STUDY ON KINETIC PARAMETERS OF PEBBLE BED REACTOR WITH TRISO DUPLEX FUEL

by

ZUHAIR *, ***Wahid LUTHFI, R. Andika Putra DWIJAYANTO, Anis ROHANDA, and SUWOTO***

National Research and Innovation Agency, KST BJ Habibie, Serpong, Tangerang Selatan, Indonesia

Scientific paper
https://doi.org/10.2298/NTRP2301001Z

Thorium, in this case, ^{232}Th has a higher thermal neutron capture cross-section than ^{238}U, which means that more fertile isotopes can be transmuted and could lead to higher fissile isotope ^{233}U. In addition, ^{233}U has a good performance in the thermal spectrum. Theoretically, a nuclear reactor using thorium fuel can also last longer than one using uranium fuel. The use of TRISO duplex fuel is predicted to produce better neutronic behavior in a pebble bed reactor. This work aims to study the kinetic parameters of a pebble bed reactor with TRISO duplex fuel. The configuration of the TRISO duplex fuel pebble consists of an inner region filled with UO_2 TRISO particles and an outer region filled with ThO_2 TRISO particles surrounded by a graphite matrix of fuel pebble. Three configurations with volume fraction of UO_2-ThO_2 were considered in this study: 80-20 %, 75-25 %, and 70-30 %. The HTR-10 reactor was chosen as a reactor model because its geometry and material specifications are known. A series of calculations were conducted using the Monte Carlo transport code MCNP6 and ENDF/B-VII.1 nuclear data library. The calculation results were then analyzed to investigate the effect of UO_2 and ThO_2 compositions in TRISO duplex fuel on the kinetic parameters of the pebble bed reactor with various TRISO packing fractions of 1-50 %. It can be concluded that the utilization of TRISO duplex fuel in a pebble bed reactor could significantly affect the core multiplication factor and kinetic parameters caused by an increase in Th content. On the other hand, the TRISO packing fraction is taking part in neutron moderation since a lower packing fraction means higher moderation for fueled pebble.

Key words: kinetic parameter, pebble bed reactor, TRISO duplex fuel, MCNP6, ENDF/B-VII.1

INTRODUCTION

Thorium is recognized as one of the possible energy sources in nuclear power plants and is considered one of the possible solutions to overcome the shortage of natural uranium in the event of a rapid expansion of nuclear power. This is because thorium, in this case, ^{232}Th has a higher thermal neutron capture cross-section than ^{238}U, which means that more fertile isotopes can be transmuted and could lead to higher fissile isotope ^{233}U. The ^{233}U has a good performance in the thermal spectrum. In addition, the abundance of thorium in the Earth's crust which is predicted to be three to four times that of uranium can meet the world's energy needs for a longer time [1].

Thorium fuel with various chemical forms has been utilized in past experimental and nuclear power reactors, such as PWR (Indian Point I, Shippingport), BWR (Elk River), MSR (MSRE ORNL), and HTGR (Dragon, Peach Bottom, AVR, Fort St Vrain, THTR300) [2]. In the last decade, the potential of thorium utilization has been studied in Pebble Bed Modular Reactor (PBMR-400) [3] to reduce the accumulation of plutonium and minor actinides in nuclear waste. Neutronic analysis of a 50 MW light water-cooled Small Modular Reactor (SMR) utilizing transuranium and thorium has been researched [4]. The Modular Gas Turbine Helium Reactor (GT-MHR) [5] has investigated the possibility of utilizing thorium with weapon-grade plutonium (WGrPu). This reactor was also used as a model reactor to study reactor fuel grade plutonium (RGPu) in the form of a mixture with ^{232}Th and ^{238}U fertile fuels [6].

The use of TRISO duplex fuel is predicted to produce better neutronic behavior in a pebble bed reactor. It provides higher burnup, better fuel utilization, and longer cycle length resulting from an improved ratio of neutron capture in fertile material to neutron absorption in fissile material. The TRISO duplex fuel is also predicted to have the capability of maintaining longer criticality, producing smaller reactivity changes, and reducing the potential for plutonium build-up. The TRISO duplex fuel has attractive neutronic characteristics, which offers possibilities for future studies [7].

This work aims to study the kinetic parameters of a pebble bed reactor with TRISO duplex fuel. Kinetic

* Corresponding author, e-mail: zuhair@brin.go.id

parameters play an important role in reactor dynamic analysis. The determination of kinetic parameters is of major importance in reactor physics calculations because it is closely related to the transitional reactivity analysis, safety, and control of nuclear reactors. The reactor kinetic parameters consist of the effective delayed neutron fraction β_{eff}, prompt neutron lifetime ℓ, and neutron generation time Λ. The exact calculation of these parameters is very crucial in conducting a nuclear reactor transient analysis to represent the reactor performance during dynamic changes caused by temperature, control rod positions, coolant flow rate, and so on along with its operation, malfunction, or even accident condition.

The configuration of the TRISO duplex fuel pebble consists of an inner region filled with UO_2 TRISO particles and an outer region filled with ThO_2 TRISO particles surrounded by a graphite matrix of fuel pebble. Three configurations with volume fraction of UO_2-ThO_2 were considered in this study: 80-20 %, 75-25 %, and 70-30 %. The HTR-10 reactor was chosen as a reactor model because its geometry and material specifications are known. A series of calculations were conducted using the Monte Carlo transport code MCNP6 [8] and ENDF/B-VII.1 nuclear data library [9]. The calculation results were then analyzed to investigate the effect of UO_2 and ThO_2 compositions in TRISO duplex fuel on the kinetic parameters of a pebble bed reactor with various TRISO packing fractions of 1-50 %.

THE HTR-10 REACTOR

The HTR-10 reactor was used as a reactor model in this study. It is a pebble bed reactor cooled by helium gas and moderated by graphite with thermal power of 10 MW. The main structural material of the reactor used for the top, bottom, and side reflectors is made of graphite. The channels for ten control rods, seven elliptical small absorber balls, and three irradiation experiments are located on the inner side of the reflector. The twenty helium flow channels are positioned on the outer side of the reflector. The reactor uses helium flowing through the space between pebbles in the core from top to bottom with a temperature of 250 °C and heating up to a temperature of 700 °C. The general reactor design parameter is given in tab. 1.

The basic geometry of HTR-10 consists of a cylindrical core with a diameter of 180 cm and an effective height of 197 cm. The active core with a nominal volume of 5 m^3 contains approximately 27 000 spherical pebbles with a composition of 57 % fuel pebbles and 43 % moderator pebbles. The packing fraction of pebbles in the core is 0.61. The moderator pebbles made of pure graphite are first dropped randomly at the lower part of the core with the same packing of 0.61. The fuel pebbles are continuously recirculated downward through the core five times using a multi-pass scheme until reaching the design burnup of 80 000 $MWdt^{-1}$.

Table 1. The reactor design parameter of HTR-10 [10]

Reactor parameter	
Thermal power [MW]	10
Inlet/outlet helium temperature [°C]	250/700
Helium pressure [MPa]	3
Helium mass flow rate at full power [kgs^{-1}]	4.3
Number of control rods	10
Number of small absorber balls	7
Core specification	
Core diameter/height [cm]	180/197
Average core power density [MWm^{-3}]	2
Number of pebbles in full load	27 000
Packing a fraction of pebbles	0.61
Average discharge burnup [$MWdt^{-1}$]	80 000
Fuel cycle scheme	Multi-pass

To study the effect of TRISO duplex fuel, in this work the TRISO particle is made up of the fuel kernel of UO_2 with 17 % enriched ^{235}U. Another TRISO particle is made up of the fuel kernel of ThO_2. Each kernel is coated by four protective coating layers: porous carbon buffer (C), inner pyrolytic carbon (iPyC), silicon carbide (SiC), and outer pyrolytic carbon (oPyC). The coating layers act as multiple defenses and barriers for fission product retention and maintain the integrity of TRISO particles under a temperature limit of 1600 °C. The configuration of a TRISO duplex fuel pebble consists of an inner region filled with UO_2 TRISO particles and an outer region filled with ThO_2 TRISO particles surrounded by a graphite matrix of fuel pebble. The fuel pebble is composed of UO_2 and ThO_2 TRISO coated particles with volume fractions of 80-20 %, 75-25 %, and 70-30 %. The schematic view of a fuel pebble is shown in fig. 1. The TRISO packing fraction of 1-50 %, defined as a ratio of total fuel particle volume to the fuel pebble volume, was considered. The specifications of fuel and moderator pebbles are given in tabs. 2 and 3, respectively.

By design, the HTR-10 core is developed to use a multi-pass scheme to achieve its 80 000 MWd/t discharge burnup, by continuously moving within the reactor core and repeating its journey within the core five times. In this study, the reactor core is assumed to be loaded with fresh fuel.

CALCULATION MODEL

The MCNP6 code with ENDF/B-VII.1 nuclear data library was used to perform all calculations. The MCNP6 is a general-purpose, continuous-energy, generalized-geometry, time-dependent, Monte Carlo transport code developed by Los Alamos National Laboratory (LANL) to track many types of particles

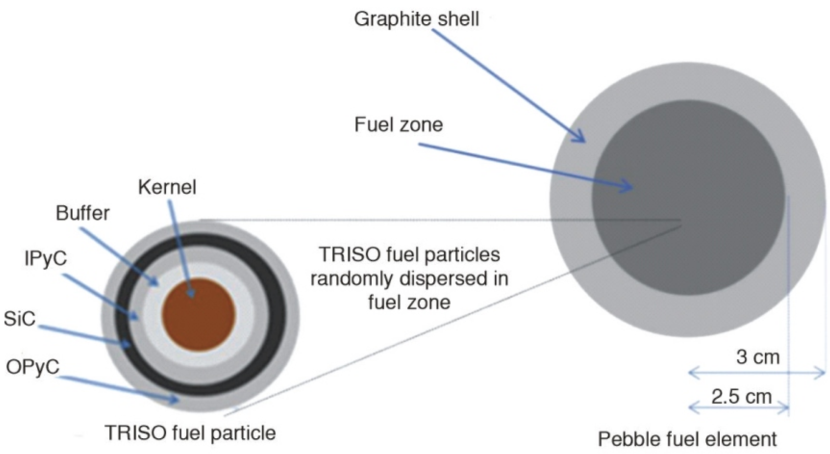

Figure 1. The schematic view of fuel pebble [11]

Table 2. Specification of fuel pebble

Fuel pebble		
Fuel composition		UO_2; ThO_2
Fuel pebble radius [cm]		3
Fueled zone radius [cm]		2.5
Graphite density in matrix/shell [gcm^{-3}]		1.73
Natural boron impurity in fuel/graphite [ppm]		1.0/1.3
TRISO coated particle		
Material	Density [gcm^{-3}]	Outer radius [cm]
Kernel UO_2; ThO_2	10.40; 9.70	0.0250
Buffer	1.10	0.0340
iPyC	1.90	0.0380
SiC	3.18	0.0415
oPyC	1.90	0.0455

Table 3. Specification of moderator pebble [12]

Moderator pebble radius [cm]	3
Graphite density in moderator pebble [gcm^{-3}]	1.84
Natural boron impurity in graphite [ppm]	1.30

over a wide energy range. The code has successfully demonstrated its powerful capability in modeling 3-D extra-complex geometries and simulating neutronic parameters of various types of the reactor [13-20].

In this work, the modeling of HTR-10 is divided into two categories: TRISO duplex with ThO_2 and UO_2 particles inside the fuel pebble and pebbles in the reactor core modeling. This model is very important before performing the neutronic calculations such as criticality, reactivity, neutron spectrum, fuel depletion and burnup, kinetic parameters, *etc*.

The TRISO particle model in fuel pebble

The UO_2 TRISO particle was modeled with a simple cubic (SC) lattice. The TRISO particle was placed in the lattice center with graphite matrix occupying the remaining region outside the particle in the lattice. The ThO_2 TRISO particle was modeled with a similar procedure. The fuel pebble was modeled by arranging the particle lattices with a configuration of UO_2 TRISO particles in the inner region and ThO_2 TRISO particles in the outer region of the fuel pebble. The 0.5-cm-thick shell graphite enveloping the fueled zone was then modeled to complete the fuel pebble model. Three configurations with volume fraction of UO_2-ThO_2 were considered in this study: 80-20 %, 75-25 %, and 70-30 %.

The repeated structure, constructed by UNIVERSE and a combination of LATTICE and FILL options was used to model the fuel pebble. This structure will raise the incomplete TRISO UO_2 and TRISO ThO_2 particles on the spherical surfaces of the inner and outer regions of the pebble-fueled zone. However, such a condition can be ignored because the packing fraction of TRISO particles which is small or even larger than 30 % will not significantly worsen the calculation results [21]. In this specific study, the TRISO duplex packing fraction of 1-50 % was considered to find the impacts on the neutronic parameters of HTR-10. The MCNP6 model for TRISO duplex particle inside fuel pebble is illustrated in fig. 2. The isotopic concentration of the fuel particle (in atom per barn per cm) is given in tab. 4 . The isotopic concentration of graphite matrix and graphite shell (in atoms per barn per cm), which is identical, is given in tab. 5.

Pebble model in the reactor core

The reactor core was modeled by arranging 27 000 pebbles in the body-centered cubic (BCC) lattice. The lattice consists of one fuel pebble placed at the center of the lattice and eight of 1/8 moderator pebbles positioned at the corners of the lattice. The empty region outside the pebbles in the lattice was occupied by helium coolant. The composition of 57 % fuel pebbles and 43 % moderator pebbles in the reactor core were preserved by reducing the radius of the moderator pebble from 3 cm to 2.7310 cm. A pebble packing fraction of 0.61 was reproduced by adjusting the pitch of the BCC lattice from 7.1853 cm to 6.8772 cm.

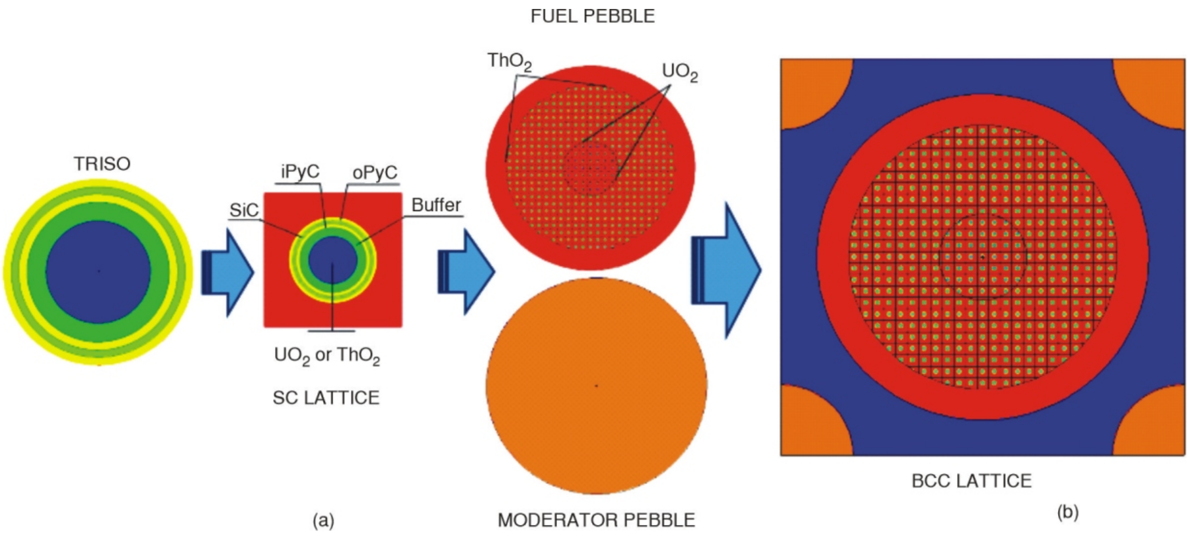

Figure 2. The MCNP6 model for (a) TRISO duplex particle and (b) fuel pebble

Table 4. The isotopic concentration of TRISO particle

	Kernel UO_2		Kernel ThO_2
^{235}U	$3.992067\ 10^{-3}$	^{230}Th	$5.078813\ 10^{-6}$
^{238}U	$1.924449\ 10^{-2}$	^{232}Th	$2.516960\ 10^{-2}$
O	$4.647329\ 10^{-2}$	O	$5.034935\ 10^{-2}$
^{10}B	$1.849637\ 10^{-8}$	^{10}B	$1.849637\ 10^{-8}$
^{11}B	$7.445022\ 10^{-8}$	^{11}B	$7.445022\ 10^{-8}$
Coating layers			
Buffer		SiC	
C	$5.51513\ 10^{-2}$	^{28}Si	$4.40195\ 10^{-2}$
iPyC/oPyC		^{29}Si	$2.24945\ 10^{-3}$
C	$9.52614\ 10^{-2}$	^{30}Si	$1.49008\ 10^{-3}$
		C	$4.77590\ 10^{-2}$

Table 5. The isotopic concentration of graphite matrix and graphite shell [12]

Graphite matrix		Graphite shell	
C	$8.674169\ 10^{-2}$	C	$8.674169\ 10^{-2}$
^{10}B	$2.244010\ 10^{-8}$	^{10}B	$2.244010\ 10^{-8}$
^{11}B	$9.032424\ 10^{-8}$	^{11}B	$9.032424\ 10^{-8}$

The repeated structure was also used to model the reactor core which causes the appearance of partial pebbles around the core. This indirectly adds extra fuel to the core. Excess fuel contributed by partial pebbles can be compensated by applying an exclusive zone of helium encircling the reactor core with a thickness of 1.71 cm. The cone at the bottom of the core was modeled by arranging moderator pebbles in a BCC lattice with helium in the empty gap between the pebbles. Graphite reflectors, helium flow channels, irradiation experiment channels, and other reactor components such as shutdown system channels consisting of control rods and small absorber balls in the inner side of the reflector were completely modeled. The MCNP6 model for the axial and radial views of the reactor core is illustrated in fig. 3. Since it was introduced by Lebenhaft in 2001 [22], this modeling procedure was used as a reference for computation models in numerous publications [23-29].

RESULTS AND DISCUSSION

All calculations were conducted using KCODE and KSRC options provided in MCNP6. The KCODE option was performed by simulating 250 000 neutrons in each cycle of 250 cycles tracked and averaged in a random step directed by interaction probabilities. The 50 cycles were discarded to ensure the fission source convergence. The real neutron history starts from neutron sources specified by the KSRC option and is located at the center of the core. Thermal neutron scattering library S (α, β) was used to consider the interaction of thermal neutrons with all graphite contained in the entire pebbles and the whole reactor at low energy below 4 eV. The KOPTS card was activated to calculate the kinetic parameters of the pebble bed reactor. All control rods were set to be in a complete withdrawal position. The outer boundary of the reactor system was assumed to be in vacuum condition. The maximum relative statistical error of k_{eff}, ℓ, Λ, and β_{eff} calculations are 0.045 %, 0.077 %, 1.116 %, and 6.931%, respectively.

The calculation results of the effective multiplication factor k_{eff} are illustrated in fig. 4. The k_{eff} is defined as the ratio of the number of neutrons produced by fission in one generation to the number of neutrons lost through absorption and leakage in the preceding generation. This factor depends on various parameters which also vary with temperature and are related to reactor safety. From the figure, it can be observed, that Duplex fuel has a lower k_{eff} value than the commonly used UO_2 fuel. This is because the ThO_2 that occupies

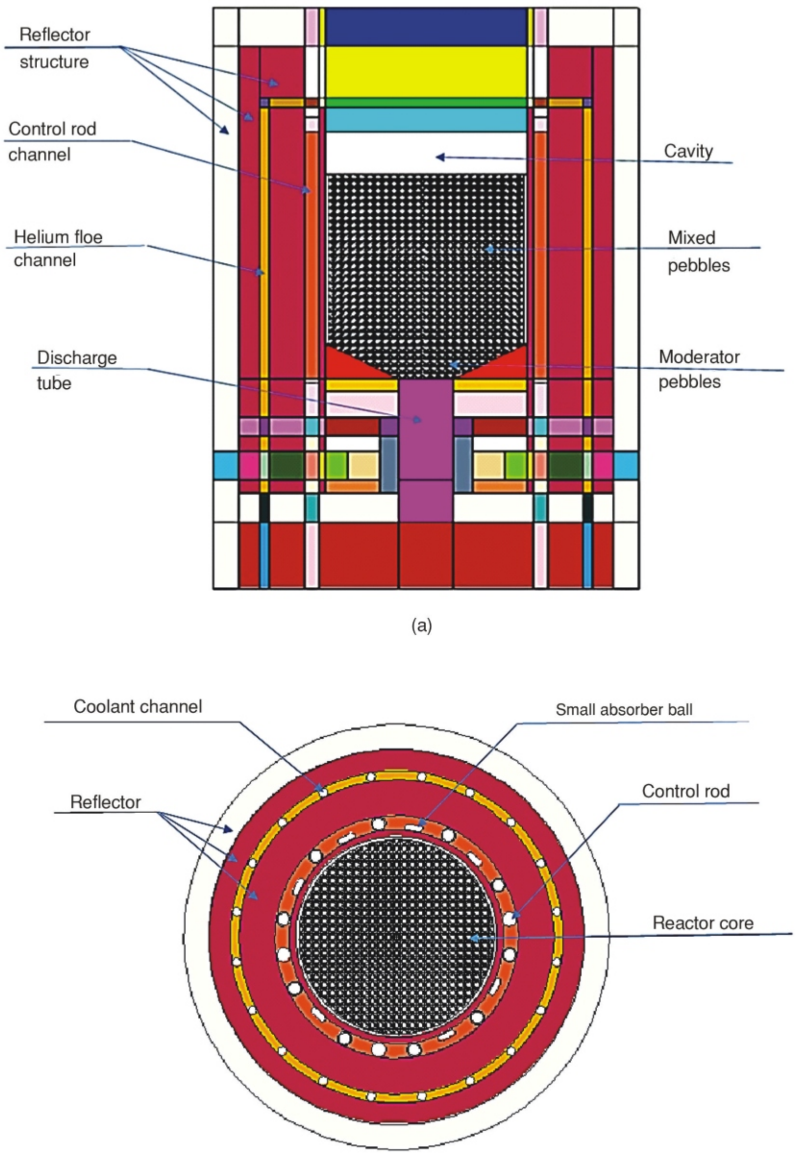

Figure 3. The MCNP6 model for (a) the axial and (b) radial views of the reactor core

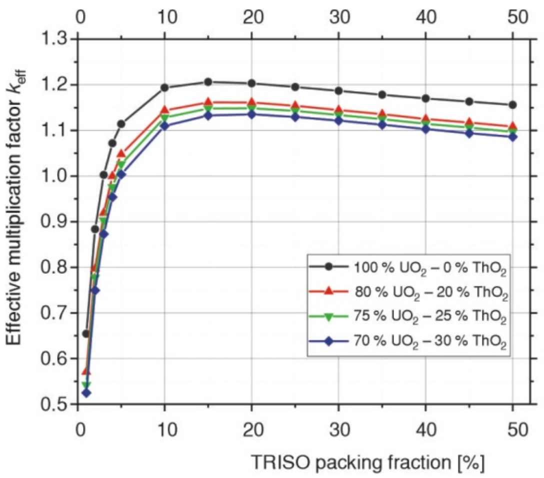

Figure 4. Effective multiplication factor k_{eff}

the duplex fuel with a certain volume fraction causes the mass of ^{235}U to decrease. The higher the volume fraction of ThO_2 in duplex fuel, the lower the core k_{eff} value. The ^{232}Th isotope which has a higher thermal neutron capture cross-section than ^{238}U loaded in the core is not strong enough to compensate for UO_2 to increase the k_{eff} value. It can be noted here, that the k_{eff} value shows a tendency to increase at low packing fractions to reach a maximum value before decreasing with increasing packing fractions. The effect of neutron moderation is behind this tendency.

Maximum k_{eff} values are achieved by duplex fuels for configurations with volume fractions of 80 % UO_2-20 % ThO_2 (1.16150 0.00037), 75 % UO_2-25 % ThO_2 (1.14850 0.00038), and 70 % $UO2_2$-30 % ThO_2 (1.13547 0.00038) at TRISO packing fractions of 15 %, 20 %, and 20 %, respectively. Consistently, the core which is only loaded with UO_2 fuel achieves the highest k_{eff} value (1.20631   0.00038) at the same packing fraction of 15 %. After the optimal k_{eff} value is reached, the thermal neutron population decreases significantly with increasing packing fraction. The increasing TRISO packing fraction will increase the loading of heavy metals in the reactor core which consequently reduces the ratio of moderators to heavy metals. This results in an increase in the neutron capture cross-section and a decrease in the reproduction factor which in turn reduces the k_{eff} value.

The calculation results of the kinetic parameters are depicted in figs. 5-7. The kinetic parameters are significant in the safety analysis of nuclear reactors and an accurate calculation of these parameters is very important in dynamic analysis for reactors operation, especially in fast transients. One of the kinetic parameters that characterize the time behavior of the neutron population is the prompt neutron lifetime ℓ. The ℓ has an impact on the time scale of the reactor core response to changes in reactivity. In reactor kinetics, the ℓ is defined as the time between the birth of a neutron from fission and its loss due to leakage, parasitic absorption, or absorption in fuel. This parameter is important in determining the time dependence of excursions in which the reactivity excess is so great that the reactor is critical or near critical on the prompt neutrons alone without the delayed neutron contribution.

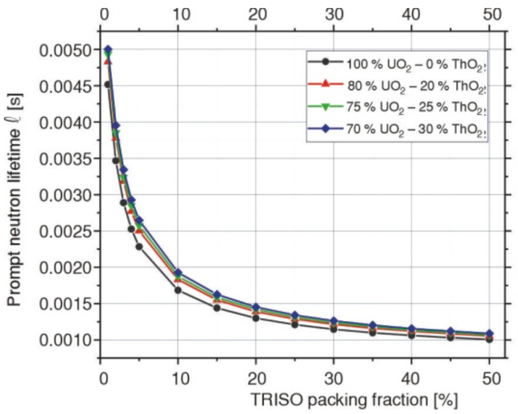

Figure 5. Prompt neutron lifetime ℓ

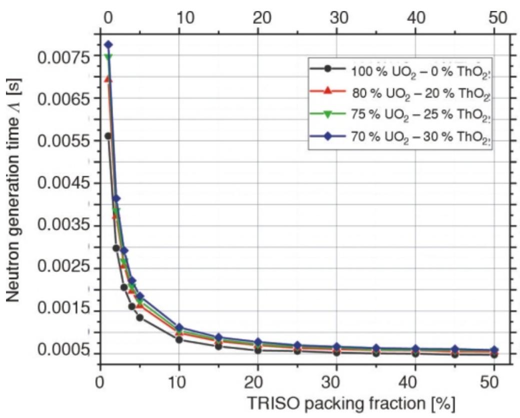

Figure 6. Neutron generation time Λ

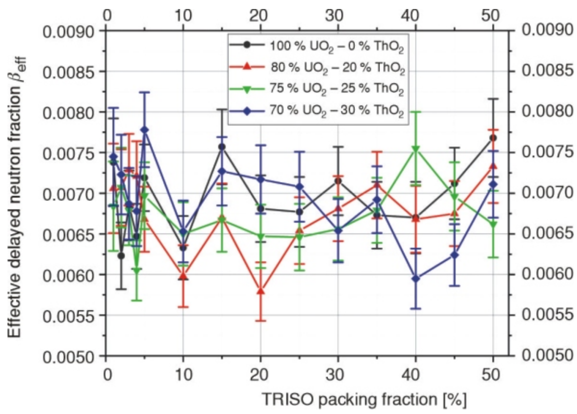

Figure 7. Effective delayed neutron fraction β_{eff}

In fig. 5 the ℓ is presented. It can be seen that, if the packing fraction increases, the ℓ will exponentially decrease. This is due to the hardening of the neutron spectrum by a decrease in fuel loading caused by the reduced packing fraction. The duplex fuel for configuration with a volume fraction of 70 % UO_2-30 % ThO_2 shows the highest ℓ than configurations with other volume fractions. The neutron generation time Λ is related to the ℓ. It is a measure of the time required for a change in the nuclear reactor multiplication factor in affecting the neutron population. For a critical system, the ℓ is equal to the Λ which means that the time of neutron removal is equal to the time for neutron creation. A similar trend of Λ to that of ℓ are shown in fig. 6, if the packing fraction increases the Λ will exponentially decrease. The duplex fuel for configuration with a volume fraction of 70 % UO_2-30 % ThO_2 also provides the highest Λ compared to configurations with other volume fractions. The higher ThO_2 volume fraction in duplex fuel clarifies better controllability of the reactor at any TRISO packing fraction.

The effective delayed neutron fraction β_{eff} as part of the kinetic parameters is also an important parameter for reactor dynamics. Its value is affecting neutron dynamics during transient calculation for reactivity insertion *i. e*,. from control rod displacement, void fractions, Doppler effect, *etc*. In general, delayed neutrons fraction and its decay constant in nuclear reactors affect reactor controllability which is related to reactor power change rate. If there is no delayed neutron, the reactor power could increase in such a short time that could lead to significant damage. A smaller β_{eff} indicates a smaller fraction of neutrons appear as delayed neutrons which makes a faster reactor response to a reactivity, inversely, a larger β_{eff} could lead to a slower response during reactivity insertion which makes it easier to control the reactor.

The results of the β_{eff} of each configuration shown in fig. 7 do not indicate the regularity of change

Table 6. The β_{eff} at maximum k_{eff} configuration

	100 % UO_2-0 % ThO_2		80 % UO_2-20 % ThO_2	
	β_{eff} = 0.00757 0.00046 TRISO packing fraction = 15 %		β_{eff} = 0.00670 0.00042 TRISO packing fraction = 15 %	
i	β_i	λ_i	β_i	λ_i
1	0.00034 0.00012	0.01334	0.00016 0.00005	0.01334
2	0.00134 0.00019	0.03273	0.00111 0.00020	0.03273
3	0.00132 0.00017	0.12079	0.00127 0.00017	0.12080
4	0.00312 0.00031	0.30292	0.00246 0.00026	0.30295
5	0.00113 0.00018	0.85021	0.00120 0.00017	0.85005
6	0.00032 0.00008	2.85478	0.00050 0.00011	2.85486
	75 % UO_2-25 % ThO_2		70 % UO_2-30 % ThO_2	
	β_{eff} = 0.00647 0.00039 TRISO packing fraction = 20 %		β_{eff} = 0.00717 0.00042 TRISO packing fraction = 20 %	
i	β_i	λ_i	β_i	λ_i
1	0.00021 0.00006	0.01334	0.00019 0.00006	0.01334
2	0.00125 0.00019	0.03273	0.00129 0.00017	0.03273
3	0.00118 0.00016	0.12079	0.00141 0.00018	0.12080
4	0.00252 0.00024	0.30293	0.00274 0.00027	0.30295
5	0.00088 0.00013	0.85042	0.00101 0.00016	0.85064
6	0.00042 0.00011	2.85472	0.00054 0.00012	2.85561

even though the delayed neutron fractions of the ^{232}Th, ^{238}U, and ^{235}U isotopes have considerable differences from each other as a standalone heavy metal material. The β_{eff}, statistical error, and decay constants of each fuel composition in 15 % and 20 % packing fractions are shown in tab. 6**.** The β_{eff} fluctuates within 3 times of statistical error of each delayed neutron group which makes the variation in fuel composition considered in this study is not showing significant changes or trends. Also, considering that this study is only focused on fresh fuel at the beginning of the cycle, fissile material ^{233}U is not produced yet, which makes its contribution to delayed neutron fraction not being accounted to this study. Some sensitivity analysis regarding the geometrical modeling of TRISO packing fraction on MCNP and its correlation to heavy metal composition is needed to make sure that β_{eff} is only related to fertile material composition at the beginning of the cycle.

Significant change might be shown if depletion calculation is carried out, but it will be part of the further calculation. Table 6 also shows that adding ThO_2 in the fuel at the BOC is not directly affecting β, since only delayed neutron groups 2, 4, 5, and 6 show some sort of trend in increasing the β_{eff} which is still inside the β_{eff} statistical error, decay constant β_i of delayed neutron precursor β_i also do not change drastically. These findings could lead to some statistical conclusion that β_{eff} in BOC is not affected by the addition of ThO_2 into the fuel kernel. Depletion calculation related to fuel burnup might show it better later.

CONCLUSION

A study on the kinetic parameters of a pebble bed reactor with TRISO duplex fuel has been conducted through a series of calculations with MCNP6 code and ENDF/B-VII.1 library. It can be concluded that the utilization of TRISO duplex fuel in a pebble bed reactor could significantly affect the core multiplication factor and kinetic parameters caused by an increase in Th content. On the other hand, the TRISO packing fraction is taking part in neutron moderation since a lower packing fraction means higher moderation for fueled pebble. The calculation results show that the maximum k_{eff} values are achieved by duplex fuels for configurations with volume fractions of 80 % UO_2-20 % ThO_2, 75 % UO_2-25 % ThO_2, and 70 % UO_2-30 % ThO_2 at TRISO packing fractions of 15 %, 20 %, and 20 %, respectively. At any TRISO packing fraction, the higher ThO_2 volume fraction in duplex fuel gives a higher prompt neutron lifetime ℓ and the neutron generation time Λ which exponentially decreases while the TRISO packing fraction increases. The β_{eff} values do not indicate the regularity of change with TRISO packing fraction changes, which turns out that in this study, some sensitivity calculation of the MCNP geometrical model for the HTR core might be needed to know how much β_{eff} is affected by fuel composition.

ACKNOWLEDGMENT

The authors gratefully acknowledge Dr. Eng. Topan Setiadipura and Prof. Surian Pinem for their encouragement and support in conducting this study. This work was financially supported by the Government of the Republic of Indonesia through Rumah Program HITN-ORTN 2023.

REFERENCES

[1] ***, International Atomic Energy Agency (IAEA), Introduction of Thorium in the Nuclear Fuel Cycle,

Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency (NEA), Paris, 2015

[2] Hore-Lacy, I., Uranium for Nuclear Power: Resources, Mining and Transformation to Fuel, Cambridge, UK: Woodhead Publishing, 2016

[3] Acir, A., Coskun, H., Neutronic Analysis of the PBMR-400 Full Core using Thorium Fuel Mixed with Plutonium or Minor Actinides, *Annals of Nuclear Energy, 48* (2012), Oct., pp. 45-50

[4] Bakir, G., Analysis of Thorium and Transuranium Utilization in a Small Modular Reactor, *Nucl Technol Radiat, 37* (2022), 3, pp. 175-180

[5] Sahin, H. M., Erol, O., Utilization of Thorium in a Gas Turbine – Modular Helium Reactor with Alternative Fuels, *Energy Conversion and Management, 53* (2012), 1, pp. 224-229

[6] Sahin, S., Erol, O., Sahin, H. M., Investigation of a Gas Turbine-Modular Helium Reactor using Reactor Grade Plutonium with ^{232}Th and ^{238}U, *Progress in Nuclear Energy, 89* (2016), May, pp. 110-119

[7] Alam, S. B., *et al*., Coupled Neutronic/Thermal-hydraulic Hot Channel Analysis of High Power Density Civil Marine SMR Cores, *Annals of Nuclear Energy, 127* (2019), May, pp. 400-411

[8] Goorley, J. T., *et al*., Initial MCNP6 Release Overview – MCNP6 version 1.0, Los Alamos National Laboratory, Los Alamos, N. Mex, USA, 2013, LA-UR-13-22934

[9] Chadwick, M. B., *et al*., ENDF/B-VII.1: Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data, *Nuclear Data Sheets, 112* (2011), 12, pp. 2887-2996

[10] Wu, Z., Lin, D., Zhong, D., The Design Features of the HTR-10, *Nuclear Engineering and Design, 218* (2002), 1-3, pp. 25-32

[11] Setiadipura, T., Irwanto, D., Zuhair, Preliminary Neutronic Design of High Burnup OTTO Cycle Pebble Bed Reactor, *Atom Indonesia, 41* (2015), 1, pp. 7-15

[12] Jing, X., Sun, Y., Benchmark Problem of the HTR-10 Initial Core - Draft Version, Institute of Nuclear Energy Technology (INET), Beijing, China 1998

[13] Kabach, O., *et al*., A Comparative Analysis of the Neutronic Performance of Thorium Mixed with Uranium or Plutonium in a High-Temperature Pebble-Bed Reactor, *International Journal of Energy Research, 45* (2021), 11, pp. 16824-16841

[14] Hassan, M., Simulation of a Full PWR Core with MCNP6, *International Journal of Science and Research, 9* (2020), 9, pp. 913-918

[15] Zuhair, *et al.*, Study on the Characteristics of Effective Delayed Neutron Fraction ($\beta_{\rm eff}$) for Pebble-bed Reactor with Plutonium Fuel, *Iranian Journal of Science and Technology, Transactions A: Science, 43* (2019), 6, pp. 3037-3045

[16] Zuhair, *et al*., The Effects of Fuel Type on Control Rod Reactivity of Pebble-Bed Reactor, *Nukleonika, 64* (2019), pp. 131-138

[17] Carter, J. P., Borrelli, R. A., Integral Molten Salt Reactor Neutron Physics Study using Monte Carlo N-Particle Code, *Nuclear Engineering and Design, 365* (2020), Aug., 110718

[18] Liem, P. H., Zuhair, Hartanto, D., Sensitivity and Uncertainty Analysis on the First Core Criticality of the RSG GAS Multipurpose Research Reactor, *Progress in Nuclear Energy, 114* (2019), Jul., pp. 46-60

[19] Zuhair, *et al*., Preliminary Study on TRU Transmutation in VVER-1000 Fuel Assembly using MCNP6, *Kerntechnik*, *87* (2022), 3, pp. 305-315

[20] Facchini, A., *et al*., Detailed Neutronic Study of the Power Evolution for the European Sodium Fast Reactor during a Positive Insertion of Reactivity, *Nuclear Engineering and Design, 313* (2017), Mar., pp. 1-9

[21] Rosales, J., *et al*., Computational Model for the Neutronic Simulation of Pebble Bed Reactor's Core using MCNPX, *International Journal of Nuclear Energy, 2014* (2014), ID 279073

[22] Lebenhaft, J. L., MCNP4B Modeling of Pebble-bed Reactors, M. Sh. thesis, Massachusetts Institute of Technology, Massachusetts, USA, 2001

[23] Zuhair, *et al*., Study on Kinetic Parameters Charateristics of Pebble Bed Reactor using HTR-Proteus Facility, *Nucl Technol Radiat, 37* (2022), 2, pp. 119-127

[24] Kabach, O., *et al*., The use of Burnable Absorbers Integrated into TRISO/QUADRISO Particles as a Reactivity Control Method in a Pebble-Bed HTR Reactor fuelled with (Th,^{233}U)O_2, *Nuclear Engineering and Design, 384* (2021), 111476

[25] Zuhair, *et al*., Study on MCNP6 Model in the Calculation of Kinetic Parameters for Pebble Bed Reactor, *Acta Polytechnica, 60* (2020), 2, pp. 175-184

[26] Alzamly, M. A., *et al*., Burnup Analysis for HTR-10 Reactor Core loaded with Uranium and Thorium Oxide, *Nuclear Engineering and Technology, 52* (2020), 4, pp. 674-680

[27] Zuhair, *et al*., The Implication of Thorium Fraction on Neutronic Parameters of Pebble Bed Reactor, *Kuwait Journal of Science, 48* (2021), 3, pp. 1-16

[28] Hosseini, S. A., Athari-Allaf, M, Effects of the Wallpaper Fuel Design on the Neutronic Behavior of the HTR-10, *Kerntechnik, 81* (2016), 6, pp. 627-633

[29] Zuhair, *et al*., The Effects of Applying Silicon Carbide Coating on Core Reactivity of Pebble-Bed HTR in Water Ingress Accident, *Kerntechnik, 82* (2017), 1, pp. 92-97

Received on November 10, 2022
Accepted on January 12, 2023

ЗУХАИР, Вахид ЛУТФИ, Р. Андика Путра ДВИЦАЈАНТО, Анис РОХАНДА, СУВОТО

СТУДИЈА КИНЕТИЧКИХ ПАРАМЕТАРА РЕАКТОРА СА ШЉУНКОВИТИМ ТРИСО ДВОЈНИМ ГОРИВОМ

Торијум ^{232}Th, у овом случају, има већи попречни пресек за захват термичких неутрона од ^{238}U, што значи да плоднији изотопи могу бити трансмутовани и довести до фисибилнијег изотопа ^{238}U. Поред тога, ^{233}U има добра својства у термичком спектру. Теоретски, нуклеарни реактор који користи торијумско гориво такође може трајати дуже од реактора који користи уранијумско гориво. Предвиђа се да ће употреба ТРИСО двојног горива произвести боље неутронско понашање у реактору са шљунковитим слојем. Овај рад има за циљ проучавање кинетичких параметара реактора са шљунковитим слојем од ТРИСО двојног горива. Конфигурација ТРИСО двојног горивног шљунка састоји се од унутрашњег региона испуњеног UO_2 ТРИСО честицама и спољашњег региона испуњеног ThO_2 ТРИСО честицама окруженог графитном матрицом од горивног шљунка. У раду су разматране три конфигурације са запреминским уделом UO_2-ThO_2: 80-20 %, 75-25 % и 70-30 %. За модел реактора изабран је реактор HTR-10 са познатом геометријом и спецификацијом материјала. Серија прорачуна спроведена је коришћењем Монте Карло транспортног кода MCNP6 и ENDF/B-VII.1 библиотеке нуклеарних података. Резултати прорачуна затим су анализирани да би се испитао утицај састава UO_2 и ThO_2 у ТРИСО двојном гориву на кинетичке параметре реактора са шљунковитим слојем, са различитим ТРИСО фракцијама паковања од 1-50 %. Може се закључити да би коришћење ТРИСО двојног горива у реактору са шљунковитим слојем могло значајно утицати на фактор мултипликације језгра и кинетичке параметре узроковане повећањем садржаја торијума. С друге стране, ТРИСО фракција паковања учествује у успоравању неутрона јер нижа фракција паковања значи веће успоравање за шљунак са горивом.

Кључне речи: кинешички йарамешар, реакшор са шљунковишим слојем, ТРИСО двојно їориво, MCNP6, ENDF/B-VII.1