Application of high-thickness integral fuel burnable absorber ZrB_2 in a dual-cooled micro-heterogeneous duplex fuel for small modular long-life reactor

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Abstract

Small modular reactors (SMRs) have emerged as a potential game changer in the nuclear industry, providing a flexible and carbon-neutral energy option to meet global energy demands. However, the design of SMRs presents unique challenges in terms of core size, safety enhancements, and extended operational lifetimes. In a recent study, we looked at assembly designs with 18 wt.% U-235 for an annular duplex UO_2-ThO_2 fuel loaded into a 13 × 13 assembly. Our findings revealed that this configuration achieved a discharge burnup of more than 90 GWd/ton, equivalent to approximately 6.2 effective full-power years of operation. This achievement was accompanied by improved safety characteristics as a result of the use of novel thorium-based duplex and dual-cooled annular fuel designs, as opposed to the conventional 15 wt.% annular all-UO_2 fuel. Although the proposed assembly requires significantly more fissile loading than most light water assemblies to achieve the desired discharge burnup, managing the significant excess reactivity at the beginning of assembly life and preserving the attained discharge burnup is critical. As a result, careful selection and optimization of the burnable absorber material, as well as its arrangement, are critical considerations during SMR design.

In this article, we present a comprehensive analysis of burnable absorbers in a dual-cooled micro-heterogeneous duplex SMR, focusing on achieving effective reactivity control. We specifically investigate the burnup characteristics of high-thickness ZrB_2 (150 μm) in the form of the integral fuel burnable absorbers (IFBAs), considering different configurations of ZrB_2 pins and B-10 enrichment in ZrB_2. Our results demonstrate that all ZrB_2 cases effectively flatten the reactivity curve, with an increasing number of IFBA pins leading to enhanced absorber longevity and reduced reactivity fluctuations. These findings offer valuable insights for optimizing burnable absorber utilization in SMR design, thereby contributing to enhanced safety and long-term operational performance.

Keywords: SMR, duplex fuel design, ZrB_2, reactivity control, discharge burnup.

1. INTRODUCTION

SMRs have been receiving a lot of attention because of their potential to provide clean and reliable nuclear energy in a variety of applications. In recent years, several countries, including the United States, Russia, China, Japan, and Korea, have been actively developing SMRs. These reactors can be categorized as integral pressurized water reactors (PWRs), boiling water reactors (BWRs), pressurized heavy water reactors (PHWRs), and high-temperature gas-cooled reactors (HTRs) [1][2][3].

A crucial requirement for SMRs is a long operational cycle that minimizes the need for frequent refueling. In a recent study, we looked at assembly designs with 18 wt.% U-235 and annular duplex UO2-ThO_2 fuel in a 13 × 13 configuration. The higher enrichment level was chosen to compensate for fuel depletion-induced reactivity loss. According to our findings, this fuel configuration achieved an impressive discharge burnup of more than 90 GWd/ton, corresponding to approximately 6.2 effective full-power years of operation. Furthermore, the incorporation of novel thorium-based duplex and dual-cooled annular fuel concepts resulted in improved safety characteristics [4]. This achievement, however, resulted in significant excess reactivity at the start of the fuel cycle, posing challenges for reactivity control. As a result, a thorough investigation into the use of burnable absorbers in this SMR PWR is required to effectively manage the excess reactivity.

The initial excess reactivity in PWRs can be effectively managed by incorporating absorbing additives, also known as a poison, into the fuel. When compared to the fuel, these absorbers have a larger absorption cross-section. However, it is critical to choose burnable absorbers that have little impact on fuel cycle performance because they can shorten cycle length and increase discharge burnup [5]. There are several types of burnable absorbers available, including integral fuel burnable absorbers (IFBAs), discrete burnable poison rods (BPRs), and burnable poison particles (BPPs) [6][7]. This research focuses on IFBAs, specifically Zirconium diboride (ZrB_2) coated on the surface of UO_2 in the UO_2-ThO_2 fuel. The study addresses the burnup characteristics of high-thickness ZrB_2 (150 m) as IFBA in various configurations, such as different arrangements of ZrB_2 pins and B-10 enrichment levels within the ZrB_2 coating. The goal is to assess the performance and effectiveness of the absorber in our proposed SMR assembly, particularly in terms of reactivity control.

2. CALCULATION METHOD AND DESIGN CONCEPT

2.1. Calculation code

In this study, we used the deterministic reactor physics code DRAGON5 to perform assembly-level calculations. We used the multi-group cross-section library ENDFB-VIII ref.0 (XMAS-172), which can be downloaded from the DRAGLIB download page, for these calculations [8][9]. DRAGON5 is a well-known and widely used software that performs deterministic neutron transport calculations for individual pins or a fuel assembly. It follows a predefined calculation path through a series of separate modules, allowing for comprehensive neutronics calculations. One of the benefits of DRAGON5 is its versatility, as it can be installed on any operating system that supports FORTRAN. Furthermore, it has undergone extensive investigation and validation, making it a reliable tool for performing neutronic calculations for both standard and modified PWR assemblies [10][11][12].

2.2. Fissile loading and proposed assembly sizing

According to existing literature, numerous studies have investigated the use of Th-232 as a fertile material in LWRs. One approach involves employing ThO_2/UO_2 fuel, where ThO_2 is homogenously mixed with UO2, resulting in a ThO_2/UO_2 fuel mixture. However, it has been found that the performance of homogeneously mixed ThO_2/UO_2 fuel is only promising in a single-batch arrangement when the U-235 enrichment exceeds 20 wt.% [13][14][12]. Subsequent studies have highlighted that the advantages of Th-232 are best realized in heterogeneous geometries, particularly in seed-blanket arrangements. These arrangements, known as heterogeneous in-forme macro-heterogeneous configurations, are associated with advanced nuclear fuel cycles that involve the partitioning and transmutation of minor actinides and plutonium isotopes However, the implementation of macro-heterogeneous configurations introduces complexities in fuel management and reloading, which undermine the goal of a single fuel batch. An additional challenge observed in the use of macro-heterogeneous configurations is the power imbalance between the blanket and the seed regions. Due to the subcritical nature of the blanket and the supercritical nature of the seed, the power density in the seed region is significantly higher than that in the blanket region [15][16][17]. In contrast, the micro-heterogeneous duplex fuel concept is recommended as it addresses the power imbalance issue and facilitates the extraction of U-233 during reprocessing [13][12][18]. Therefore, this study aims to evaluate the performance of dual-cooled micro-heterogeneous UO_2-ThO_2 duplex fuel when loaded in a single-batch strategy. As a basis for comparison, we also assess the performance of dual-cooled UO_2 fuel. The fissile loadings for the UO_2-ThO_2 duplex and UO_2 fuels were determined based on enrichment sensitivity studies conducted in our previous research, aiming to maintain criticality in the assemblies for a burnup of 90-100 GWd/ton (equivalent to 6 to 7 effective full power years, as demonstrated in El Kheiri et al.) [4]. From this study, it is evident that achieving the desired discharge burnup will require an initial enrichment of 18% and 15% U-235 for the dual-cooled UO_2-ThO_2 duplex and dual-cooled UO_2 fuels, respectively. For this study, we also utilized a 13 × 13 annular fuel array assembly with 9 guide thimbles [19]. The geometry layout of the assembly can be found in Figure 1. To provide comprehensive information, Table 1 summarizes the design data for the annular UO_2 fuel and the annular duplex fuels proposed for the SMR. Furthermore, Table 2 presents the specifications of the fuel and non-fuel materials used for analysis.

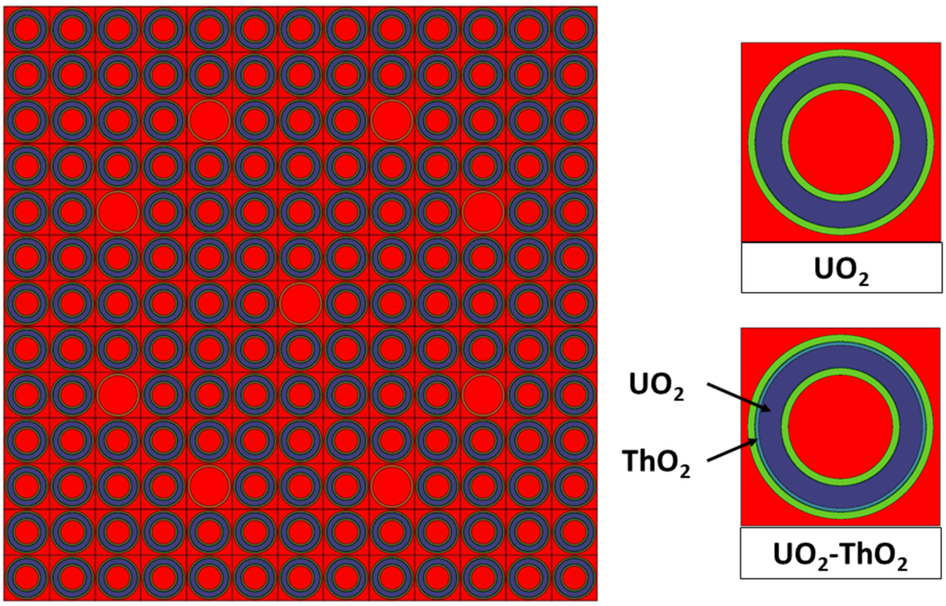

Figure 1. View of the basic model of the proposed SMR assembly.

Table 1. Assembly-level parameter values considered in the simulations, modified from Ref. [4].

Parameter	Value	
Rod array	13 × 13 UO_2	13 × 13 UO_2-ThO_2
Number of fuel rods	160	160
Number of guide tubes	9	9
Assembly pitch (cm)	21.5	21.5
Rod lattice pitch (cm)	1.648	1.648
Inner clad inner radius (cm)	0.43165	0.43165
Inner clad outer radius (cm)	0.48865	0.48865
Inner helium gap outer radius (cm)	0.49485	0.49485
Fuel outer radius (cm)	0.70515	0.70515
Outer helium gap outer radius (cm)	0.71135	0.71135
Outer clad outer radius (cm)	0.76835	0.76835
ThO_2 area per fuel rod (cm^2)	-	0.67389
UO_2 area per fuel rod (cm^2)	0.79281	0.11892
Guide tube		
Guide tube inner radius (cm)	0.710	0.710
Guide tube outer radius (cm)	0.770	0.770

Table 2. Data for material specification [4].

Zone	Parameter		Value
Fuel pellet	UO_2	UO_2 enrichment	15 wt.% (U-235)
		UO_2 density	10.53 g/cm^3
	UO_2-ThO_2	ThO_2 enrichment	100 wt.% (Th-232)
		ThO_2 density	9.95 g/cm^3
		UO_2 enrichment	18 wt.% (U-235)
		UO_2 density	10.53 g/cm^3
Fuel cladding	Cladding material		Zirlo™
	Cladding density		6.50 g/cm^3
Gap	Gap material		Helium
	Gap density at 600 K		1.2049E-02 g/cm^3
	Gap density at 293.6 K		1.6252E-04 g/cm^3
Moderator	Moderator material		Light water
	Moderator density at 600 K		0.711 g/cm^3
	Soluble boron concentration		0 ppm soluble boron-free
Guide tube cladding	Cladding material		Stainless Steel type 304
	Cladding density		8.03 /cm^3

Table 3. ZrB_2 model for the UO_2-ThO_2 fuel calculated in this study.

Model No.	Fuel type	Burnable absorber	Number of burnable absorber rods	Enrichment of B-10 in ZrB_2 (wt. %)
Model 0	UO_2		No burnable poisons	
Model 1	UO_2-ThO_2		No burnable poisons	
Model 2	UO_2-ThO_2	ZrB_2	16	Nature
Model 3	UO_2-ThO_2	ZrB_2	24	Nature
Model 4	UO_2-ThO_2	ZrB_2	28	Nature
Model 5	UO_2-ThO_2	ZrB_2	32	Nature
Model 6	UO_2-ThO_2	ZrB_2	40	Nature
Model 7	UO_2-ThO_2	ZrB_2	16	30
Model 8	UO_2-ThO_2	ZrB_2	24	30
Model 9	UO_2-ThO_2	ZrB_2	28	30
Model 10	UO_2-ThO_2	ZrB_2	32	30
Model 11	UO_2-ThO_2	ZrB_2	40	30
Model 12	UO_2-ThO_2	ZrB_2	16	50
Model 13	UO_2-ThO_2	ZrB_2	24	50
Model 14	UO_2-ThO_2	ZrB_2	28	50
Model 15	UO_2-ThO_2	ZrB_2	32	50
Model 16	UO_2-ThO_2	ZrB_2	40	50

2.3.Integral fuel burnable absorbers

Among the various burnable absorbers (poisons) available, an IFBA is a Westinghouse product that is widely used in PWRs today [20]. The IFBA acts as a thin coating of ZrB_2 that is deposited on the outside of fuel pellets. Its primary goal is to reduce excessive reactivity at the beginning of cycle (BOC). For standard PWRs like the AP1000, the IFBA layer is typically 0.001 cm thick [19][21]. Boron, specifically B-10, is present in the IFBA layer and acts as an effective neutron absorber. The IFBA reduces the neutron population in the vicinity of the IFBA rod by incorporating B-10. It is important to note that the IFBA design ensures complete depletion of B-10 during the first fuel cycle, eliminating any residual reactivity penalty. Moreover, the implementation of IFBA does not displace any fuel within the core. The utilization of IFBA in reactor designs contributes to improved core design efficiency, resulting in cost savings associated with fuel expenditure. Thus, IFBA plays a crucial role in the overall reactor design, and it is essential to accurately model its behavior and effects [22].

In this study, we focused on investigating the impact of a high-thickness ZrB_2 coating (150 μm) on burnup in a fuel rod. Different calculation models were employed, as outlined in Table 3. The high-thickness ZrB_2 coating, proposed by Alam et al. [23], was utilized in this study to achieve an essential self-shielding effect. This effect aims to reduce excessive reactivity at BOC caused by the increased enrichment. The calculation models used in the study are as follows: Model 0 represents the dual-cooled UO_2 assembly, while Model 1 represents the basic dual-cooled UO_2-ThO_2 duplex assembly model without ZrB_2. Models 2–6, Models 7–11, and Models 12–16 represent different ZrB_2 assembly arrangements (as depicted in Figure 2), all containing the same burnable absorber content of ZrB_2. To enhance the neutronic effectiveness, an increased B-10 enrichment was employed in the ZrB_2 coating. This adjustment aimed to optimize the performance of the burnable absorber.

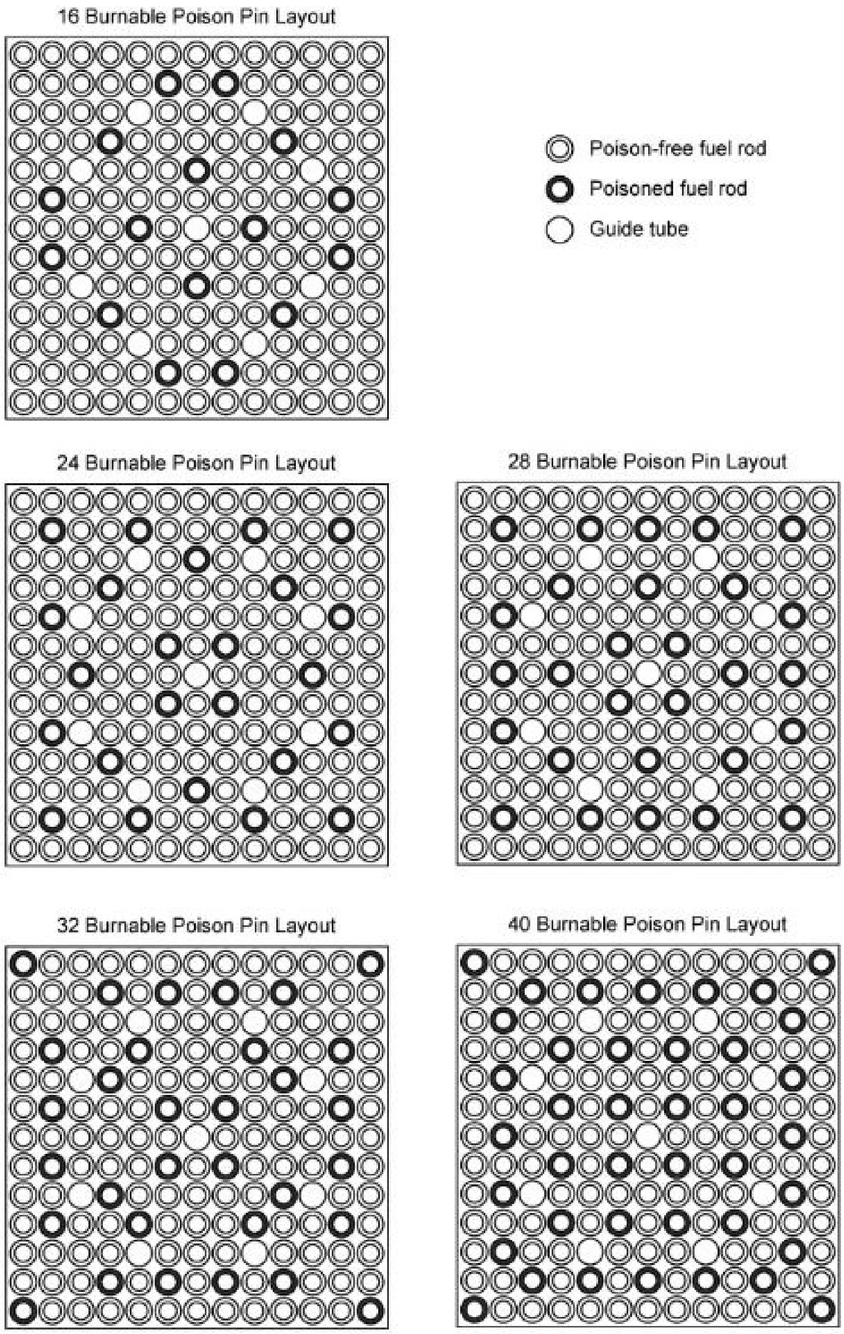

Figure 2. Configurations for the IFBA rods in the 13 × 13 fuel assembly [24].

3. BURNUP CHARACTERISTIC RESULTS

This section highlights the burnup characteristics obtained by running the DRAGON code. The fuel pins in the assemblies were divided into several rings to ensure an accurate estimation of major isotope absorption. This allows for a more precise burnup calculation. The simulations of depletion characteristics were carried out at the temperatures listed in Table 2 and at a power density of 40 kW/kg. It's worth noting that the neutronic calculations assumed the assemblies had reflective outer surfaces, which eliminated neutron leakage. However, neutron leakage rates in SMR cores are typically around 7% [25][26]. As a result, the criticality period in this context refers to the burnup period during which the infinite multiplication factor (k_{inf}) reaches 1.07.

Figures 3, 4, and 5 show the burnup characteristics of ZrB_2 with various assembly arrangements and levels of B-10 enrichment. For comparison, the UO_2 assembly (Model 0) is also included in these figures. The figures show that increasing the number of IFBA pins results in longer absorber longevity, except for natural boron, and a lower reactivity swing. Furthermore, increased B-10 enrichment in ZrB_2 results in a slight improvement in reactivity suppression. This is due to the stronger self-shielding effect provided by the ZrB_2 layer, as shown in Table 4.

Additionally, Table 4 shows that the ZrB_2 designs have a negligible burnup penalty when compared to the gadolinia (Gd_2O_3) and erbia (Er_2O_3) designs used in our previous work [4]. In terms of initial reactivity suppression, ZrB_2 clearly outperforms Gd_2O_3 and Er_2O_3 as a burnable absorber. This is because, in previous work, Gd_2O_3 and Er_2O_3 were homogeneously mixed with the fuel, reducing the self-shielding effect compared to ZrB_2, which is coated onto the fuel and capable of capturing incident neutrons. Furthermore, ZrB_2 outperforms Er_2O_3 in terms of reactivity suppression. This is since Er_2O_3, which has a smaller absorption cross-section than B-10, is uniformly mixed with the fuel, displacing fissile contents.

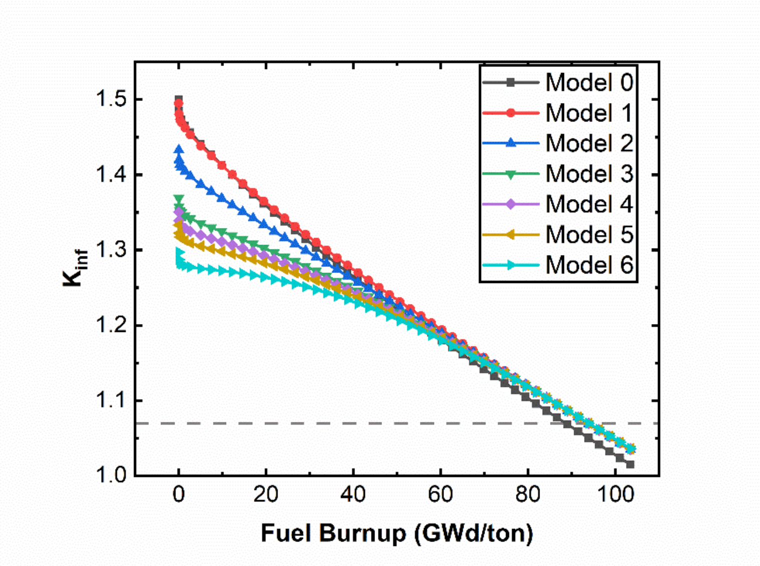

Figure 3. Variation of k_{inf} versus burnup with different ZrB_2 arrangements (B-10 Nature).

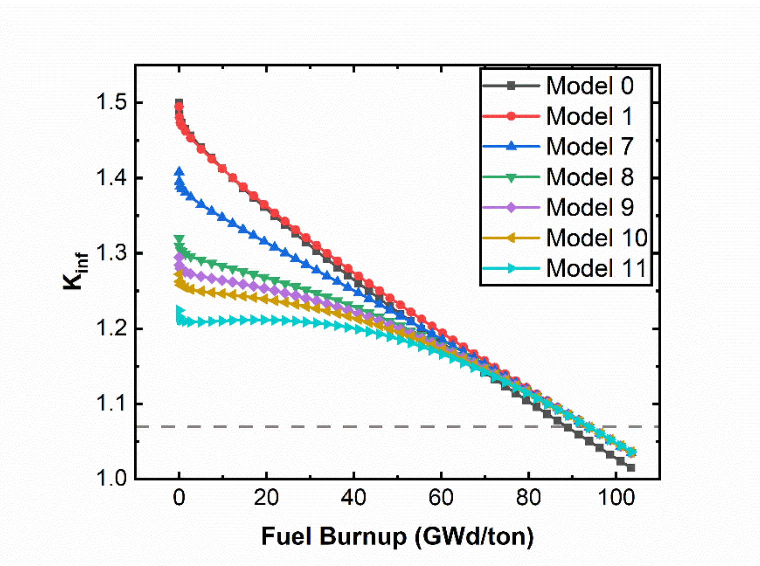

Figure 4. Variation of k_{inf} versus burnup with different ZrB_2 arrangements (B-10 30 wt.%).

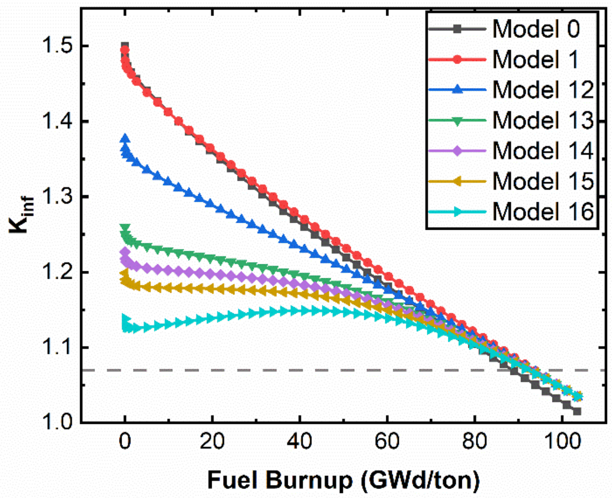

Figure 5. Variation of k_{inf} versus burnup with different ZrB_2 arrangements (B-10 50 wt.%).

Table 4. Reactivity obtained at BOC considering 7% neutron leakage and criticality period for the various ZrB_2 model.

Model No.	Reactivity (Δk/k)	Criticality period (GWd/ton)
Model 0	0.28645	88.57
Model 1	0.28427	93.54
Model 2	0.25319	93.61
Model 3	0.21851	93.70
Model 4	0.20758	93.73
Model 5	0.19741	93.76
Model 6	0.17518	93.79
Model 7	0.23994	93.48
Model 8	0.18936	93.50
Model 9	0.17342	93.48
Model 10	0.15892	93.47
Model 11	0.12608	93.39
Model 12	0.22271	93.10
Model 13	0.15059	92.86
Model 14	0.12780	92.70
Model 15	0.10737	92.49
Model 16	0.05977	92.05

4. SUMMARY AND CONCLUSIONS

The results of this study confirm that the proposed assembly, which uses dual-cooled micro-heterogeneous duplex UO_2-ThO_2 fuel, can operate for more than 90 GWd/ton, which means more than 6 effective full power years, without refueling. Furthermore, the goal of this research was to examine the neutronic performance of ZrB_2 as an integral fuel burnable absorber in the dual-cooled duplex UO_2-ThO_2 fuel design using various alternative loading schemes. The key findings of this neutronic study show that using ZrB_2 as an IFBA design effectively reduces early excess reactivity at the beginning of the cycle while imposing a negligible burnup penalty at the end of the cycle. These findings have, therefore, important implications for the design of small, long-life pressurized water reactors that use dual-cooled duplex UO_2-ThO_2 fuel cycles. It is important to note that the scope of this study is limited to neutronic feasibility in terms of the burnup characteristics of the candidate absorber. Future research will consider other neutronic and practical implications.

Credit authors statement

Oussama El Kheiri and Ouadie Kabach shared co-first authorship for this work. Ouadie Kabach contributed to the supervision and analyses of the main results. Abdelouahed Chetaine and Abdelmajid Saidi contributed to supervision and provided technical feedback.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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