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Conversion of Small Modular Reactors Fuel to Use Mixed (U-Th)O_2 Fuel

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ABSTRACT

The concept of Integral Small Modular Reactor (SMR) isn't new but it seems that the proper time for using this idea has been coming. According to the International Atomic Energy Agency (IAEA), the reactors with electrical power lower than 300 MW have been defined as small reactors, although SMRs are categorized by this fact that more advantages and design features are attained when intentionally make reactors small. In fact, these reactors use their size as advantage to attain more design purposes. The scalability, modularity, improved safety characteristics and more important than other, lower up-front cost of the SMRs, offer great advantages over large common nuclear power plants. According to the IAEA reports there are many interests all over the world to move toward using of these kinds of reactors. There are many different type of SMRs under various stages of design, licensing and construction. Nowadays, there are many initiatives to use thorium in nuclear reactors and fuel cycles. Thorium is three times more abundance than Uranium, however, despite of several initiatives and researches on Th-232 utilization in many types of reactors, this fuel hasn't been commercialized yet.

Most of The SMRs have been designed to have long cycle, so they must use a lot of poisoning material in the beginning of the cycle. Taking in the account that Thorium can be used as a absorber in the beginning of the cycle and also be used as a fertile material during the cycle, it seems to be a good option to use mixed (U-Th)O_2 as SMR's fuel. This paper briefly is going to review the research about Thorium utilization as a nuclear fuel and the possibilities of using mixed (U-Th)O_2 fuel as an alternative option for SMRs fuel. The Korean System Integrated Modular Advanced Reactor (SMART) categorized as SMR that has received its standard design approval, was chosen as reference core for our calculations. The calculations have been performed by MCNPX code as a well-known Monte Carlo code. Geometry and all materials were kept the same as the SMART core, and the only variable was the fuel pin material, in which we use several mass proportion of uranium and thorium but keeping the enrichment in U-235, lower than 5 wt%. The results confirm that it's possible to use mixed (U-Th)O_2 with lower burnable absorber at the beginning of the cycle and have a longer burnup cycle.

Keywords: *(U-Th)O_2 fuel, Fuel management, Small Modular Reactor, MCNPX*

1 INTRODUCTION

The International Atomic Energy Agency (IAEA) classifies any nuclear reactor with a power output of less than 300MWe as small. Those with outputs between 300 and 700 MWe are considered medium-sized reactors, while those with outputs greater than 700 MWe are classified as large reactors. SMRs come in a wide range of sizes and adopt a wide range of technologies. According to the IAEA (2016) report, 18 pressurized water SMRs are under developing that their design status are presented in Table 1. There are many interests all over the world to use these kinds of reactors. There are diverse types of SMRs under distinct stages of design, licensing and in construction. Russia (KLT40s), Argentina (CAREM) and China (HTR-PM) have three types of SMRs under construction now and are scheduled to begin commercial operation between 2018 and 2020. Korean System Integrated Modular Advanced Reactor (SMART) has a certified design and Russian VBER-300 is under the licensing stage. There are many other SMR designs that will be prepared for near term deployment, although realistically it seems that the first commercial group of SMRs, start the operation near 2025 – 2030 [1].

Table 1: Pressurized Water SMRs under developing all over the world [1].

Reactor design	Reactor type	Designer, country	Capacity MWe	Design status
CAREM-25	Integral pressurized water Reactor	CNEA, Argentina	27	Under construction
ACP-100	Integral pressurized water Reactor	CNNC (NPIC/CNPE), China	100	Detailed design
Flexblue	Subsea pressurized water Reactor	DCNS, France	160	Conceptual design
IRIS	Integral pressurized water Reactor	IRIS, International Consortium	335	Basic design
IMR	Integral modular water Reactor	Mitsubishi Heavy Industries, Japan	350	Conceptual design completed
SMART	Integral pressurized water Reactor	KAERI, Republic of Korea	100	Licensed/Design certification received in July 2012
KLT-40S	Pressurized water reactor	OKBM Afrikantov, Russian Federation	35 x 2	Under construction, target of operation in 2016 – 2017
VBER-300	Integral pressurized water reactor	OKBM Afrikantov, Russian Federation	325	Licensing stage
ABV-6M	Pressurized water reactor	OKBM Afrikantov, Russian Federation	6 x 2 modules	Detailed design
RITM-200	Integral pressurized water reactor	OKBM Afrikantov, Russian Federation	50	Under construction, planned commercial start 2017
VVER-300	Water-cooled water moderated power reactor	OKB Gidropress, Russian Federation	300	Conceptual design
RUTA-70	Pressurized water reactor	RDIPE, IPPE, Russian Federation	70	Conceptual design
SHELF	Pressurized water reactor	RDIPE, Russian Federation	6	Conceptual design
ELENA	Pressurized water reactor	Kurchatov Institute Russian Federation	0.068	Conceptual design
mPower	Integral pressurized water reactor	B&W Generation mPower, USA	180 x 2 modules	Basic design
NuScale	Integral pressurized water reactor	NuScale Power LLC., USA	45 x 12 modules	Basic design
Westinghouse SMR	Integral pressurized water reactor	Westinghouse Electric Company LLC, USA	225	Preliminary design completed
SMR-160	Pressurized water reactor	Holtec International, USA	165	Conceptual design

Beside than power range definition, SMRs are categorized by this fact that more advantages and design features are attainable when intentionally make reactors small. In fact, these reactors use their size as an advantage to attain more design purposes. The scalability, modularity (many of the major components can be assembled anywhere far from the site and then shipped to the main site), improved safety characteristics and more important than other, lower up-front cost of the SMRs, offer great advantages over large conventional nuclear power plants. The total system Levelized costs of SMRs in comparison with other energy systems are shown in Figure 1 [2]. Also, many countries and regions (like many of Asian and African countries) lack suitable sites for producing electricity and water desalination or generally, for the countries with small electric grids, less developed infrastructure and limited investment capabilities, SMRs can be the best solution.

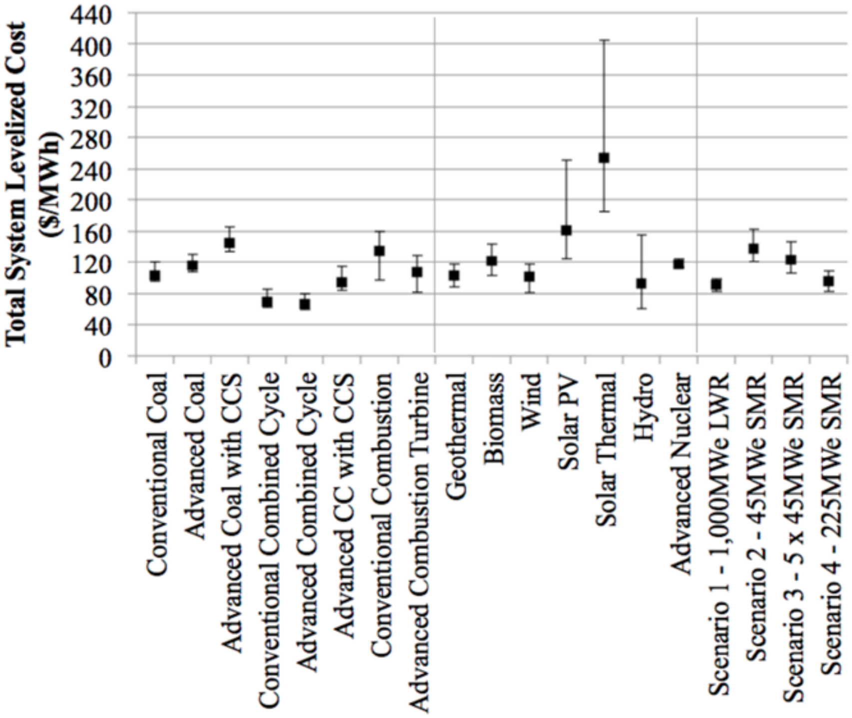


Figure 1: The total system Levelized costs of SMRs in comparison with other energy systems [2].

Many researchers and engineers all over the world are trying to assess and survey different aspects of these new reactors like in economics, environmental, nuclear characteristics and many other fields [3-7]. The main objective of the current work is to evaluate the possibilities of using Thorium fuel in the SMRs. The Korean SMART reactor as the first integral SMR with certified design has been chosen as the reference core for our calculations.

The natural thorium isotope (Th-232) as a fertile fuel can finally be converted to a fissile U-233 isotopes after a thermal neutron capture reaction. As shown in equation (1), Thorium, which is 100 percent Th-232 in its natural form, produces a fissile material, U-233, after a neutron absorption in Th-232 and two successive beta decays.

$$n + {}^{232}_{90}Th \longrightarrow {}^{233}_{90}Th \xrightarrow{\beta^-} {}^{233}_{91}Pa \xrightarrow{\beta^-} {}^{233}_{92}U \qquad (1)$$

The feasibility of using Thorium in different kind of reactor has been studied [8-14].The main purpose of this study is to obtain a new core configuration in which we convert the reference SMART core to one with $(U/Th)O_2$, with the same geometry and operational parameters for the all core components, as much as possible. The objective of the work is to demonstrate the design feature of the proposed $(U/Th)O_2$ core. For the SMART core simulation in this study, we used

MCNPX; a general purpose Monte Carlo radiation transport code that's designed to track many particle types over broad ranges of energies [15-16].

The remainder of the paper is organized as follows. Section 2 presents an overview of the SMART reactor and its operational parameters. In the sections 3, the MCNP code and calculation procedure have been presented. Sections 4 and 5 contain the results and conclusion.

2 REFERENCE CORE

SMART (System-integrated Modular Advanced Reactor), which is conceptually developed by KAERI (Korea Atomic Energy Research Institute), is a small-sized advanced integral PWR that produces 330 MW of thermal energy under full power operating conditions. SMART is a multi-purpose SMR that furthermore than electricity production can be used for different applications including: process heat for industries and small isolated grids, district heating and sea water desalination. This SMR has been designed with enough output to meet the fresh water and electricity demands of a city with one hundred thousand populations. As shown in Figure 2 major components, including reactor coolant pumps, steam generators and a self-pressurizer are integrated within a single pressure vessel, in which the arrangement of components differs from the conventional loop-type reactors [17-18].

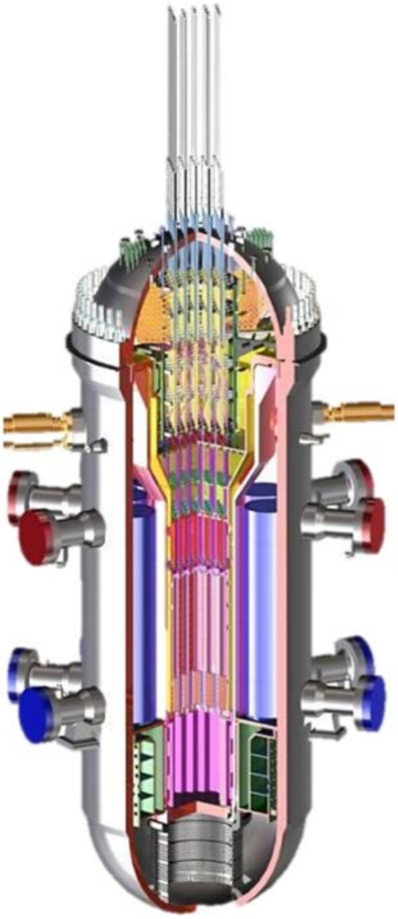


Figure 2: Smart reactor integral pressure vessel.

SMART core general design parameters and fuel assembly, fuel rod, control rod, guide tube, central channel and burnable absorber cross section are presented in Tables 2 and 3 [19-20].

Table 2: SMART core main parameters.

Parameter	**Unit**	**Value**
Reactor thermal output	MWth	330
Power plant output, gross	MWe	100
Mode of operation	------	Load follow
Non-electric applications	------	Desalination, District heat
Lattice geometry	------	Square
Equivalent core diameter	m	1.8316
Average fuel power density	KW/kgU	23.079
Average core power density	MW/m3	62.62
Average discharge burnup of fuel	MWd/kg	36.1
Fuel cycle length	Months	36
Primary coolant flow rate	kg/s	2090
Reactor operating pressure	MPa	15
Core coolant inlet temperature	°C	295.7
Core coolant outlet temperature	°C	323

Table 3: SMART fuel assembly general specifications.

	Unit	Value
Active core height	cm	200.0
Assembly pitch	cm	21.504
Pin pitch	cm	1.2598
UO_2 Fuel		
Pellet radius	cm	0.4096
Material		UO_2
Stack height density	g/cm^3	10.286
$UO_2+Gd_2O_3$ Fuel		
Pellet radius	cm	0.4096
Material		$UO_2+Gd_2O_3$
Stack height density	g/cm^3	10.017
Fuel clad		
Inner radius	cm	0.41875
Outer radius	cm	0.47500
Material		Zircaloy-2/4
Density	g/cm^3	6.56
Guide and instrumentation tube		
Inner radius	cm	0.56150
Outer radius	cm	0.61200
Material		Zircaloy-2/4
Density	g/cm^3	6.56
Control rod absorber		
Radius	cm	0.43305
Material		Ag-In-Cd
Density	g/cm^3	10.17
Control rod clad		
Inner radius	cm	0.43690
Outer Radius	cm	0.48385
Material		SS-304
Density	g/cm^3	7.9

Cross view of SMART reactor core configuration is presented in Figure 3 and also Table 4 describes the different core configuration quantities.

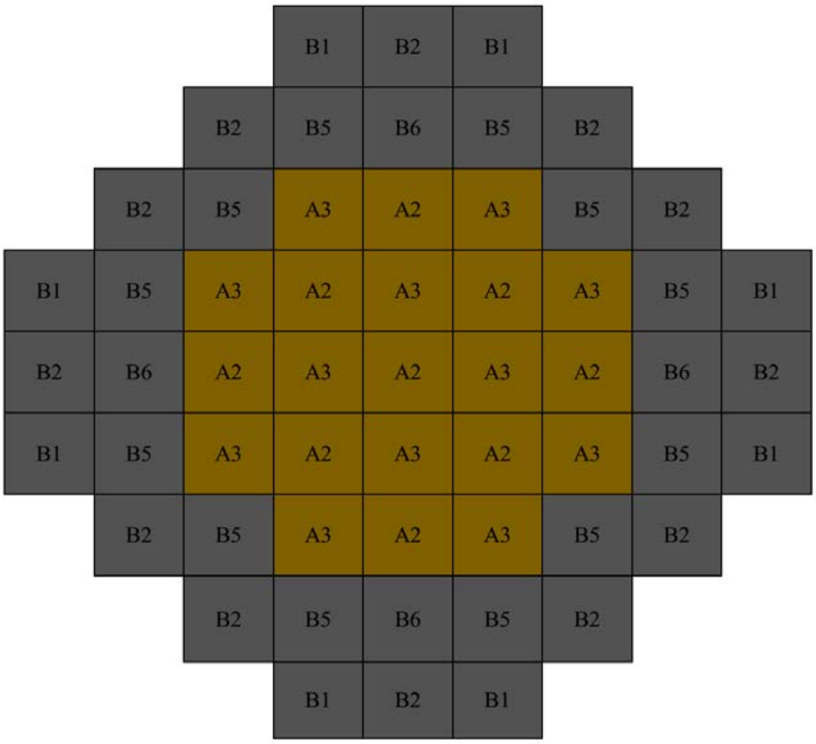


Figure 3: Cross view of SMART reactor core.

Table 4: description of the different core configuration quantities.

Assembly type	No. of Assemblies	Normal fuel enrichment (w/o U-235)	No. of normal fuel rods per assembly	No. of Gd fuel rods per assembly	Gd content (w/o Gd_2O_3)
A2	9	2.82	256	8	8.0
A3	12		252	12	8.0
B1	8	4.88	260	4	8.0
B2	12		256	8	8.0
B5	12		244	20	8.0
B6	4		240	24	8.0

The reactor core has 57 square lattice fuel assemblies with 2 m active height. Each fuel assembly contains 265 fuel rods (some fuel rods contain a mixture of UO_2+Gd_2O_3 that known as IFBA (Integral Fuel Burnable absorber)), 24 guide tubes and a central instrumentation channel. Core reactivity in SMART reactor is controlled only by IFBA rods and soluble poison while most other typical PWRs use fixed burnable absorber rods (SMART Report, 2012; SMART SSAR, 2010).

In the SMART core design, IFBA rods are present in all the fuel assemblies with different arrangements (Figure 4). All IFBA rods have same 8 weight percent of Gd_2O_3 to reduce the large initial K_{eff} value and also flatten the power distribution during the core working cycle.

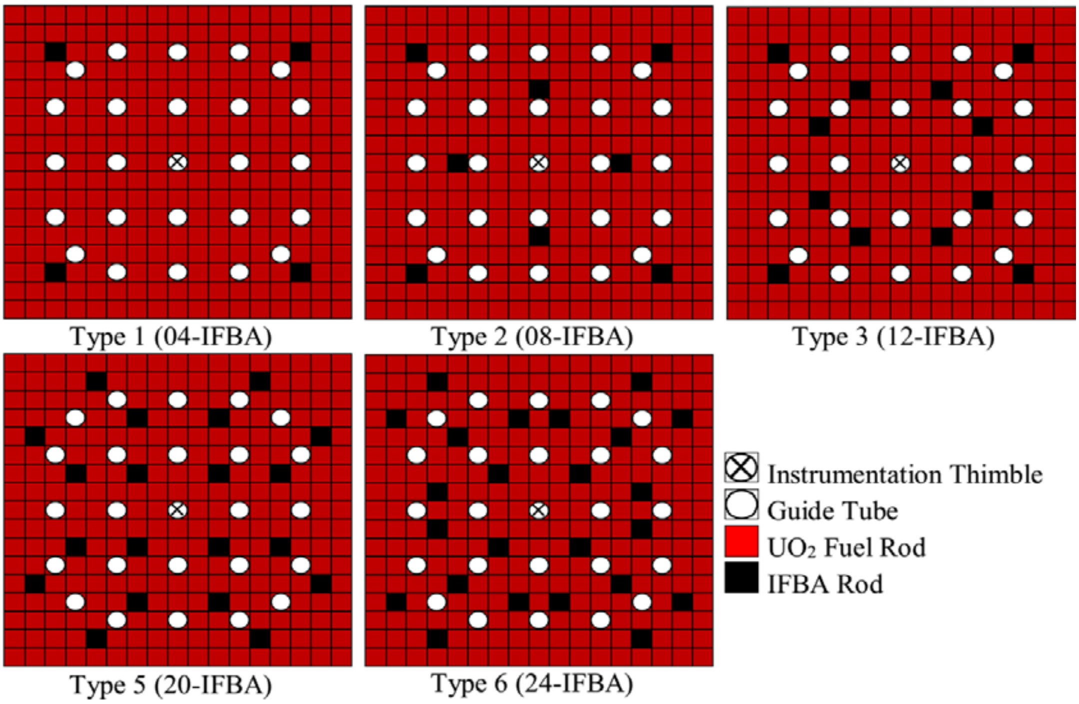
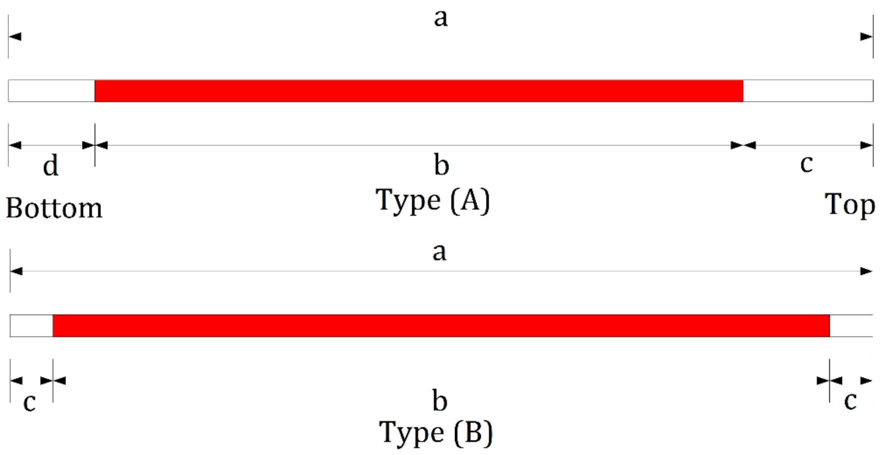

Type 1 (04-IFBA)
Type 2 (08-IFBA)
Type 3 (12-IFBA)
Type 5 (20-IFBA)
Type 6 (24-IFBA)

Figure 4: IFBA arrangement in fuel assemblies.

The SMART core fuel assemblies are categorized into A and B according to the presence of Gd_2O_3 at the top and bottom of the IFBA rods (Figure 5). The fuel assemblies placed near the center of core have 2.82 wt% U-235 and other fuel assemblies have 4.88 wt% U-235 fuel enrichment but the IFBA rods are exceptions. The IFBA rods have 1.6 wt% U-235 at a part of top and bottom of the rod and 1.8 wt% U-235 at other parts [19-20].



a = 200.0 cm (Active Core Height)

b = 150.0 cm ($UO_2+Gd_2O_3$, 1.8 w/o U-235, 8.0 w/o Gd_2O_3)

c = 30.0 cm (UO_2 Cutback, 1.6 w/o U-235)

d = 20.0 cm (UO_2 Cutback, 1.6 w/o U-235)

Type (A)

a = 200.0 cm (Active Core Height)

b = 180.0 cm ($UO_2+Gd_2O_3$, 1.8 w/o U-235, 8.0 w/o Gd_2O_3)

c = 10.0 cm (UO_2 Cutback, 1.6 w/o U-235)

Type (B)

Figure 5: IFBA axial arrangement.

3 CALCULATIONS METHODOLOGY

In this study, MCNP code as a verified calculation tool for various parameters in the different reactors has been used. It was designed to track photons, electrons, neutrons, protons, and ions over nearly all energies. MCNPX is a Fortran90 computer language code that models the interaction of radiation with matter. This Monte Carlo code has a good capability of calculating different core parameters that one of its most important features is burnup calculations during cycle by using CINDER90 module.

In this study, the main objectives have been defined in neutronic field. These objectives are including:

1. Achieving longer cycle length in comparison with reference SMART core;
2. Using fewer amount of integral fuel burnable absorber rods in comparison with reference SMART core;
3. Reducing the amount of using soluble boron at the beginning and also during the cycle in comparison with reference SMART core;
4. One of most important objectives of this work, is to extend the SMART core cycle length simultaneously keeping the enrichment of U-235 less than 5%;
5. Producing some amount of U-233 at the end of cycle that can be used for the next cycles;
6. By increasing the amount of used thorium in SMART core, less amount of plutonium will be produced at the end of the cycle (less High-Level radioactive nuclear Waste (HLW) will be produced).

In this study, many different cases and configuration for converting SMART core to the $(U/Th)O_2$ have been surveyed. The calculation procedure that has been used in this study is presented as follows:

- Ensuring from the input data and geometry by comparing BOC results with standard safety analysis report (SSAR) of SMART core.
- Choose a SMART core configuration for comparing different $(U/Th)O_2$ core configurations with this benchmark.
- Considering a set of assumption for $(U/Th)O_2$ core configurations which, according to that, proposed cores have minimum changes in geometry and operational parameters.
- Proposing possible (U/Th)O2 core configurations for SMART core (Figure 6)
- Performing the core calculations at the beginning of cycle and during the cycle for different proposed $(U/Th)O_2$ core configurations to check if the parameters met the criteria.
- Comparison between the results and choose the best configuration that met the assumptions and the criteria.

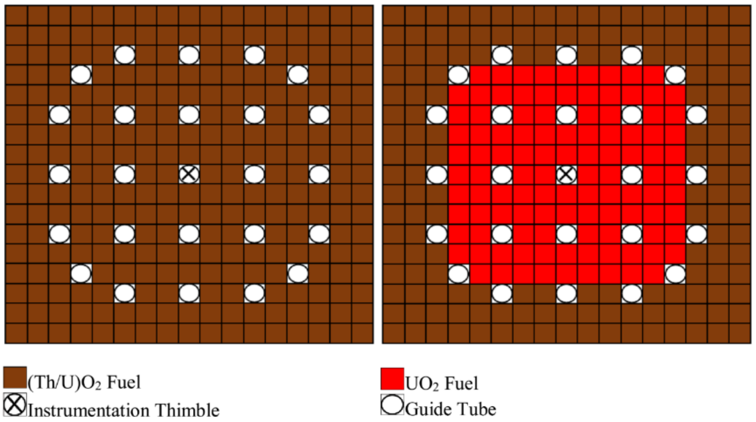
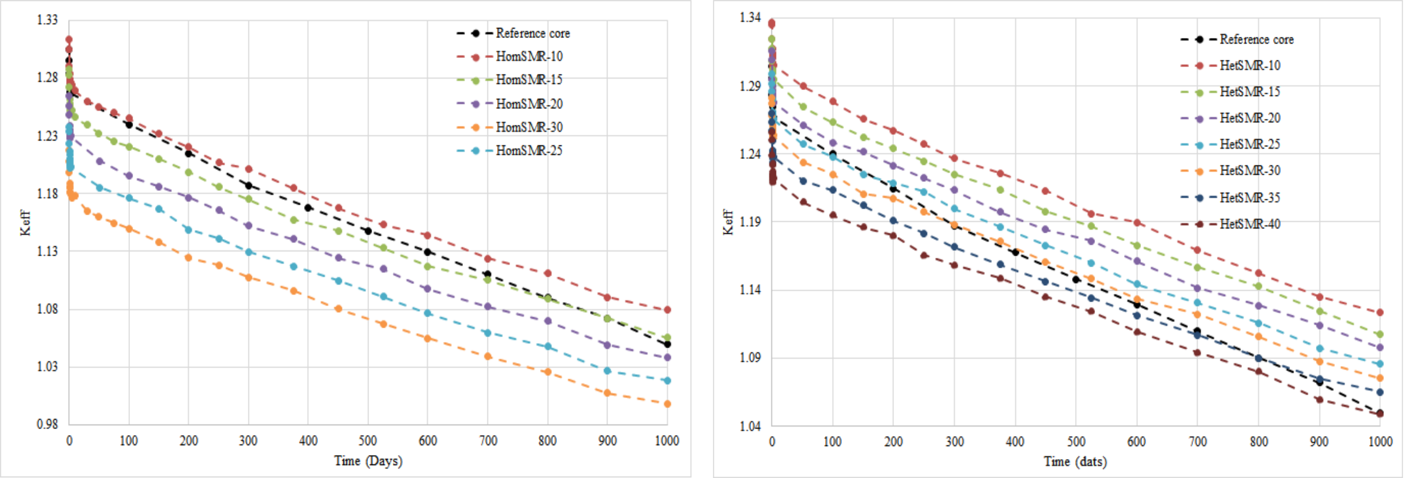


Figure 6: Homogeneous and heterogeneous fuel assembly models.

4 RESULTS

Before starting our main calculations, the input data, geometry and other model needed for our calculation must be verified to see that SMART core has been correctly modelled. Due to this purpose, some test cases that have been presented in SMART SSAR, have been modeled and the MCNP results have been compared by SSAR results. This comparison showed proper match between SSAR and MCNP results.

According to the mass proportion for thorium and uranium different configurations of homogeneous and heterogeneous fuel assemblies have been considered. The results for different mass proportion of homogeneous and heterogeneous configurations in comparison with SMART reference core with same operational parameters and also same number of MCNP histories are shown in Figure 7.



a b

Figure 7: results for different mass proportion of homogeneous (a) and heterogeneous (b) configurations.

By comparing the burnup results between homogeneous and heterogeneous configurations during the cycle, It shows that the heterogeneous configuration with Radkowsky seed and blanket concept satisfy all of our neutronic criteria. One of the main neutronic purpose of this work is to have an extended burnup cycle so between all of the heterogeneous curves, mixed oxide heterogeneous configuration with 35% thorium has been selected to be analysed in next steps. This selected heterogeneous configuration without any control material in the core, is shown in Figure 8.

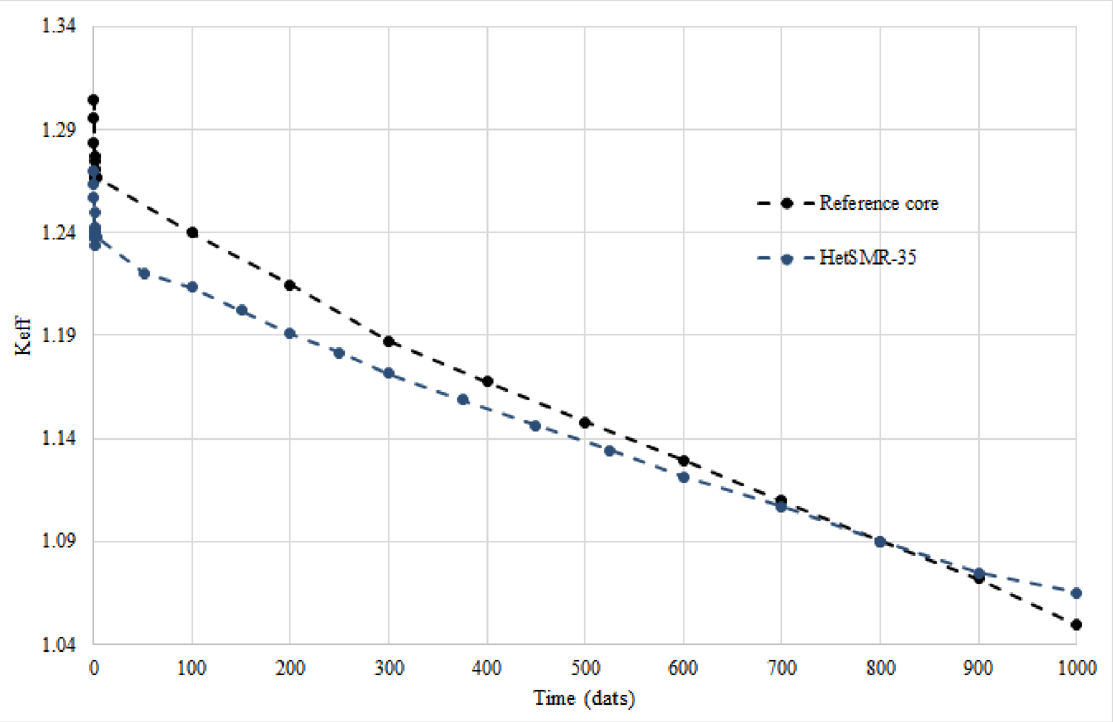


Figure 8: selected heterogeneous configuration by using Thorium.

The next step is using the burnable poison in the core, because even by using thorium in the beginning of the cycle, there is large excess reactivity in the core. By using a part of the burnable absorber for the selected heterogeneous $(Th/U)O_2$ mixed fuel, the K_{eff} changes during the SMART core cycle length, are shown in Figure 9.

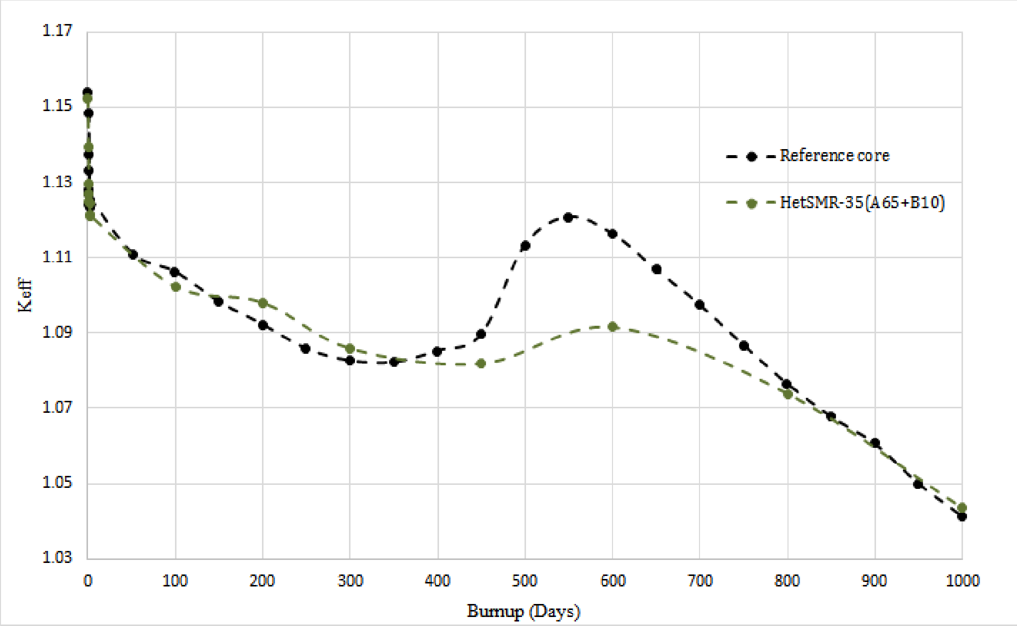


Figure 9. The K_{eff} changes during the cycle for the final selected $(Th/U)O_2$ SMART core.

Table 5 shows the different values of important isotopes for the SMART reference core and mixed oxide heterogeneous configuration [21].

Table 5: The comparison between reference core and (Th-U) O_2 Core.

Parameter	Reference Core		(Th-U) O_2^{***} Core	
	BOC*	EOC**	BOC*	EOC**
UO_2 Mass (kg)	16314	15752	12410	11946
U-235 Mass (kg)	569	268	540	239
U-238 Mass (kg)	13760	13550	10400	10230
ThO_2 Mass (kg)	0	0	3841	3771
Th Mass (kg)	0	0	3376	3312
Pu-239 Mass (kg)	0	81	0	67
U-233 Mass (kg)	0	0	0	38
Avg. Burnup (GWd/MTU)	-----	22.96	-----	23.06
Max. Burnup (GWd/MTU)	-----	24.67	-----	27.18

* Beginning Of the Cycle of first core
** End Of the Cycle of first core
*** 40% ThO_2 + 60% UO_2 for heterogeneous fuel assembly arrangement

5 CONCLUSION

In this work a neutronic assessment to convert a Small Modular Reactor (SMR) with uranium core to the thorium mixed oxide core with minimum possible changes in the geometry and main parameters of SMR core, has been performed. Two different homogeneous and heterogeneous fuel assembly configuration have been evaluated that heterogeneous configuration of $(Th/U)O_2$ fuel shows better neutronic characteristic. By using heterogeneous configuration with Radkowsky seed and blanket concept, the neutronic characteristics of SMART core improve significantly.The final obtained results show that the heterogeneous fuel assembly is the one which gives longer cycle length and used lower amount of burnable poison and soluble boron, and also consumes almost the same amount of U-235.

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