pu vector used in the study was taken from [4] and could be found in Table 2.

Table 2: Pu vector extracted from PWR spent fuel

Burnup, GWD/MTU	Pu-238	Pu-239	Pu-240
43.0	2%	52.5%	24.1%
	Pu-241	Pu-242	Am-241
	14.7%	6.2%	0.5%

Given Pu composition was mixed with Th-232 and then used for fuel fabrication. Fissile part of Pu in all FAs is 8.498 wt%.

Based on given FA design and fuel composition, the LP shown on Figure 3 was developed.

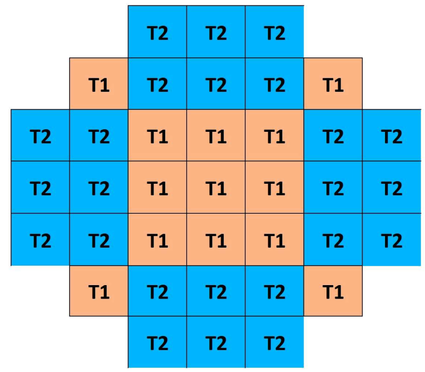


Fig. 3. Th-Pu LP for SMR.

For generating cross-sections and preparing FA level design, Studsvik CASMO-4 code was used. Determination of LP and full-core calculations of nuclear characteristics were performed using SIMULATE 3 code [5].

As it is shown on Figure 3, only two types of FA are needed to make a LP for SMR using Th-Pu fuel. Pu contents and FR design in all FAs is uniform for all loaded fuel. Relatively high fissile content required for making this LP compared to conventional UO_2 fuel could be explained by neutron spectrum hardening effect of ^{240}Pu and ^{242}Pu isotopes in given 17*17 Westinghouse type FA geometry. In more details, necessity of relatively high amount of loaded Pu is discussed in [3]. In general, SMR requires relatively high amount of loaded fissile material due to its' small size.

Finally, for improving neutron behavior in the peripheral FAs, a graphite-steel based reflector mentioned in [2] was introduced in this work. It showed improved neutron economy if compared to conventional steel-based reflectors. However, comparison of different types of reflectors was not in the scope of this study and therefore was not performed.

3. Core performance and nuclear characteristics of thorium-plutonium loading pattern for SMR

As it was stated in previous sections, the main goal of this study is to produce a design of a SMR LP using Th-Pu fuel. Moreover, this LP should satisfy all initially set design requirements. The following criteria were set as the goal:

- Cycle length of more than 4 years.
- Maximum pin peaking power not exceeding 1.6.
- Negative values of MTC and FTC over the entire cycle length.
- Sufficient control rod worth for granting subcritical reactor state during Hot Full Power (HFP) to Hot Zero Power (HZP) transient.
- Excess reactivity should be fully suppressed by control rods with achieving sufficient value of SDM [1].

Through calculations, the following results were obtained. Change of core reactivity over the cycle is shown on Figure 4.

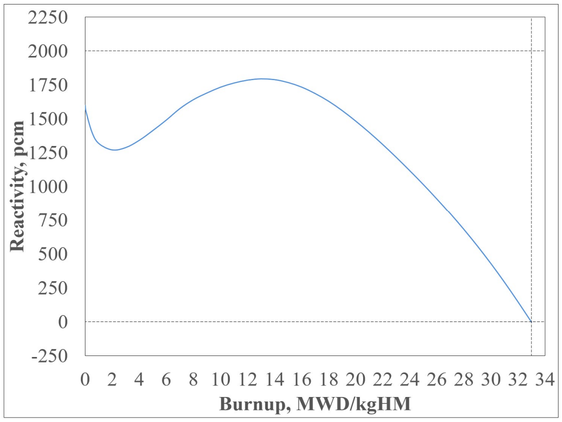


Fig. 4. Reactivity change over cycle.

As shown on the graph, reactivity is securely suppressed under the 1900 pcm value, having 1599 pcm in the beginning of cycle (BOC) and reaching cycle maximum of 1794 pcm at 13 MWD/kgHM burnup point. Reactivity in the middle of cycle (MOC, 16 MWD/kgHM) was found as 1733 pcm. As for reaching desired cycle length, performed calculations showed value of more than 32 MWD/kgHM, which corresponds to more than 4.45 years cycle. There is potential for further increase of cycle length by loading higher amount of Pu with corresponding increase of boron concentration in IFBA coating as it was done in [3]. This could allow to reach any reasonably desired cycle length without exceeding the limitation of maximum uranium enrichment used in [1] and [2].

As expected, due to use of IFBA-coated fuel pellets together with BA zoning that was introduced earlier, maximum value of pin peaking power was found as 1.52 in the BOC, decreasing during the cycle. This value is within given design criteria.

Both MTC and FTC were found negative over the entire cycle length. In more details, they are shown on Figures 5 and 6, correspondingly.

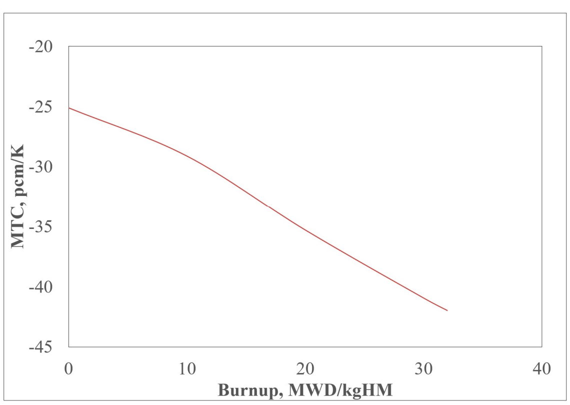


Fig.5. Change of MTC over cycle length

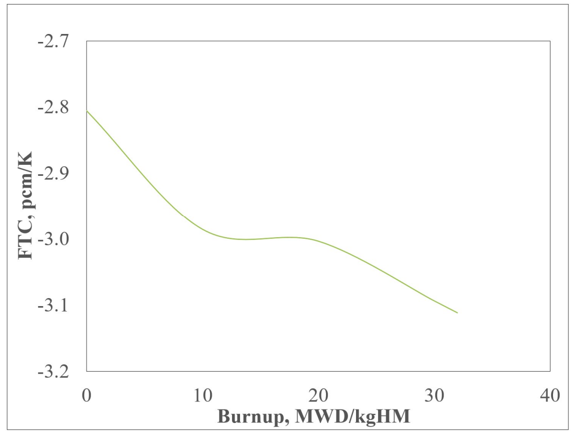


Fig. 6. Change of FTC over cycle length

While the value of MTC is naturally becoming more negative over fuel burnup, the value of FTC shows more complicated shape. This shape could be explained by comparing the graphs given on Figure 6 and Figure 4. The behavior of FTC curve shows correlation with BA burning out, which is occurring at the same stage of fuel cycle as shown on Figure 4.

In addition to MTC and FTC determination, values of power defect (PD), CRW and SDM were obtained. These values for BOC, MOC and EOC are given in Table 3.

Table 3: Safety-related nuclear characteristics for Th-Pu SMR

BOC 0.0 MWD/kgHM	Excess reactivity control, pcm	1599
	PD, pcm	1513
	CRW, pcm	12240
	N-1 CRW, pcm	11491
	Uncertainty in N-1 CRW calculation, 5%	575
	SDM, pcm	9403
MOC 16.0 MWD/kgHM	Excess reactivity control, pcm	1746
	PD, pcm	1584
	CRW, pcm	13760
	N-1 CRW, pcm	12925
	Uncertainty in N-1 CRW calculation, 5%	647
	SDM, pcm	10694
EOC 32.0 MWD/kgHM	Excess reactivity control, pcm	190
	PD, pcm	1942
	CRW, pcm	16667
	N-1 CRW, pcm	15610
	Uncertainty in N-1 CRW calculation,	781
	SDM, pcm	12887

For calculating values given in Table 3, Ag-In-Cd control rods were used. Due to chosen type of BA, which is not loaded into guide tubes, all FAs were designed as control element assemblies (CEA), which is important due to soluble boron-free mode of operation.

Values of PD were obtained with eliminating xenon effect, which provides more conservative value required to be compensated by control rods.

Calculating of N-1 CRW was based on assumption that one control rod with highest CRW stuck and was not inserted into the core. Further calculations of SDM were based on the N-1 CRW value, considering worst possible case. Additionally, CRW and N-1 CRW were found with consideration of excess reactivity control by control rods, and therefore these values show only effective available CRW. To include possible uncertainties in CRW calculations, additional 5% N-1 CRW uncertainty was calculated and used for determination of SDM.

Finally, total reactivity balance of determined core is provided in Table 4.

Table 4: Reactivity balance of Th-Pu SMR

BOC	Total excess reactivity, pcm	16558
	Burnable absorbers	14959
	Control rods	1599
	Subtotal	0
MOC	Total excess reactivity, pcm	9637
	Burnable absorbers	7891
	Control rods	1746
	Subtotal	0
EOC	Total excess reactivity, pcm	190
	Burnable absorbers	0
	Control rods	190
	Subtotal	0

As it is shown in subtotal section of the table, excess reactivity is fully compensated by combination of BA and control rods with no soluble boron injection. It is also important to point out that initial excess reactivity of Th-Pu SMR is noticeably lower compared to conventional uranium-based model shown in [1]. Therefore, no strong BA (such as Gd) is needed to reach required design criteria such as cycle length and maximum excess reactivity during cycle.

4. Conclusion

In this study, a new LP for SMR was developed using Th-Pu fuel. The results of nuclear characteristics determination show that all initial design criteria including safety-related factors were satisfied. Compared to conventional uranium model of SMR that was discussed in [1], new Th-Pu model shows longer cycle length, better reactivity balance performance, which allows using less BA, less complicated LP configuration that requires only two types of FA with no difference in loaded fuel composition. Additionally, due to strong potential of Pu utilization in Th-Pu based reactors that was discussed in [3], further work is expected on this subject.

Acknowledgments

This research was supported by the 2018 Research Fund of KINGS, Republic of Korea.

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