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The utilization of thorium in Small Modular Reactors – Part I: Neutronic assessment

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A B S T R A C T

This work presents 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. This option is due to most of SMR are designed to be strongly poisoned in the beginning of cycle and to have a long cycle. Thorium can be used as an 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 $(Th/U)O_2$ as SMR's fuel. The main neutronic objectives of this study is achieving longer cycle length for SMR by using the minimum possible amount of burnable poison and soluble boron in comparison with reference core. The Korean SMART reactor as a certified design SMR has been chosen as the reference core. The calculations have been performed by MCNP code for homogeneous and heterogeneous seed and blanket concept fuel assemblies. The results obtained 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 ^{235}U.

1. Introduction

During the past decades, most of nuclear power has been produced by water cooled reactors that use UO_2 as fuel in a once through fuel cycle. The high rate of uranium consumes, make the natural resource of this fuel limited to this century even at the high cost of uranium ore (NEA/IAEA, 2016). To increase the utilization of uranium, the plutonium has been already recycled in thermal reactors and it is use as mixed oxide fuel (MOX) of U/Pu in the same reactors (OECD/NEA, 2007). Another option is the utilization of (thorium/uranium) oxide as a mixed fuel.

The natural thorium isotope (^{232}Th) as a fertile fuel can finally be converted to a fissile ^{233}U isotopes after a thermal neutron capture reaction. It has been estimated that thorium is approximately three times more abundant than uranium present in the earth's crust (IAEA, 2000).

Using of Thorium base fuel option in nuclear reactor has many advantages: the highest number of neutrons produced per neutron absorbed among all thermally fissile isotopes; neutron poison (Xenon and Samarium) production is 20% lower than other fissionable isotopes; reducing the radiotoxicity of the spent fuel, and non-proliferation. Besides the neutronic advantages, Thorium oxide (ThO_2) is relatively inert and does not oxidize further, unlike UO_2. It has higher thermal conductivity and lower thermal expansion coefficients compared to UO_2, as well as a much higher melting point (3300 °C). The fission gas release in irradiated nuclear fuels is much lower than in UO_2. These properties tend to improve the nuclear and thermal hydraulic characteristics of Uranium and Thorium mixed oxide fuels compared to current uranium oxide fuels (Kutty et al., 2013).

The thorium fuel has been used in Shippingport reactor core and successfully showed breeding of ^{233}U. The Radkowsky seed and blanket concept (seed is an U/Zr alloy and the blanket is $(Th_{0.9}\text{-}U_{0.1})O_2$) has been used in the last core of the Shippingport reactor with high enriched uranium fuel (HEU) and 1200 effective full power days and final burnup of 60 MWD/kg (Kasten, 1998).

Recently, the feasibility of using Thorium in different kind of reactor has been studied: Tucker et al. (2015, 2018) have studied

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the using of a thorium–plutonium mixed oxide fuel for a Westinghouse-type 17 × 17 PWR; Maiorino et al. (2017a, 2017b, 2014) have investigated the using of (U-Th)O_2 fuel for PWR reactors; Permana et al. (2011) have analyzed the heavy metal closed-cycle water cooled thorium reactor; Lindley et al. (2014) have studied the closed thorium-transuranic fuel cycle in reduced-moderation PWRs and BWRs and Ashely et al. (2014) have modelled the open cycle thorium-fuelled nuclear energy systems. In this work, the possibility of using Thorium fuel for the new type of reactors, that known as Small Modular Reactors (SMRs), will be evaluated.

SMRs aren't a new concept but they are an idea whose time has come. Over the past decade, SMRs have increasingly been recognized as a potential alternative to large-scale nuclear reactors. The International Atomic Energy Agency (IAEA) classifies any nuclear reactor with a power output of less than 300 MWe 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 (IAEA, 2016).

SMRs ("modular" because many of major components can be assembled anywhere far from the sites and then shipped to the main sites) have been getting a lot of positive attention in the recent years, although the nuclear energy industry has tried to be economically viable. SMRs may present many advantages over older technologies including: the possibility to construct in a modular way, reducing up-front capital costs by simpler, less complex power plants. SMRs designs can also bring more efficiency and inherently safe systems. Furthermore, besides electricity generation, SMRs could be used in all energy systems like district heating, co-generation, energy storage, desalination, or hydrogen production.

According to the IAEA report currently, at least 50 SMR designs for different application are under various stages of design, licensing and construction all over the world. Three of these SMRs are under different stages of construction: KLT40s (a floating power unit from Russia), HTR-PM (a high temperature gas cooled reactor from China) and CAREM (an integral PWR from Argentina). These three SMRs are planned to start their operation between 2017 and 2020. Furthermore, the Korean Nuclear Safety and Security Commission approved the Standard Design of the 100 MWe System Integrated Modular Advanced Reactor (SMART). Also, there are many other of SMR designs that will be prepared for near term deployment. According to the IAEA report realistically it seems that the first commercial group of SMRs, start operation near 2025 – 2030. Although, large group deployment of SMRs will only occurred beyond 2030 (IAEA, 2016).

Due to this great interest in developing SMRs, researchers all over the world are trying to survey different aspect of these reactors (Akbari-Jeyhouni et al., 2018; Nian, 2017). Iyer et al. (2014) surveyed the SMRs as a solution for climate changes or Cooper (2014) tried to evaluate the role of the SMRs in the future of nuclear power. Also, there are several researches about safety and thermal hydraulic features of SMRs (Zaman et al., 2017; Li et al., 2017). In this work, we try to introduce an alternative fuel for SMRs fuel. SMR cores are designed to stand for a complete cycle, without the need to be refueled, but they need to be strongly poisoned at the beginning of life. So, since thorium can be used as a poison and also a fertile fuel, it could be a good option to be used as mixed oxide with uranium, and so we could reduce the burnable and soluble poison and also have an extended burnup cycle.

In this study, we used Korean SMART reactor (the SMR reactor that has received design certification (IAEA, 2016)) as the basis of our calculations. An assessment has been performed to achieve 5-year cycle SMART core design using thorium fuel by using more enrichment of uranium (20 wt%) mixed with Thorium and increasing the burnable poison amounts for SMART core design in its conceptual design status (Cho et al., 2000; KAERI/TR-1775, 2001), while in present work, it has been tried to keep the fuel enrichment below 5 wt% and using lower amounts of burnable poison and soluble boron for the final design of SMART core after its licensing stage. 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.

The remainder of the paper is organized as follows. Section 2 presents an overview of the SMART reactor and its operational parameters. In Section 3, the material and methods including calculation procedure, MCNP code, (U/Th)O_2 SMART core configurations and verification of calculations have been presented. Section 4 presents the results of the calculations for different mixed U/Th SMART core configurations that have been compared with reference SMART core and finally, conclusion and remarks are given in Section 5.

2. Description of SMR case

Korean Atomic Energy Research Institute (KAERI) has been developing the system-integrated modular advanced reactor, an advanced integral pressurized water reactor, since 1997. The conceptual and basic designs of SMART with a desalination system were completed in March of 1999 and March of 2002. SMART Pilot Plant and Pre-Project for the SMART were completed in 2006 and 2007, respectively. In July 2012, the Korean Nuclear Safety and Security Commission issued the Standard Design Approval for the SMART (IAEA, 2016).

SMART is expected to be one of the first new Nuclear power plants in the range of 100 MWe, which is a very useful energy for various industrial applications. This SMR has been designed with enough output to meet the fresh water and electricity

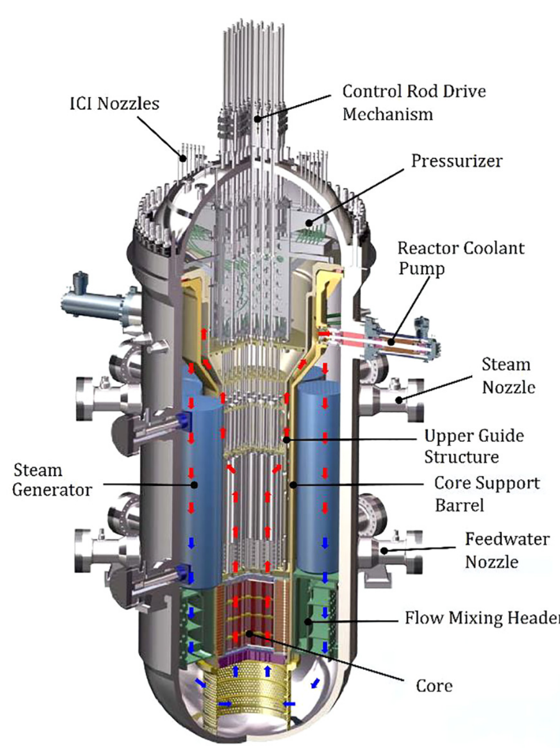

Fig. 1. Schematic view of Korean SMART reactor (IAEA, 2011; Lee, 2010).

demands of a city with one hundred thousand populations. As shown in Fig. 1 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 (IAEA, 2011; Lee, 2010).

The core components which affect the core nuclear characteristics are the fuel assemblies, the fuel rods, the control rods, the burnable absorbers, and the material used in the grids, guide tubes, fuel rod cladding, and the in-core instruments. The main core parameters of SMART have been presented in Table 1 (SMART Report, 2012; SMART SSAR, 2010).

The SMART core is composed of 57 fuel assemblies, with a design and performance based on the 17 × 17 KOFA technology (Seo, 1997), which has been well proven through many years of commercial operations in Korean PWRs. The specification of fuel assembly has been presented in Table 2. Respectively 4.88 and 2.82 w/o 235U enriched uranium dioxide as fuel assembly type A and B are used to provide enough reactivity required for a three-year or 990 effective full power days (EFPD) (IAEA, 2011; Lee, 2010).

Each fuel assembly contains 264 fuel rods with 2.0 m active height, 24 symmetrical guide tubes and one central channel for positioning of control rods and instrumentation. In this reactor Ag-In-Cd is used as 3 banks of regulating rod and two banks of shutdown rods in 25 fuel assemblies as control assembly. Gd_2O_3 mixed with UO_2 is used as an integral fuel burnable absorber (IFBA) to smooth the excess reactivity and power distribution during core cycle. There are different arrangements of IFBA models in the fuel assemblies for the SMART core that are shown in Fig. 2.

The configuration of the SMART core with different type of fuel assemblies is depicted in Fig. 3. Also, description of SMART core configuration included numbers of IFBA and weight percent of Gd_2O_3/UO_2 is presented in Table 3 (SMART Report, 2012; SMART SSAR, 2010).

3. Material and methods

3.1. Calculation procedure

The main purpose of this work is to convert SMART core with uranium fuel to a reactor with mixed uranium–thorium fuel with minimum possible change in the SMART core. To meet this goal, a set of criteria has been assigned to our calculations, including:

1. All core geometry (all fuel, control, burnable absorber and instrument rod diameters and pitch) must be kept fixed.
2. ^{235}U fuel rods must have lower enrichment than 5 w/o. (Enriching the ^{235}U more than 5% for power reactor is not common and economically reasonable, and also it has been one of the main objectives of the SMART designers).
3. Keep temperature coefficient of reactivity negative and near to SMART reference core values.
4. Keep the kinetics parameter value near to SMART reference core values.
5. Keep the fuel cycle length at least 3 Years.

Table 1
The Korean 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 2
The Korean SMART fuel assembly characteristics.

	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

In order to meet these requirements in our works, the following steps have been undertaken respectively:

a. Ensuring from the input data and geometry by comparing BOC results with standard safety analysis report (SSAR) of SMART core in different conditions according to the SMART SSAR.
b. Choose a SMART core configuration for comparing different $(U/Th)O_2$ core configurations with this benchmark. In the parametric study, both the reference SMART core and Th-U core were calculated first without any burn up poison.
c. 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.
d. Proposing possible $(U/Th)O_2$ core configurations for SMART core. For this purpose, two possible fuel assembly arrangement have been considered: homogenous mixed U/Th fuel assemblies and heterogeneous seed-blanket concept with Uranium fuel in the center and mixed U/Th in the outer region of fuel assembly (Fig. 4).
e. 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 and assumptions. In this part due to an enormous amount of calculations a reduced number of histories and simplification will be used.

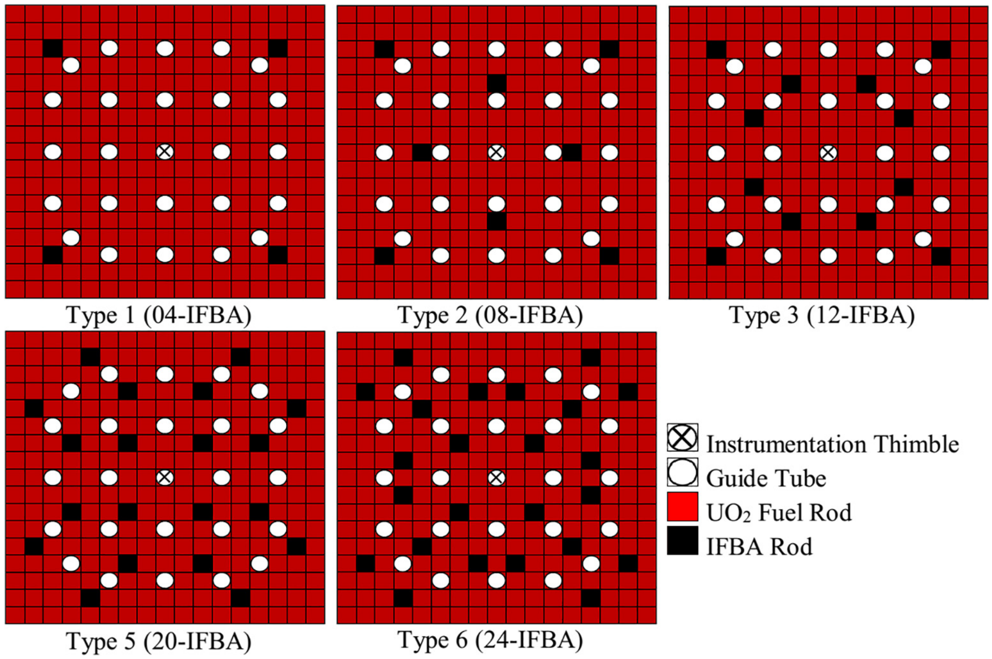

Fig. 2. Different burnable absorber arrangements in the fuel assemblies of the SMART core.

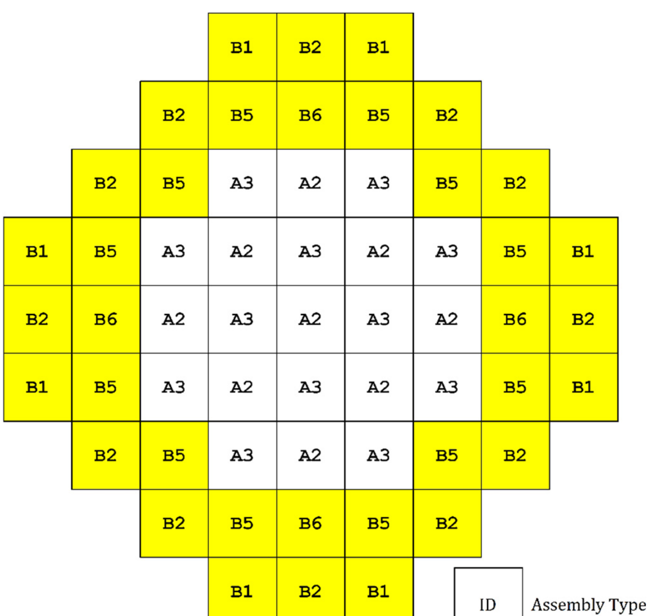

Fig. 3. The Korean SMART core configuration.

f. Comparison between the results and choose the best configuration that met the assumption and the criteria.

Also, to choose the proper $(U/Th)O_2$ SMART core configuration, a set of computational objectives has been assigned as follows:

1. Achieving longer fuel cycle length than reference core,
2. Using less amount of burnable poison than reference core,
3. Using less amount of soluble boron than reference core,
4. Using less amount of ^{235}U than reference SMART core than reference core,
5. Producing some amount of ^{233}U at end of cycle (EOC) than reference core,
6. Producing less amount of plutonium than SMART reference core (to reduce long lived waste isotopes).

3.2. MCNP code

MCNP code has been validated for the calculation of several core parameters in the different type of reactors and is known to be reliable code. In this study this code has been chosen in order to performing calculations, because of its vast capability, including: burnup calculation, effective delayed neutron fraction, reactivity coefficients and flux and multiplication factor for several conditions, such as full power, zero power, cold and hot, with and

Table 3
The Korean SMART core configuration description.

Assembly type	No. of Assemblies	Normal fuel enrichment (w/o 235U)	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

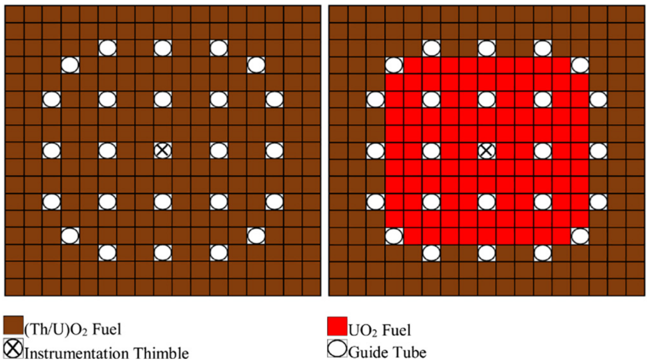

Fig. 4. Homogeneous and heterogeneous fuel assembly models.

without xenon (Briesmeister, 2000). In MCNP code after each steady-state neutron transport calculation, the attained results such as keff, reaction rates, the energy-dependent flux distribution and fission multiplicity is passed to the CINDER90 (activated by BURN card) to perform depletion calculations and generate new number densities at the end of each desired time step (Wilson, 1997), this coupling may be source of some uncertainty in the calculations. For most problems, twenty-five million histories (500 active KCODE cycles of 50,000 histories) were sufficient to obtain a low relative error. In this work, the ENDF/B-VII.0 has been used as MCNP library (Briesmeister, 2000).

3.3. $(U/Th)O_2$ SMART core configurations

In the first step, we used the exact same geometry of SMART core, but without any burnable absorber or soluble boron and performed calculations for this reference SMART core. In the next step we considered two different arrangements of homogeneous and heterogeneous fuel assemblies (Fig. 4). As shown in Fig. 4, heterogeneous configurations have been arranged according to the seed and blanket concept. In the homogeneous configuration all rods have same amount of the U/Th mixed fuel but, in heterogeneous configuration the central fuel rods contain UO_2 and outer region fuel rods in the fuel assembly contain U/Th mixed fuel. As a target we want to the maximum amount of ^{235}U proposed core be same as the reference SMART core to be same as that in the reference SMART core. This forces us to use ^{235}U enrichment lower than 5 w/o, so we used ^{235}U enrichment of 5% in the proposed configurations. Twelve different configurations (7 heterogeneous and 5 homogeneous) have been considered as proposed $(U/Th)O_2$ configurations according to their acceptable values of K_{eff} at the BOC. Tables 4 and 5 show the different mass proportion of U/Th in proposed $(U/Th)O_2$ SMART core configurations for homogeneous and heterogeneous fuel assemblies.

3.4. Verification of calculations

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 (Table 6), have been modeled and the MCNP results have been compared by SSAR results. Also given that this study is mainly depended on the burnup calculations, as an independent procedure, burnup calculation of SMART core during cycle has been performed by deterministic codes (DRAGON/PARCS codes) (Marleau et al., 2016, Downar et al., 2006) and the results have been compared by MCNP code.

The DRAGON code has a collection of models for simulating the neutronic behavior of a unit cell or a fuel lattice in a nuclear reactor. Some capabilities of DRAGON code are as follows: microscopic cross sections interpolation from standard libraries; resonance self-shielding and multigroup neutron flux calculations in multidimensional geometries; transport-diffusion and transport-transport equivalence calculations; and modules for editing condensed and homogenized nuclear properties for reactor calculations. This code uses the collision probability method and also Method of characteristics. The IAEA WLUP microscopic cross section library with 172 group energies has been used in this work for DRAGON code (Marleau et al., 2016).

PARCS code solves the steady state, time-dependent, and multigroup neutron diffusion equation and the SP3 transport equation for performing the core calculations of the boiling and pressurized water, pressurized heavy water and pebble bed reactors. In this study, the two groups homogenized macroscopic cross section for different types of fuel assemblies, obtained from cell calculation (DRAGON code) is fed to the PARCS code input (Downar et al., 2006).

4. Results and discussion

At the beginning, for the verification of the MCNP model, calculation according to the SMART SSAR cases for different core parameters (different temperature and boron concentration) has been performed. These presented cases in Table 6 are based on core configuration showed in Fig. 3. The comparison between SSAR and MCNP results are shown in Table 7. This comparison shows that the MCNP model results are very similar to the SSAR results and can be used for other calculation in the BOC.

For MCNP burnup calculation verification, the SMART core burnup calculations with all normal operation parameters (without considering soluble boron poison), have been performed by MCNP and DRAGON/PARCS codes separately. The attained k_{eff} for the MCNP and DRAGON/PARCS at the EOC is 1.034 and 1.035 respectively. This excess reactivity at the EOC is usually used as power maneuver. The differences between the MCNP and DRAGON/PARCS model results at EOC are acceptable, so the SMART MCNP model during cycle burnup can be used as our calculation model. Comparison between SMART core power peaking factors obtained from DRAGON/PARCS and MCNP codes have been shown in Fig. 5. According to the Fig. 5, the average relative difference of power peaking factors between these two methods is 1.5% that is acceptable. Besides than the using different methods, this difference resulted from the different cross section libraries used by these codes and also this fact that unlike MCNP code, PARCS code can't be used to model the exact geometry of the core (exact fuel assembly, reflectors and etc.).

At first step for feasibility to used Th/U mixed oxide in SMART reactor core, as discussed in section 4, two different configurations of homogeneous and heterogeneous fuel assemblies have been considered. According to the mass proportion for thorium and uranium for homogeneous fuel assembly (Table 4), burnup calculations during the cycle with core parameters same as normal operation but without any Gd_2O_3 burnable absorber or soluble boron, have been performed. The results for different thorium masses for the homogeneous configurations have been compared with those from the SMART reference core, using the same operational parameters and MCNP histories in Fig. 6.

As shown in Fig. 6, in homogeneous configurations, when less than 15% of thorium be replaced with uranium, the core cycle length can be at least same as reference core. On the other hand, if we replace less than 15% amount of uranium with fuel, the ^{235}U weight will be more than ^{235}U weight in the reference SMART

Table 4
The Different mass proportion and Keff at BOC for homogeneous configuration.

Configuration	^{232}Th (w/o)	^{238}U (w/o)	^{235}U (w/o)	O_2 (w/o)	K_{eff} at BOC
HomSMR-10	8.788	75.411	3.919	11.882	1.31079
HomSMR-15	13.182	71.222	3.701	11.895	1.28919
HomSMR-20	17.576	67.032	3.483	11.908	1.26758
HomSMR-25	21.970	62.843	3.266	11.921	1.24364
HomSMR-30	26.364	58.653	3.048	11.935	1.21500

Table 5
The Different mass proportion for heterogeneous configuration.

Configuration	^{232}Th (w/o)	^{238}U (w/o)	^{235}U (w/o)	O_2 (w/o)	K_{eff} at BOC
HetSMR-10	8.788	75.411	3.919	11.882	1.34078
HetSMR-15	13.182	71.222	3.701	11.895	1.32311
HetSMR-20	17.576	67.032	3.483	11.908	1.30963
HetSMR-25	21.970	62.843	3.266	11.921	1.29334
HetSMR-30	26.364	58.653	3.048	11.935	1.28667
HetSMR-35	30.758	54.4638	2.830	11.948	1.27228
HetSMR-40	35.152	50.2743	2.613	11.961	1.25620

Table 6
SMART SSAR cases for the MCNP model verification.

Case	Core temperature (°C)	Boron concentration (ppm)
Case 1	20	0
Case 2	20	3100
Case 3	200	0

Table 7
Comparison between MCNP model results and SMART SSAR.

Case	K_{eff}*	Reactivity*
Case 1	1.241/1.23812	0.194/0.192
Case 2	0.916/0.91063	-0.092/-0.098
Case 3	1.199/1.20558	0.166/0.170

* SSAR/MCNPX.

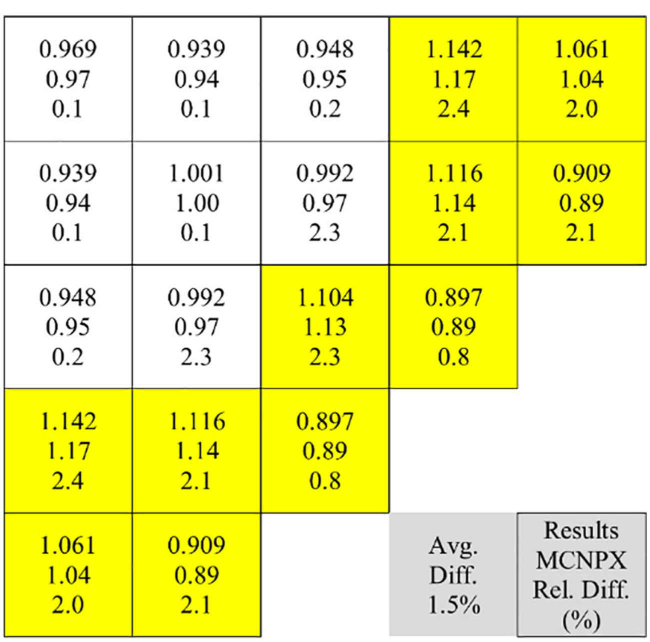

Fig. 5. The Comparison between SMART core PPFs, obtained from DRAGON/PARCS and MCNP codes.

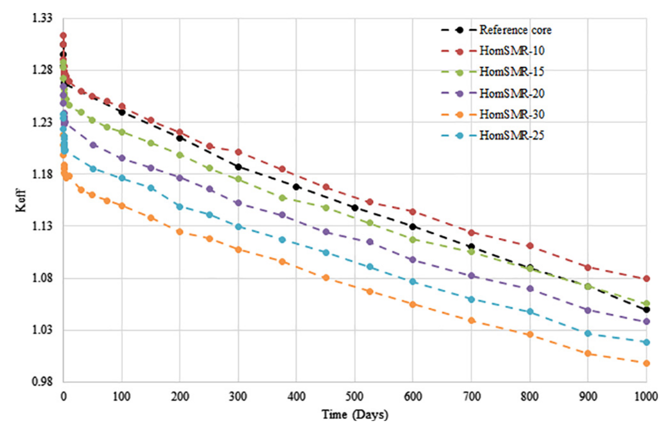

Fig. 6. The burnup results for different mass proportion of homogeneous configurations.

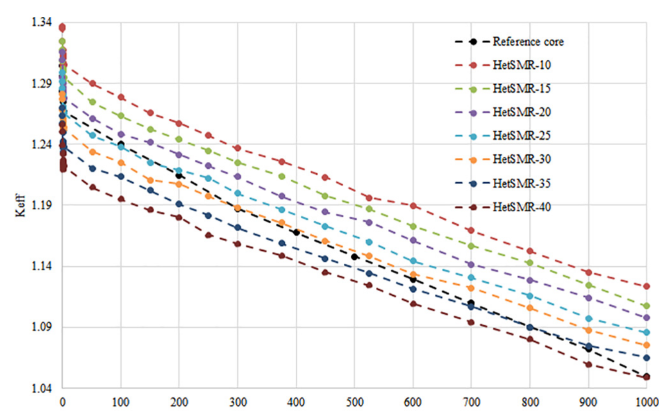

Fig. 7. The burnup results for different mass proportion of heterogeneous configurations.

core that not satisfied our main neutronic criteria. Heterogeneous fuel assembly configuration with different mass proportion (Table 5), is our another option. The burnup calculations for each mass proportion of heterogeneous configuration has been performed and compared with the reference SMART core with same normal operation parameters and without any absorber (Fig. 7).

According to the Fig. 7, the Radkowsky concept that has been used in heterogeneous configuration shows its effect clearly and we can have more excess reactivity than homogeneous with using same amount of Th/U fuel. To be more distinguishable, homogeneous configuration (green curve in Fig. 3) with 600 kg ^{235}U have same burnup cycle as heterogeneous configuration (dark red curve in Fig. 4) with 540 kg ^{235}U, while SMART reference core (black curve in Figs. 6 and 7) with 569 kg ^{235}U, reaches to similar cycle length. Also to make this discussion clearer, Table 8 shows the different values of important isotopes for the reference core and mixed oxide heterogeneous configuration.

According to the previous discussion and Table 8, it's obvious from neutronic sight to choose mixed oxide fuel with heterogeneous configuration. One of the main neutronic purpose of this work is to have an extended burnup cycle so, mixed oxide heterogeneous configuration with 35% thorium has been selected to be analyzed in next steps (Fig. 8).

The BOC excess reactivity for selected $(Th/U)O_2$ is much lower than reference SMART core, but still it's too high to use it, so it's necessary to use some burnable poison. The Thorium has a high neutron capture cross section and in other side, central part of heterogeneous fuel assembly without any burnable absorber will have a too high pin powers. Beside these factors, as an main criteria, we want to have as much as possible minimum change, so the best option is to eliminate the burnable absorber in outer side of heterogeneous fuel assembly (zone with mixed Th/U fuel), and using burnable absorber rods in central zone of fuel assembly with arrangement like reference SMART core.

In this work we just studied neutronic parameters, but power peaking factor (PPF) of fuel assemblies in whole core, also have very important role in the both neutronic and thermal hydraulic performances of the core. We must try to maintain the maximum power peaking factor as low as possible like in the reference SMART core. In SMART reactor, the core has been divided into the two parts by two types of fuel assemblies with two different amounts of ^{235}U. The outer zone of the core has more ^{235}U enrichment than central zone of the core, accordingly we tried to divide the $(Th/U)O_2$ SMART core, into two zones (A and B) with similar ^{235}U weight fraction as reference SMART core. Due to this reason, we tried to distribute selected 35w/o thorium mixed fuel to the different fraction (close to the ^{235}U fraction in reference SMART) between outer and inner zone of the selected $(Th/U)O_2$ SMART core to flatten the power distribution like in the reference SMART core. Fig. 9 shows the results for different fraction of thorium between central and outer zone of the core (this configurations averagely use about 35 w/o thorium).

By checking our main neutronic goals including, achieving the maximum possible cycle length, using the minimum possible amount of burnable poison and also minimum possible amount of soluble boron, the core with 65 and 10 w/o Thorium respectively in zones A and B with averagely near 35 w/o Thorium in the whole core has been selected (Fig. 10). All the UO2 fuel assemblies are been converted to the new (Th/U)O2 fuel assemblies as shown in Fig. 11.

In the new core, the comparison between Figs. 2 and 11 shows that the amount of using Gd_2O_3 as burnable absorber has been reduced considerably in the new core. Also, Fig. 12 shows that the amount of soluble boron has been reduced too.

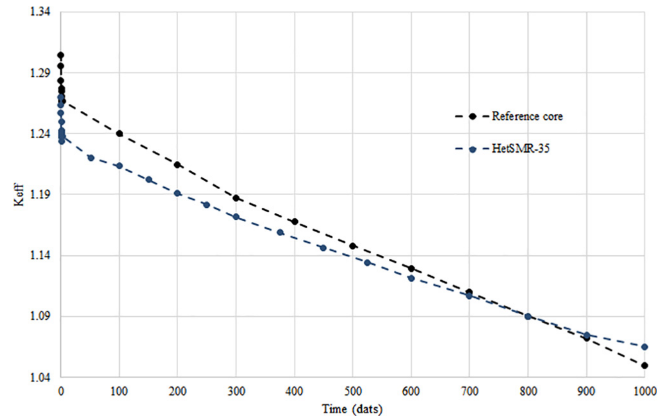

Fig. 8. Comparison between SMART core and selected heterogeneous configuration burnup.

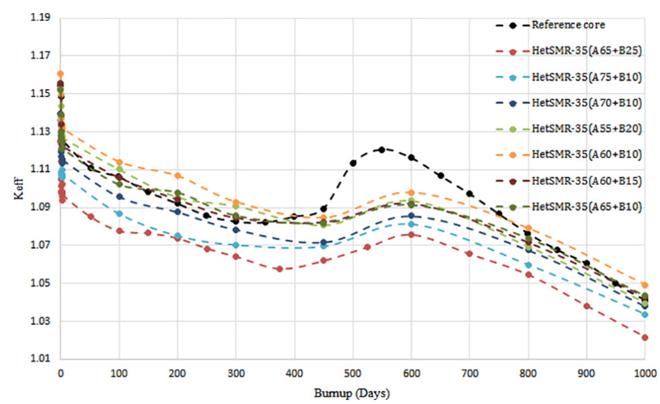

Fig. 9. The burnup results for the different fraction of thorium between central and outer zone of the core.

Table 8
Comparison between reference SMART core and heterogeneous mixed oxide core.

Parameter	Reference Core		(Th-U) O_2*** Core	
	BOC*	EOC**	BOC*	EOC**
UO_2 Mass (kg)	16,314	15,752	12,410	11,946
^{235}U Mass (kg)	569	268	540	239
^{238}U Mass (kg)	13,760	13,550	10,400	10,230
ThO_2 Mass (kg)	0	0	3841	3771
Th Mass (kg)	0	0	3376	3312
^{239}Pu Mass (kg)	0	81	0	67
^{233}U 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.

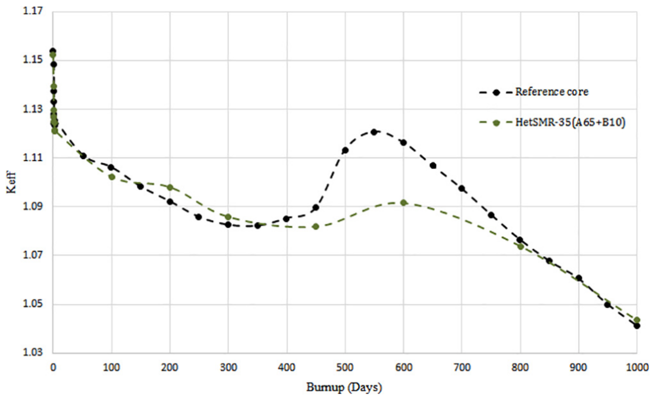

Fig. 10. The burnup calculation of final selected $(Th/U)O_2$ SMART core.

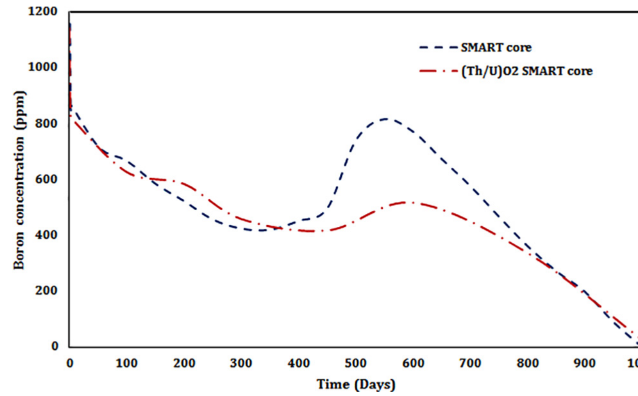

Fig. 12. Soluble boron changes for reference SMART and $(Th/U)O_2$ SMART cores during the cycle.

As a very Important core parameter, the PPFs for the reference core and proposed $(Th/U)O_2$ SMART core have been shown in Figs. 13 and 14. Obviously due to the using a single enrichment for ^{235}U and also using the seed and blanket concept for the fuel assemblies of proposed $(Th/U)O_2$ SMART core, the maximum PPF of the proposed core is higher than reference SMART core but it is still in acceptable range.

The maximum PPF for reference SMART core is 1.19 and in proposed $(Th/U)O_2$ SMART core is 1.31. In the future work for using Thorium mixed fuel in SMART core, it will be tried to improve this parameter and other thermal hydraulic parameters by using neutronic and thermal hydraulic code with applying optimization methods to improve all parameters as much as possible.

The fuel and moderator reactivity coefficients for reference SMART core and proposed $(Th/U)O_2$ SMART core are presented in Table 9. Both fuel and moderator reactivity coefficients for $(Th/U)O_2$ SMART core are negative but less negative than the values for the reference.

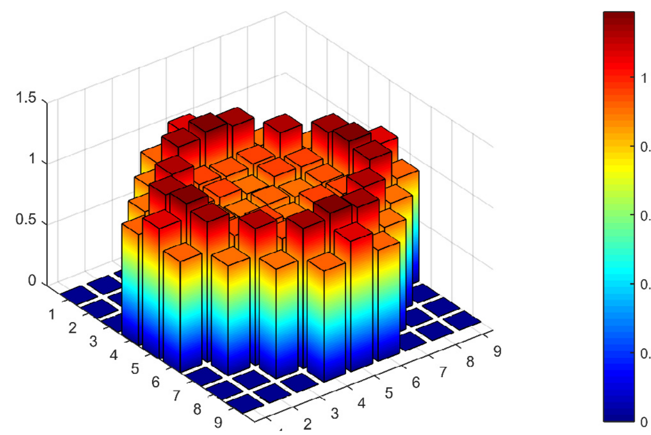

Fig. 13. PPFs of the reference SMART core at the BOC.

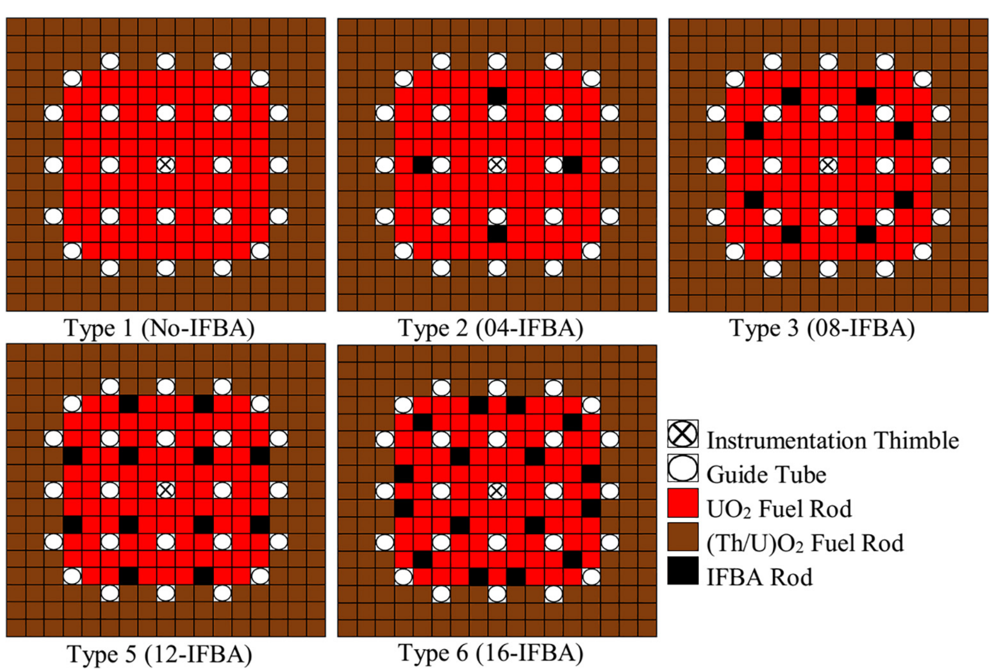

Fig. 11. Different arrangement of Fuel assemblies for proposed $(Th/U)O_2$ SMART core.

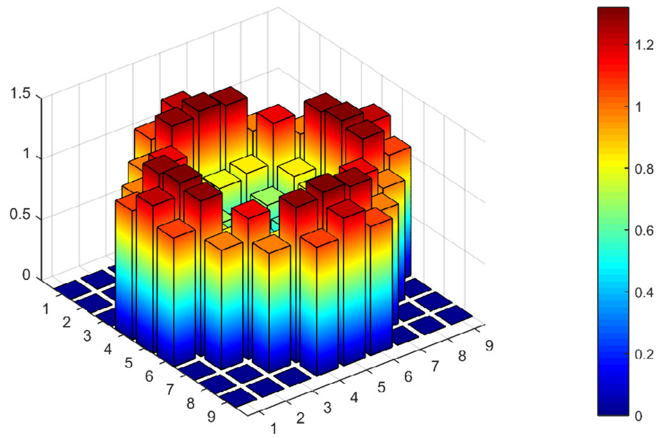

Fig. 14. PPFs of the proposed $(Th/U)O_2$ SMART core at the BOC.

Table 9
Comparison of the reactivity coefficients between SMART reference and $(Th/U)O_2$ cores.

Parameter	SMART	$(Th/U)O_2$ SMART
Doppler reactivity coefficient, α_F (pcm/K)	-4.01 ± 0.18	-3.10 ± 0.19
Moderator reactivity coefficient, α_M (pcm/K)	-7.58 ± 0.59	-5.96 ± 0.61

5. Conclusion

In this study, a neutronic feasibility study to convert Korean Small Modular Reactor (SMART) core with UO_2 fuel to the $(Th/U)O_2$ fuel with minimum possible change in the structure and the main core parameters has been performed. Initial calculations for the core without any poisoning (burnable poison and soluble boron) showed that, for the exact same cycle length as the reference core, $(Th/U)O_2$ heterogeneous configuration uses 5% less amount of ^{235}U while homogeneous configuration uses 5% more amount of ^{235}U in comparison with reference core. After choosing heterogeneous configuration, it has been tried to use near same fraction of ^{235}U between central and outer zone of the core as reference core and also similar burnable poison arrangement in the central zone to maintain the power peaking factors close to those of the reference core. Finally, a mixed fuel core with 65% and 10% thorium respectively in the central and outer zones, has been proposed that has a longer cycle than reference core. In the reference core 680 burnable absorber rods have been used while in the proposed thorium mixed oxide core 388 burnable absorber rods have been used, with a large reduction in the amount of poison material. Analysis of the soluble boron changes during the cycle shows that in the proposed core we can used less amount of soluble boron during the cycle. Finally, neutronic analysis shows that $(Th/U)O_2$ fuel can be used in SMRs as a good fuel option.

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