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NEUTRONIC DESIGN OF SMALL MODULAR LONG-LIFE PRESSURIZED WATER REACTOR USING THORIUM CARBIDE FUEL AT A POWER LEVEL OF 300–500 MWth

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This study presents the neutronic design of a small modular long-life Pressurized Water Reactor (PWR) using thorium carbide fuel with ^{233}U fissile material. The target optimization for this study is a reactor designed to operate for 20 years, with excess reactivity throughout the reactor operational cycle consistently below 1.00 % dk/k. The analysis involves dividing the reactor core into three fuel regions with ^{233}U enrichment levels ranging from 3 % to 8 %, with a 1 % difference for each fuel region. To achieve optimum conditions, ^{231}Pa was randomly added to the fuel. The fuel volume fraction in this design varied from 30 % to 65 %, with a 5 % incremental variation. Power level variations are also studied within the 300–500 MWth with increments of 50 MWth. Calculations were performed using the Standard Reactor Analysis Code (SRAC) program with the PIJ and CITATION modules for cell and core calculations utilizing JENDL-4.0 nuclide data. Neutronic calculations indicate that the fuel with a 60 % volume fraction achieves optimum conditions at a power level of 300 MWth. The best performance was observed with a fuel volume fraction of 65 %, reaching optimum conditions across power levels ranging from 300 to 500 MWth. For the fuel with the best performance, the power density distributions for low and high power levels follow the same pattern radially and axially. The power peaking factor (PPF) for all fuel configurations approaching the optimum conditions remains below two, a safe limit for the PWR. Other neutronic safety parameters, such as the Doppler coefficient and void fraction coefficient, also stay within the safe limits for the PWR, with both values remaining negative throughout the reactor operational cycle

Keywords: thorium, core design, Doppler reactivity, void fraction coefficient, CITATION

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1. Introduction

Nuclear energy is a carbon-emission-free electricity source. Currently, nuclear energy constitutes approximately 10 % of the world's total electricity supply [1]. Pressurized Water Reactors (PWR) are the most widely used nuclear reactors for power generation. In addition to electricity generation, PWR have been utilized in submarines, aircraft carriers, and icebreakers [2]. In their early development, PWR were primarily used for large-scale power generation. However, the current focus of PWR development has shifted towards small-scale power generation, known as Small Modular Reactors (SMR). This reactor type is suitable for remote areas such as small islands or regions far from the main grid. Currently, various PWR-based SMRs are under development, some of which are in the status of conceptual design, basic design, detailed design, and licensed design, and some are even under construction, such as CAREM-25 from Argentina [3]. Long-life SMR are crucial for maintaining a sustainable electricity supply for an extended period in remote areas.

Generally, the widely used fuel for Pressurized Water Reactors (PWR) is UO_2, consisting of the fissile isotope ^{235}U and the fertile isotope ^{238}U. The byproducts of burning this fuel include various minor actinides and other fission products that constitute radioactive waste [4]. This poses a significant challenge for the development of nuclear power plants. In addition, the availability of uranium is expected to become increasingly limited in the future. Another potential hazard is the misuse of plutonium, a fission product of uranium that poses a threat to the security of proliferation [5]. Various studies using alternative fuels, other than traditional UO_2, have been conducted to address these challenges.

One fascinating solution is the replacement of ^{238}U, a fertile material currently used in nuclear reactors, with ^{232}Th [6]. Thorium is a fertile material that can transform into fissile material ^{233}U upon neutron absorption [7]. In the thermal spectrum, the isotope ^{233}U has an η-factor (the ratio of neutrons produced from fission reactions to the number of neutrons absorbed) greater than two [8]. Thorium-based fuels offer several advantages, including a 3–4 times greater abundance of thorium compared to uranium, a higher conversion ratio, and the production of significantly fewer minor actinides. Aside from offering several advantages, thorium-based fuel also faces several technical challenges that need to be addressed to optimize its performance and safety. Among these, the production of ^{233}U from the β- decay of ^{233}Pa, which has a half-life of 27 days, can lead to an increase in reactivity after the reactor is shut down. Additionally, the ^{232}U gamma makes the refabrication of thorium fuel difficult, although this also makes thorium fuel resistant to proliferation [9].

Thorium-based fuel is one of the potential candidates to replace uranium fuel. Besides having numerous advantages, thorium-based fuel also presents several technical challenges that must be overcome for its safe and optimal use. Therefore, studies on using thorium carbide fuel in small modular long-life PWR cores at power levels of 300–500 MWth are relevant and necessary to develop the utilization of thorium-based fuel in these reactors.

2. Literature review and problem statement

Various studies have been conducted on using thorium-based fuels in PWR cores in recent years. The paper [10] conducted further research to ascertain the viability of thorium as fuel in PWR cores. This study compared the thermal-hydraulic performance and solid structure of thorium-based fuels to those of UO_2 fuels. The research results provide a deeper understanding of the potential use of thorium as a fuel in PWR reactors, considering its thermal-hydraulic aspects and solid structure. Using Er_2O_3 as an absorber material also resulted in improved reactivity management and reduced power peaking in the reactor. The neutronic aspects discussed in this paper are limited to the power peaking factor (PPF), actinide inventory, and non-actinide inventory. The paper [11] explored the possibility of converting the UO_2 core of a Westinghouse AP1000 reactor into a (U-Th) O_2 core. The research results indicated advantages compared to the original UO_2 core, including a lower power density while maintaining the same 18-month cycle and reducing the concentration of soluble boron poisons. In this paper, numerous neutronic aspects are discussed, however, the discussion is limited to the use of (U-Th) O_2 fuel for an 18-month cycle. The paper [12] focused on the neutronic assessment of converting a SMR with a reference SMART Korea reactor, which has a uranium core, into a thorium oxide mixed core with minimal changes to the geometry and main parameters of the SMR core. The research findings showed that a heterogeneous fuel assembly provides a longer cycle than a homogeneous fuel assembly. Using fewer burnable poisons and soluble boron effectively achieved longer cycle goals. Using (Th/U) O_2 as fuel also resulted in ^{235}U consumption nearly identical to the reference core. In this paper, the possibility of using (Th/U) O_2 fuel for longer cycles has not been discussed yet.

Various studies examining the performance of thorium-based fuels in PWR cores have also been conducted, including research in the paper [13] focusing on the axial offset (AO) parameter used to monitor the axial power distribution in the reactor core. AO is crucial for the safe operation of nuclear reactors. The research results indicate that using a U-Th fuel assembly in the reactor core produces a more homogenous radial and axial power distribution, enhances core stability, reduces AO, and allows for more flexible reactor operation and increased power output. In this paper, the influence of using U-Th fuel on the change in void reactivity coefficient has not been discussed yet. The paper [5] analyzed the neutron physics properties of duplex micro-heterogeneous fuel combining ThO_2 and UO_2 and compared it with UO_2 fuel in terms of burnup depth, reactivity coefficients, and radioactive waste. The research findings show that using ThO_2-UO_2 duplex fuel results in higher and more economical burnup cycles, with a negative temperature coefficient and a high control rod worth maintaining reactor safety. In addition, it exhibits lower power peaking factors and a more uniform power distribution, making it suitable for reactor operations. In this paper, the fissile material used is ^{235}U contained within UO_2. Furthermore, the paper [14] sought to explain how to achieve ^{233}U breeding in a thorium fuel cycle (Th-^{233}U) by considering several crucial factors. The main parameter analyzed is η, which measures the number of neutrons produced per neutron absorbed in the thorium fuel cycle. The results suggest that the thorium fuel cycle in a PWR reactor could be a promising alternative to address issues such as uranium resource scarcity, nuclear waste management, and nuclear proliferation. However, the results are highly dependent on the moderator-to-fuel ratio and require further consideration of the design parameters based on holistic considerations.

In addition to the utilization of thorium-based fuels in standard PWR cores and research on the performance of such fuels, various studies on the utilization of thorium-based fuels in conceptual PWR cores have also been conducted. Among them, the paper [15] explored the potential use of (Th, U) O_2 fuel in designing a nuclear reactor with low power density capable of providing a 15-year reactor core to propel a container ship with a power requirement of 110 MWe. The research results indicate that, although the reactor core design with (Th, U) O_2 fuel exhibits neutronic characteristics similar to UO_2 fuel design, (Th, U) O_2 fuel experiences a decrease in thermal performance and worse irradiation behavior. This research has significant implications when considering using (Th, U) O_2 fuel in nuclear reactors with low power density. In this paper, the fissile material used is ^{235}U, and the possibility of using thorium carbide and nitride fuel has not been discussed yet. The paper [16] conducted research focused on developing a small PWR core with a long lifespan, loaded with thorium fuel and ^{231}Pa as a burnable poison to control reactivity. The research resulted in a small PWR reactor designed for up to 10 years with excess reactivity below 1.00 % dk/k. The neutronic aspects discussed in this paper are limited to reactor criticality and power density. The paper [17] focused on the comparison of thorium nitride (ThN) and uranium nitride (UN) fuels in the context of a Small Modular Pressurized Water Reactor (PWR). The research findings indicate that ThN fuel is more suitable for PWR reactors because it has a smaller excess reactivity value and can operate for 10 years without refueling. In this paper, neutronic calculations are only performed at the power level of 300 MWth and no analysis has been conducted at higher power levels yet.

From papers [10–17], most focus on using thorium dioxide (ThO_2) fuel to replace standard UO_2 fuel. The discussion also covers the use of thorium nitride (ThN) fuel. Another type of fuel that is also potentially developable is carbide fuel. Like nitride fuel, carbide fuel also possesses high density, melting point, and excellent thermal conductivity compared to oxide fuel [18]. Therefore, neutronic studies regarding using thorium carbide (ThC) based fuel in small modular long-life PWR cores are crucial to conduct. This investigation is necessary to evaluate the neutronic performance of this fuel in the analyzed reactor core.

3. The aim and objectives of the study

The aim of this study is to conduct a neutronic design of a small modular long-life PWR with thorium carbide fuel capable of operating for 20 years with excess reactivity throughout the cycle of less than 1.00% dk/k at a power level of 300–500 MWth.

To achieve this aim, the following objectives are accomplished:

– to determine the fuel configuration with the optimum effective multiplication factor (K_{eff});

– to analyze power density distribution;

– to calculate the Power Peaking Factor (PPF);

– to calculate the Doppler coefficient and void reactivity coefficient;

– to analyze burnup level.

4. Materials and methods

The object of this research is the small modular long-life PWR fueled by thorium carbide. This study hypothesizes that the (Th-^{233}U)C fuel has better neutronic characteristics than standard uranium fuel when used in a small modular long-life PWR-type reactor. Since (Th-^{233}U)C has superior neutronic characteristics, it is possible to assume the reactor can operate for 20 years with excess reactivity below 1.00 % dk/k. This study focuses on performing neutronic analysis using the Standard Reactor Analysis Code (SRAC) 2006.

The fuel cells used in the calculations are square-shaped, as shown in Fig. 1, with a pitch distance of 1.40 cm. In addition to containing ^{232}Th and ^{233}U, the fuel cell area also includes ^{231}Pa, a burnable absorber.

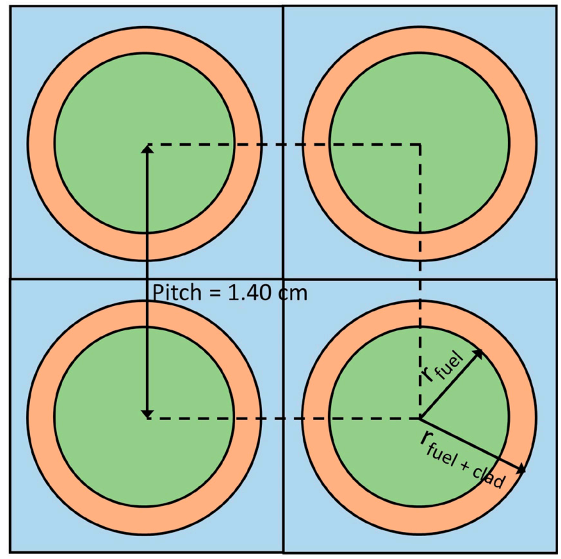


Fig. 1. Fuel cell arrangement

At the reactor core level, let's simplify by employing a cylinder model with a two-dimensional cross-sectional segment of the reactor core, referred to as the R-Z geometry. In reactor core level calculations, the R-Z geometry is utilized by dividing the core into three fuel regions with a 1 % difference in ^{233}U enrichment between regions (heterogeneous core), as illustrated in Fig. 2. The core configuration is designed by placing the fuel region with the lowest ^{233}U enrichment closest to the reactor core center (F1) and the fuel with the highest ^{233}U enrichment closest to the reflector (F3) [19]. As a result, F2 represents the fuel region with ^{233}U enrichment between F1 and F3. This study explores four types of heterogeneous cores, including 3–4–5 %, 4–5–6 %, 5–6–7 %, and 6–7–8 % ^{233}U. Table 1 presents the design parameters of the small modular long-life PWR under investigation.

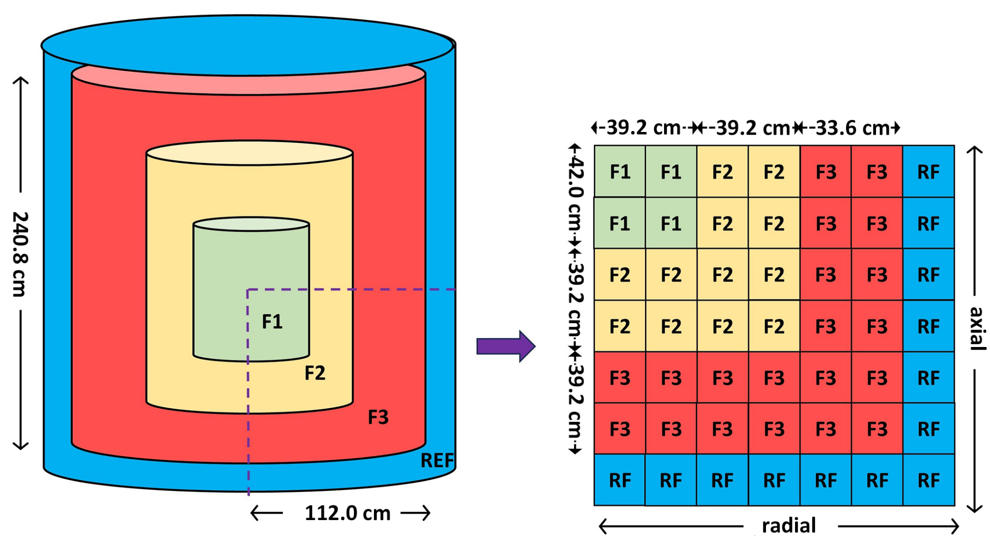


Fig. 2. Small long-life PWR core configuration

Table 1

Small modular long-life PWR design parameters

Parameters	Specification
Thermal power reactors (MWth)	300–500
Fuel	(Th-^{233}U)C
Cladding structure	Zircaloy-4
Coolant	H_2O
Reflector	Stainless steel and H_20
Fuel cell geometry	Square cell
^{233}U percentage (%)	3–8
Fuel volume fraction (%)	30–65
Cladding density (g/cm^3)	6.5
Cladding thickness (cm)	0.057
Coolant density (g/cm^3)	0.72
Pin pitch (cm)	1.4 cm
Active core diameter (cm)	224.0 cm
Active core height (cm)	240.8 cm

In this study, the SRAC software for neutronic calculations is utilized. The PIJ module is employed at the fuel cell level, operating based on the Collision Probability Method (CPM) and providing neutron flux, macroscopic, and microscopic cross-section data as the calculation results. The CITATION module, operating based on multigroup diffusion equations, utilizes these calculations at the core level. Let's use JENDL 4.0 as the nuclear data library source for these calculations. Fig. 3 provides an overview of the calculation system using SRAC [20].

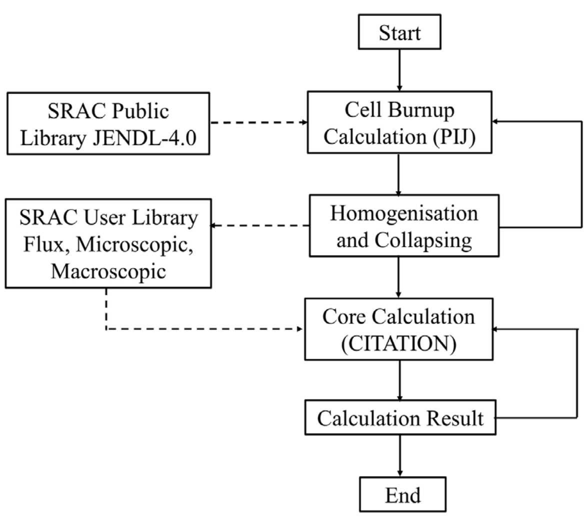


Fig. 3. Calculation scheme of Standard Reactor Analysis Code

In this study, the reactor power level is varied from 300 to 500 MWth with a 50 MWth increment. Additionally, it is possible to explore variations in the fuel volume fraction, ranging from 30 % to 65 % in 5 % increments. Changes in the power level and fuel volume fraction significantly impact the reactor's ability to maintain critical conditions per the optimum target. Therefore, ^{231}Pa was randomly added to each configuration to obtain optimal values. In addition to the effective multiplication factor (K_{eff}), several neutronic aspects investigated in this study include power density distribution, power peaking factor, void reactivity coefficient, Doppler coefficient, and burnup level.

5. Results of neutronic design of small modular long-life PWR using thorium carbide fuel

5. 1. Determining the fuel configuration with the optimum effective multiplication factor (K_{eff})

K_{eff} values were calculated for five different power level variations by varying the fuel volume fraction and using ^{231}Pa as a burnable absorber to control reactivity. This study aimed to determine the optimum condition for the reactor to remain in a critical state for 20 years, with excess reactivity consistently below 1.00 % dk/k. The results of these calculations, at a power level of 300 MWth, are presented in Fig. 4. It is evident from the figure that fuels with volume fractions of 60 % and 65 % are capable of achieving the optimum conditions. Fuels with volume fractions of 50 % and 55 % also approach the optimum condition, with maximum excess reactivity slightly exceeding 1.00 % dk/k.

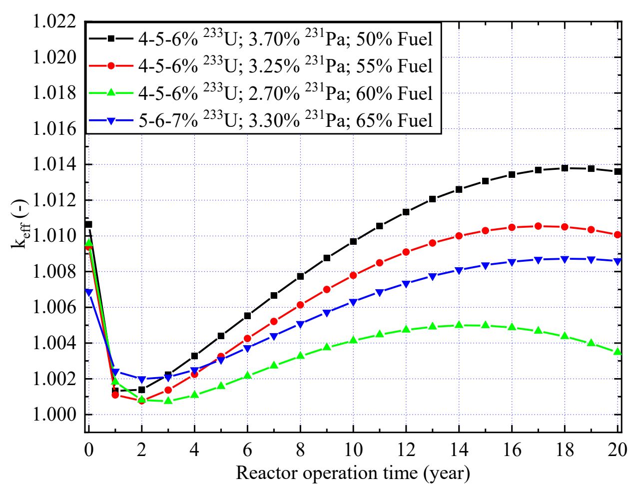


Fig. 4. The effective multiplication factor (K_{eff}) for small modular long-life PWR with (Th-^{233}U)C fuel at power level 300 MWth

Fig. 5 shows the calculation results of K_{eff} at a power level of 350 MWth. At this power level, the fuel with a volume fraction of 65 % can achieve the optimum conditions. Meanwhile, fuel with a volume fraction of 50 %, 55 %, and 60 % can sustain critical conditions for 20 years but with a maximum excess reactivity slightly exceeding 1.00 % dk/k.

Fig. 6, 7 show the calculation results of K_{eff} at 400 and 450 MWth power levels. The K_{eff} calculation results at both the power levels exhibited a similar pattern. At power levels of 400 and 450 MWth, only fuel with a volume fraction of 65 % can achieve the optimum condition. Meanwhile, others can sustain critical conditions for 20 years but with a maximum excess reactivity slightly exceeding 1.00 % dk/k. Even for fuel with a volume fraction of 60 %, a larger fissile material is required with a configuration of 5–6–7 % ^{233}U to achieve critical conditions for up to 20 years.

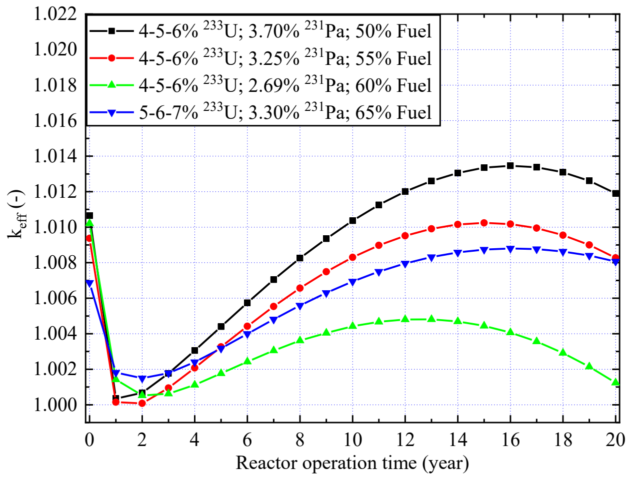


Fig. 5. The effective multiplication factor (K_{eff}) for small modular long-life PWR with (Th-^{233}U)C fuel at power level 350 MWth

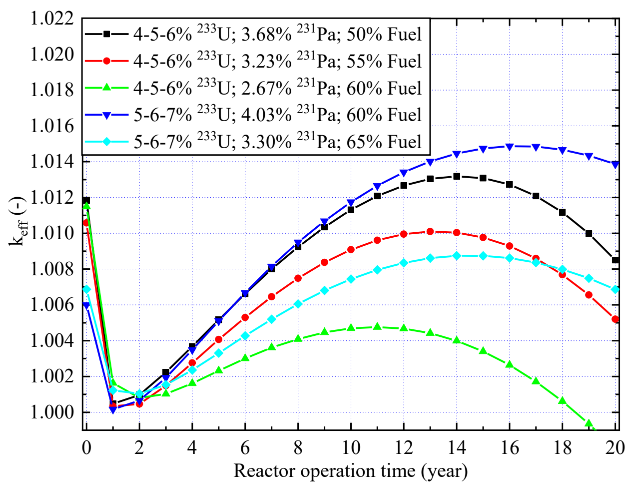


Fig. 6. The effective multiplication factor (K_{eff}) for small modular long-life PWR with (Th-^{233}U)C fuel at power level 400 MWth

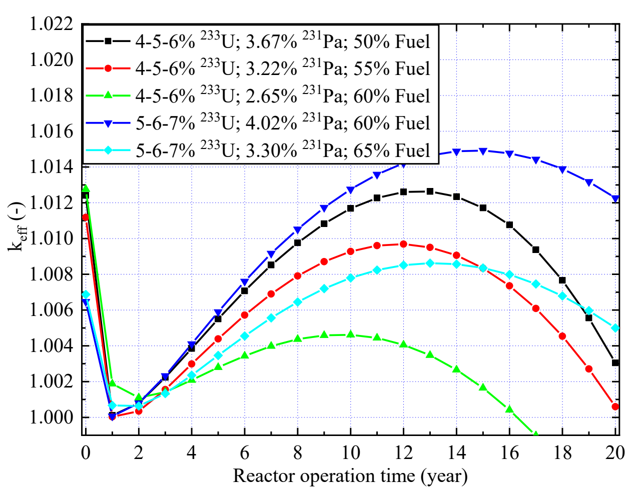


Fig. 7. The effective multiplication factor (K_{eff}) for small modular long-life PWR with (Th-^{233}U)C fuel at power level 450 MWth

Fig. 8 shows the calculation results of K_{eff} at a power level of 500 MWth. Only a fuel volume fraction of 65 % achieved the optimum condition at this power level. Fuel with a volume fraction of 60 % can sustain critical conditions for 20 years but with a maximum excess reactivity exceeding 1.00 % dk/k. Configurations with other fuel volume fractions cannot achieve critical conditions for 20 years, with excess reactivity approaching 1.00 % dk/k.

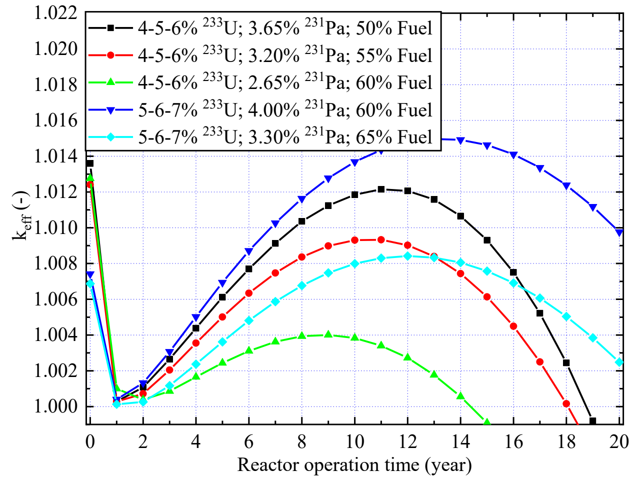


Fig. 8. The effective multiplication factor (K_{eff}) for small modular long-life PWR with (Th-^{233}U)C fuel at power level 500 MWth

Table 2 shows the calculation results of the excess reactivity approaching the optimum conditions at the five power levels. This table provides comprehensive information about the ^{233}U enrichment configuration in the fuel and the percentage of added ^{231}Pa. The table shows excess reactivity at the beginning of life (BOL), end of life (EOL), and maximum excess reactivity conditions.

Table 2

The calculation results of excess reactivity

Power (MWth)	%^{233}U	%^{231}Pa	Fuel Fraction (%)	Excess reactivity (% dk/k)		
				BOL	EOL	Maximum
300	4–5–6	3.25	55	0.93	1.00	1.04
300	4–5–6	2.70	60	0.95	0.35	0.95
300	5–6–7	3.30	65	0.68	0.85	0.86
350	4–5–6	3.25	55	0.93	0.82	1.01
350	4–5–6	2.69	60	1.01	0.12	1.01
350	5–6–7	3.30	65	0.68	0.80	0.87
400	4–5–6	3.23	55	1.05	0.52	1.05
400	5–6–7	3.30	65	0.68	0.68	0.87
450	5–6–7	3.30	65	0.68	0.50	0.85
500	5–6–7	3.30	65	0.68	0.25	0.83

Table 2 shows that fuel with a volume fraction of 65 % can achieve critical conditions for 20 years with excess reactivity below 1.00 % dk/k for all power levels from 300 to 500 MWth. Fuel with a fuel volume fraction of 60 % can also achieve critical conditions for 20 years with excess reactivity below 1.00 % dk/k for power levels of 300 MWth.

5. 2. Analysis of power density distribution

Using the CITATION module, power density distribution values were obtained from the small modular long-life PWR core calculations. In this section, only the power density distributions at the lowest power level, i. e., 300 MWth, and the highest power level, i.e., 500 MWth, are presented in Fig. 9, 10, respectively. These two power levels adequately represent the power density distribution for all five power levels, exhibiting similar patterns both radially and axially. The difference lies in the power density values that correspond to the power levels used in the calculations.

In Fig. 9, *a* and Fig. 10, *b* the radial power density patterns for the 300 and 500 MWth power levels appear identical. Radially, the peaks of power density, which mark the boundaries between the fuel regions F1, F2, F3, and the reflector, are more pronounced at the 500 MWth power level. At both power levels, it is evident that the highest power density distribution occurs radially at the end of life (EOL), particularly in regions F1 and F2. In region F3, the power density values at the medium of life (MOL) started to rise, approaching the values at EOL. Meanwhile, the power density at the beginning of life (BOL) remained at its lowest level.

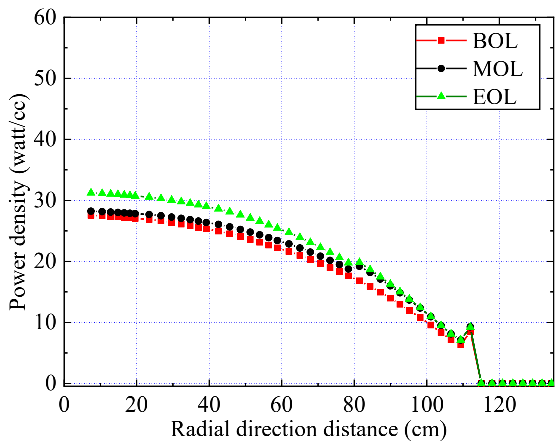
In Fig. 9, *b* and Fig. 10, *b* the axial power density distribution for the 300 and 500 MWth power levels also exhibits a similar pattern. Axially, the peaks of the power density were more distinct for both power levels. In regions F1 and F2, the highest power density peaks occurred at EOL, followed by MOL, and the lowest power density values occurred at BOL. However, in region F3, the highest power density occurs at BOL, followed by MOL, and the lowest at EOL.

There are several clear peaks of power density in the axial direction. These peaks represent the boundary areas between fuel regions F1 and F2, F2 and F3, and F3 and the reflector. Outside the fuel regions, the power density approaches zero.

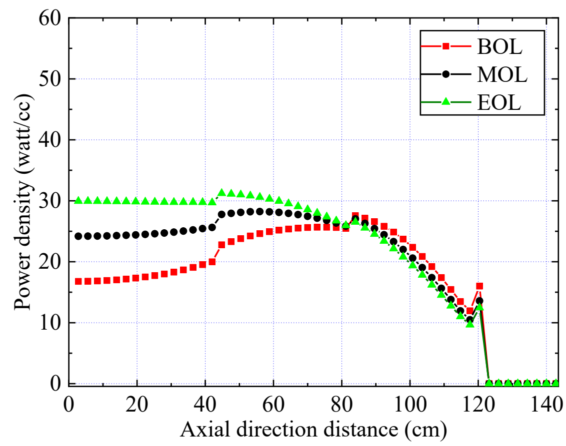
5. 3. Calculation of power peaking factor

The Power Peaking Factor (PPF), which represents the ratio of the maximum power density to the average power density, was obtained from the calculations using the CITATION module. Observing Table 3 reveals that the radial PPF values are consistently higher than the axial PPF values for all fuel configurations and power levels that achieved the optimum conditions.

Table 3 shows that the highest PPF value occurs radially in the fuel configuration of 5–6–7 % ^{233}U with a fuel volume fraction of 65 % at a power level of 400 MWth, reaching 1.70. The average PPF value for all conditions across all displayed fuel configurations approaches 1.40. Generally, the PPF values for the designed small modular long-life PWR remain within the safe limits, as they are well below two.

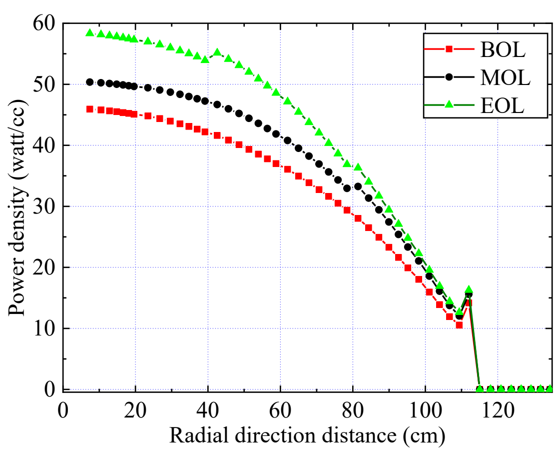


a

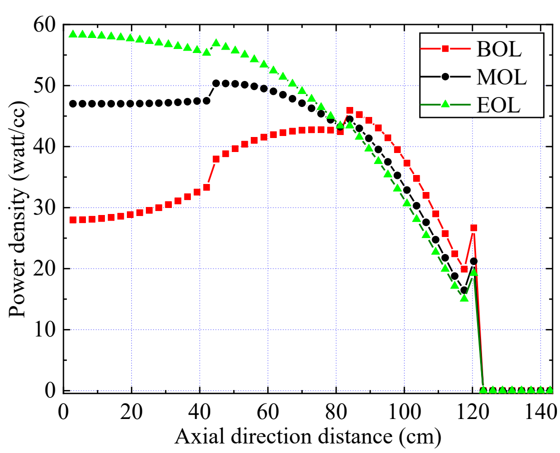


b

Fig. 9. Power density distribution for (Th-^{233}U)C fuel at 5–6–7 % ^{233}U, 3.30 % ^{231}Pa, fuel volume fraction of 65 %, and power level 300 MWth; *a* – radial direction; *b* – axial direction (1 mesh=2.80 cm)



a



b

Fig. 10. Power density distribution for (Th-^{233}U)C fuel at 5–6–7 % ^{233}U, 3.30 % ^{231}Pa, fuel volume fraction of 65 %, and power level 500 MWth; *a* – radial direction; *b* – axial direction (1 mesh=2.80 cm)

Table 3

The calculation result of power peaking factor

Power (MWth)	$\%^{233}U$	$\%^{231}Pa$	Fuel Fraction (%)	BOL		MOL		EOL	
				Radial	Axial	Radial	Axial	Radial	Axial
300	4–5–6	3.25	55	1.59	1.43	1.54	1.18	1.66	1.21
300	4–5–6	2.70	60	1.60	1.40	1.55	1.18	1.64	1.21
300	5–6–7	3.30	65	1.64	1.31	1.56	1.18	1.63	1.20
350	4–5–6	3.25	55	1.59	1.43	1.55	1.18	1.57	1.23
350	4–5–6	2.69	60	1.60	1.40	1.56	1.18	1.68	1.22
350	5–6–7	3.30	65	1.64	1.31	1.57	1.18	1.67	1.21
400	4–5–6	3.23	55	1.59	1.43	1.57	1.18	1.63	1.26
400	5–6–7	3.30	65	1.64	1.31	1.57	1.19	1.70	1.22
450	5–6–7	3.30	65	1.64	1.31	1.60	1.19	1.60	1.24
500	5–6–7	3.30	65	1.64	1.31	1.59	1.19	1.64	1.26

5. 4. Calculations of Doppler coefficient and void reactivity coefficient

The Doppler coefficient is the ratio of the reactivity change to the average fuel-temperature change. In this study, the Doppler coefficient was determined by raising the fuel temperature by 100 K, then calculating the reactivity change and comparing it to the fuel temperature change. Designers typically ensure that nuclear reactors have negative Doppler coefficients because the Doppler coefficient is a key element in reactor safety, used to assess the feedback reactivity effects [21].

Fig. 11 shows the results of Doppler coefficient calculations for a fuel configuration with 5–6–7 % ^{233}U, 3.30 % ^{231}Pa, and a fuel volume fraction of 65 % for all evaluated power levels in the calculation. The selection of this fuel configuration as a representative for Doppler coefficient calculations is because this fuel configuration has optimum criticality conditions at all power levels.

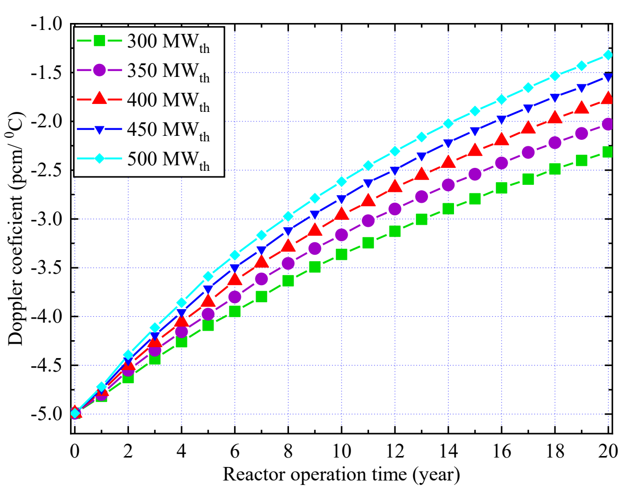


Fig. 11. Doppler coefficient of (Th-^{233}U)C fuel at 5–7–7 % ^{233}U, 3.30 % ^{231}Pa, and fuel volume fraction of 65 %

In Fig. 11, the calculated Doppler coefficient values are presented for fuel with an enrichment configuration of 5–6–7 % ^{233}U and a fuel volume fraction of 65 %, with the addition of ^{231}Pa at a rate of 3.30 % for all power levels ranging from 300 to 500 MWth. This fuel configuration can achieve the optimum conditions for all power levels. As the power level increases, the reduction in the negative value of the Doppler coefficient becomes more significant.

The void reactivity coefficient (α_v) is the ratio of the reactivity difference when a void occurs to the non-void reactivity to the percentage of voids. Similar to the Doppler coefficient, α_v of a nuclear reactor is also designed to be negative. If a reactor has a void percentage of 20 %, 80 % of the coolant volume remains. Table 4 presents the calculation results for α_v.

Table 4

Void reactivity coefficient for the (Th-^{233}U)C fuel at 5–6–7 % ^{233}U, 3.30 % ^{231}Pa, and fuel volume fraction of 65 %

% Void	300 MWth			400 MWth			500 MWth		
	α_v (dk/k/%volume)			α_v (dk/k/%volume)			α_v (dk/k/%volume)		
	BOL	MOL	EOL	BOL	MOL	EOL	BOL	MOL	EOL
1	–0.16	–0.11	–0.08	–0.16	–0.10	–0.07	–0.16	–0.09	–0.06
2	–0.16	–0.11	–0.08	–0.16	–0.10	–0.07	–0.16	–0.09	–0.06
3	–0.16	–0.11	–0.08	–0.16	–0.10	–0.07	–0.16	–0.09	–0.06
4	–0.16	–0.11	–0.08	–0.16	–0.10	–0.07	–0.16	–0.09	–0.06
5	–0.16	–0.11	–0.08	–0.16	–0.10	–0.07	–0.16	–0.09	–0.06
10	–0.17	–0.12	–0.09	–0.17	–0.10	–0.07	–0.17	–0.09	–0.06
20	–0.18	–0.12	–0.09	–0.18	–0.11	–0.07	–0.18	–0.10	–0.06
50	–0.22	–0.14	–0.10	–0.22	–0.12	–0.07	–0.22	–0.11	–0.06
70	–0.25	–0.15	–0.10	–0.25	–0.13	–0.07	–0.25	–0.11	–0.05

Table 4 shows the calculated α_v with an enrichment configuration of 5–6–7 % ^{233}U and a fuel volume fraction of 65 %, with the addition of ^{231}Pa at a rate of 3.30 % for power levels of 300, 400, and 500 MWth. At BOL conditions, it is possible to observe that the α_v value becomes more negative with an increase in the void percentage. As the reactor power level increased, there was a decrease in the negative α_v values under MOL and EOL conditions.

5. 5. Analysis of burnup level

Fig. 12, 13 depict the variation in burnup levels based on the fuel volume fraction for 300 MWth and 500 MWth power levels. Observing the decrease in fuel volume fraction, one can note an increase in the burnup level. Fig. 12, 13 show that fuel with a 50 % volume fraction has the highest burnup level, whereas fuel with a 65 % volume fraction has the lowest burnup level. The burnup level also increased with increasing power level, as shown in Fig. 14.

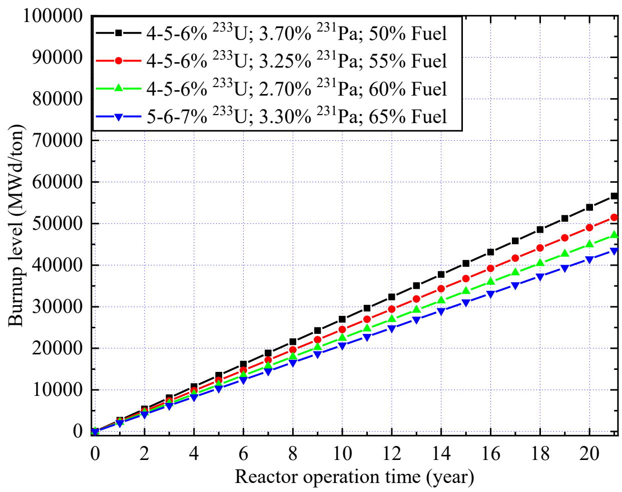


Fig. 12. Burnup level of (Th-^{233}U)C at 300 MWth power

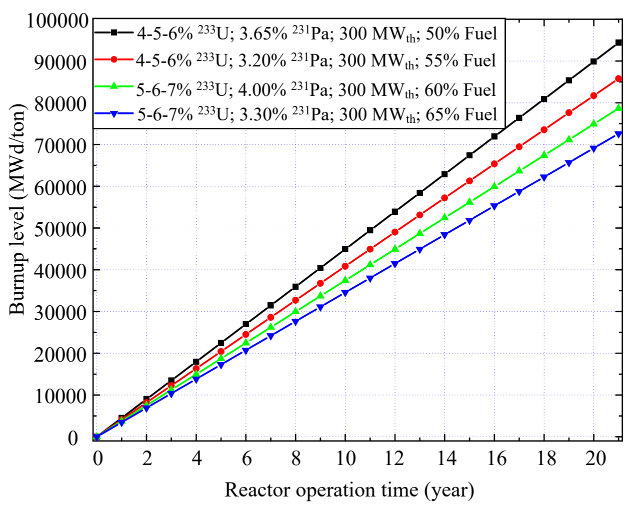


Fig. 13. Burnup level of (Th-^{233}U)C at 500 MWth power

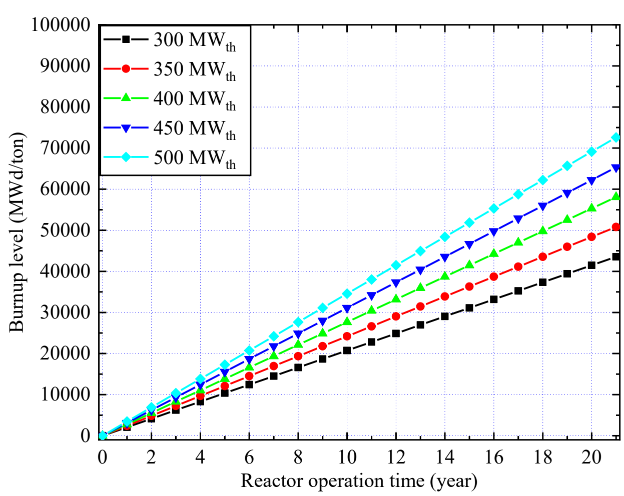


Fig. 14. Burn level of (Th-^{233}U) C fuel at 5–6–7 % ^{233}U, 3.30% ^{231}Pa, and fuel volume fraction of 65 % with varying power levels

Among all fuel configurations capable of achieving critical conditions for 20 years with excess reactivity below 1.00 % dk/k, the highest burnup level is found in the fuel with a fuel volume fraction of 65 %, with a configuration of 5–6–7 % ^{233}U and 3.30 % ^{231}Pa. This fuel configuration can achieve a burnup level of 72.60 GWD/ton.

6. Discussion of the neutronic design of small modular long-life PWR using thorium carbide fuel

The optimum target of the neutronic design for small modular long-life PWR is for the reactor to operate for 20 years without refuelling with excess reactivity of less than 1.00 % dk/k. The maximum limit of this excess reactivity is aimed at enhancing neutronic safety. Previously, [16] also achieved a similar optimum condition for a shorter reactor operating time of 10 years.

The calculation results of K_{eff} in Fig. 4–8 indicate that the best performance is achieved with fuel configured with 5–6–7 % ^{233}U enrichment, 3.30 % addition of ^{231}Pa, and a fuel volume fraction of 65 %. This fuel can reach the optimum conditions for all power levels from 300 to 500 MWth. Fuel with a configuration of 4–5–6 % ^{233}U, an addition of ^{231}Pa at 2.70 %, a fuel volume fraction of 60 %, and a power level of 300 MWth is another fuel arrangement capable of achieving optimum conditions in the small modular long-life PWR core. The calculations reveal that fuels with ^{233}U enrichment less than 4–5–6 % or more than 5–6–7 % are challenging to approach the desired optimum conditions. If the amount of fissile material ^{233}U is too low, the reactor cannot reach critical conditions throughout the 20-year operational cycle.

Conversely, if there is an excess of fissile material, the excess reactivity increases. The calculations indicate that (Th-^{233}U)C with a fuel volume fraction of less than 50 % cannot approach the desired optimum conditions. At fuel volume fractions lower than 50 %, the reactivity at the BOL will be higher but quickly decrease, preventing the reactor from reaching critical conditions throughout the operational cycle.

The power density distribution patterns depicted in Fig. 9, 10 for 300 and 500 MWth power levels are identical in axial and radial structure. Peaks in the power density emerge at each boundary between the fuel regions and reflectors. These peaks occurred because of the increase in ^{233}U enrichment from the core center to the reflector. Radially, the power density distributions for the BOL, MOL, and EOL conditions appear more uniform than the power density distribution in the axial direction. As shown in Table 3, the PPF values were greater radially than axially. This condition indicates that changes in the power density radially fluctuate more than those in the axial direction. Generally, the PPF values for the small modular long-life PWR design remain well below two, a safe limit for a standard PWR design.

The Doppler coefficient and void reactivity coefficient exhibited consistent negative values over the entire operational cycle of the reactor, as indicated in Table 4 and Fig. 11, respectively, based on the calculations performed. The negative values for both parameters followed a similar pattern, with the most negative values occurring at BOL and a reduction in the negative values observed until EOL. This condition is due to decreased reactivity values between BOL and EOL.

As shown in Fig. 12–14, the burnup calculation results indicate that the fuel burnup value is proportional to the reactor power level but inversely proportional to the fuel volume fraction. As the power level increased, the burnup rate increased, resulting in a higher fuel burnup. Conversely, with a larger fuel volume fraction, the production of thermal neutrons decreases, reducing the fission reaction rate and subsequently lowering fuel burnup. However, with a smaller fuel volume fraction, the production of thermal neutrons increases, enhancing the fission reaction rate and elevating the burnup level. Fig. 14 shows that the fuel configuration with the best performance can achieve a burnup level of up to 72.60 GWD/ton, which is higher than the maximum fuel rod average burnup of the AP1000, which is 60.00 to 62.00 GWD/ton [22].

The neutronic analysis conducted in this research has successfully achieved the optimum target, where the small modular long-life PWR designed can remain in critical condition for 20 years with an excess reactivity below 1.00 % dk/k. However, the calculations are still limited to using the SRAC code, which operates based on a deterministic model. Therefore, for further research, as a comparative analysis, it is also necessary to conduct this analysis using a code that operates based on a stochastic model such as the Monte Carlo Code. Additionally, the model constructed still needs to improve because the design is still based on two-dimensional reactor core calculations. Hence, for excellent reliability, it is necessary to perform reactor core calculations with a three-dimensional model that depicts the arrangement of fuel materials within the fuel assembly and reactor core in more detail. These three-dimensional calculations require more complex inputs and longer computation times than reactor core calculations with a two-dimensional model.

7. Conclusions

1. The best-performing configuration to achieve optimum conditions at 300-500 MWth power levels is found in fuel with a 5–6–7 % ^{233}U enrichment, 3.30 % ^{231}Pa addition, and a fuel volume fraction of 65 %.

2. Power density distributions for low and high-power levels follow the same pattern radially and axially, with peaks of power density representing the boundaries of fuel regions appearing more distinct in the radial direction.

3. The power peaking factor (PPF) has an average close to 1.40 and the highest is 1.70. These values are still within the safety limits of PWR reactor types.

4. The Doppler and void reactivity coefficients consistently maintained negative values throughout the operational cycle.

5. The best-performing fuel can achieve a burnup level of up to 72.60 GWD/ton at a power level of 500 MWth.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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