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NEUTRONIC INVESTIGATION ON THORIUM MOX FUEL IN VVER-1000 REACTOR ASSEMBLY

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The accumulation of plutonium produced by LWR operations causes public concern related to its radiotoxicity and proliferation issue. Therefore, there is some interest in developing various methods for consuming plutonium through plutonium incineration i.e., by utilising thorium-based nuclear fuel. Thorium-plutonium mixed oxide fuel (Thorium MOX) is an attractive option considered for plutonium incineration. The aim of the study is to investigate the neutronic characteristics of Thorium MOX fuel in VVER-1000 nuclear reactor fuel assemblies. The VVER-1000 Benchmark model was utilised in the present study. A series of calculations were performed with the MCNP6 code and the ENDF/B-VII library. The calculation results show that a proper increase in Pu content could increase k_{inf} of ThMOX fuel, so it could have almost the same k_{inf} with MOX fuel or increase Pu content when needed. It was also shown that Thorium MOX fuel assembly had more negative Doppler reactivity due to neutron capture by thorium (^{232}Th). The moderator temperature coefficient was found to be more negative than the Doppler coefficient, and it could be concluded that replacing uranium with thorium could reduce the amount of plutonium produced while increasing plutonium consumption.

Keywords: *ENDF/B-VII, MCNP6, thorium MOX, VVER-1000 reactor assembly.*

1. INTRODUCTION

A continuous and rapid global population increase and economic growth in many countries cause the world's energy demand to increase. Nowadays, around 81 % of the world's energy demand is supplied by fossil fuels, but it increases CO_2 emissions causing global warming and climate change, endangering the environment and society in the future. Utilising nuclear energy which generates low-CO_2 electricity is a realistic choice to mitigate the effects of global warming and climate change answering the increase in energy demand [1], [2]. Currently, there are 443 operating nuclear power plants (NPPs) in more than 30 countries around the globe. All these NPPs, which are dominated by light water reactors (LWR), take up to 10 % of the world's electric energy demand.

In addition to generating a large amount of electricity, NPPs are also producing nuclear waste which is classified as high-level waste (HLW), intermediate-level waste (ILW), and low-level waste (LLW). HLW consists of fission products and transuranic elements generated within fuel elements during reactor operation, while LLW represents waste produced during reactor operation such as neutron-activated structural materials, tools or equipment, radiation protection clothing, and residues from industries.

As previously mentioned, HLW consists of transuranic (TRU) and fission products. TRU is a product of transmutation mostly found in the uranium fuel cycle, which came from fertile isotope ^{238}U, and it captures neutrons and transmutes into heavier isotopes. It provides a significant contribution to the radiotoxicity of nuclear waste, which came from isotopes of plutonium (Pu) and minor actinide (MA) isotopes, such as Neptunium (Np), Americium (Am), and Curium (Cm) [3].

The accumulation of plutonium produced by LWR operations causes public concern related to its radiotoxicity and proliferation issue [4]. Therefore, there is some interest in developing various methods for consuming plutonium through plutonium incineration, i.e., by utilising thorium-based nuclear fuel. Thorium-plutonium mixed oxide fuel (Thorium MOX) is an attractive option that has been considered for plutonium incineration, which significantly produces less plutonium during incinerating plutonium [5]. Several studies successfully demonstrated the superior capabilities of Thorium MOX fuel for plutonium incineration using deterministic code [6]–[10]. However, the neutronic characteristics of the reactor core using Thorium MOX fuel should be examined because plutonium could give a considerable impact on the operational and safety parameters of the reactor [11].

The aim of the study is to investigate the neutronic characteristics of Thorium MOX fuel in VVER-1000 nuclear reactor fuel assemblies. The VVER-1000 Benchmark model [12] was utilised in the present investigation to examine the effect of replacing MOX fuel with Thorium MOX fuel on the same fuel assembly configuration. A series of calculations were performed with the Monte Carlo transport code MCNP6 [13] and the continuous nuclear data library ENDF/B-VII [14]. The analysis was focused on the neutronic performance between MOX and Thorium MOX fuel assemblies such as excess reactivity, fuel temperature coefficients of reactivity (DTC), moderator temperature coefficients of reactivity (MTC), and plutonium incineration.

2. VVER-1000 ASSEMBLY

VVER-1000 (Vodo-Vodyanoi Energetichesky Reactor or Water-Water Energetic Reactor) is a type of pressurized water reactor with 3000 MW thermal power that could convert into 1000 MW electric power. The benchmark model for VVER-1000 consists of two typical hexagonal fuel assemblies from advanced Russian fuel designs, a LEU fuel assembly and MOX fuel assembly. These two assemblies are calculated as verification to VVER-1000 fuel calculation code, and supporting the mission to reduce weapon-grade plutonium proliferation [12].

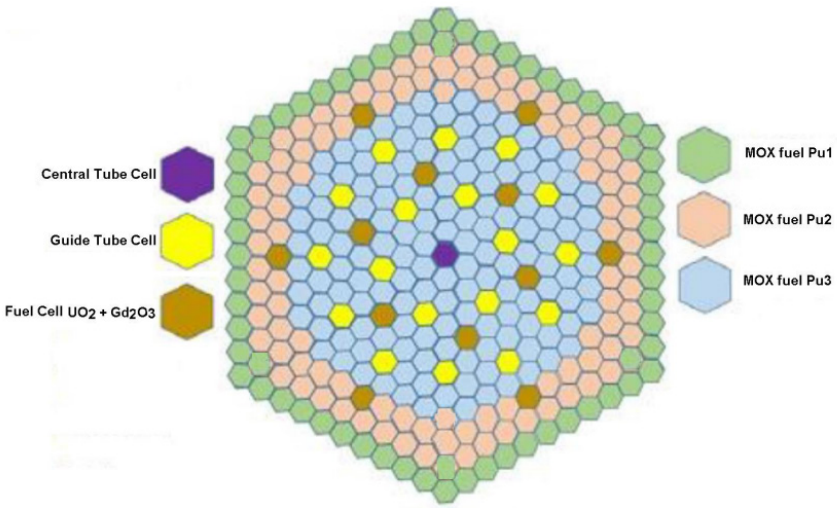


Fig. 1. VVER-1000 MOX fuel assembly.

The MOX fuel assembly consists of 300 MOX fuel rods, 12 GD1 fuel rods, 18 guide tubes, and one central tube. The fuel rods and guide tubes are arranged in a twelfth symmetry, and there are three different plutonium contents in MOX fuel assembly. The outermost ring of MOX assembly is loaded with 66 fuel rods with 2.0 wt% fissile plutonium (PU1), while the second and third inner rings are filled with 96 fuel rods with 3.0 wt% fissile plutonium (PU2). The central region (138 fuel rods) has the highest plutonium content of 4.2 wt% (PU3). The Gd_2O_3 content is used in the fuel assembly to suppress excess reactivity at the beginning of cycle, i.e., GD1 in this model is a UO_2 fuel with 3.6 wt% ^{235}U enrichment mixed with 4 wt% Gd_2O_3 [15]. The configuration of the VVER-1000 MOX fuel assembly is shown in Fig. 1, and reactor design parameters are given in Table 1.

In this study, the thorium MOX fuel was loaded into the fuel assembly by replacing the regular MOX fuel without significant assembly modifications, called Thorium MOX fuel. The Thorium MOX fuel being analysed in this paper consists of two types: ThMOX1 with plutonium content adjusted from 2 wt% to 3 wt%, 3 wt% to 4.5 wt%, and 4.2 wt% to 6.3 wt%, or increased 1.5 times, and ThMOX2 with plutonium content adjusted from 2 wt% to 6 wt%, 3 wt% to 9 wt%, and 4.2 wt% to 12.6 wt% or increased three times. The three plutonium

compositions being used remain unchanged and are given in Table 2. The plutonium content is increased to anticipate the reduction in nuclear fission reactions due to the replacement of uranium to thorium.

Table 1. Design Parameters of the VVER-1000 MOX Fuel Assembly

Number of MOX fuel cell (PU1)	66
Number of MOX fuel cell (PU2)	96
Number of MOX fuel cell (PU3)	138
Number of UO_2+Gd_2O_3 fuel cell (GD1)	12
Number of guide tubes	18
Number of central tube	1
Inner/outer radius of fuel cell (cm)	0.3860/0.4582
Inner /outer radius of central tube cell (cm)	0.4800/0.5626
Inner/outer radius of guide tube cell (cm)	0.5450/0.6323
Pitch of fuel cell (cm)	1.2750
Pitch of fuel assembly (cm)	23.6
Temperature of fuel (K)	1027
Temperature of non-fuel (K)	575
Enrichment of ^{235}U (wt%)	3.6
Density of Gd_2O_3 (g/cm^3)	7.4

Table 2. Plutonium Isotopic Composition

Isotope	PU1	PU2	PU3
^{239}Pu	0.9290	0.9310	0.9300
^{240}Pu	0.0610	0.0590	0.0599
^{241}Pu	0.0100	0.0100	0.0101

3. CALCULATION MODEL

In this study, a series of calculations using MCNP6 code and ENDF/B-VII nuclear data have been performed to investigate the neutronic aspect of Thorium MOX fuel of the VVER-1000 fuel assembly. MCNP6 is a general-purpose, continuous-energy Monte Carlo radiation transport code developed by Los Alamos National Laboratory (LANL) to track neutron, photon, electron, or combined radiation particles over broad ranges of energies. MCNP6 is the latest Monte Carlo transport code created by merging and integrating all features of MCNP5 [16] and MCNPX [17]. Code capabilities have been demonstrated in simulating fuel assembly and complex core configurations on various reactor types [18]–[29].

Modelling the VVER-1000 MOX fuel assembly began with modelling the fuel, central tube, and guide tube cells. The fuel rod was modelled with a radius of 0.3860 cm surrounded by water that made up a hexagonal lattice. The zircaloy-4 cladding in the fuel rod was modelled encasing the fuel with a thickness of 0.0722 cm. Zr-Nb-Hf alloys are utilised as a structural material. The MOX fuel has three different plutonium contents: 2.0 wt% fissile plutonium (PU1), 3.0 wt% fissile plutonium (PU2),

and 4.2 wt% (PU3). The GD1 fuel cell was modelled with a similar technique as the MOX fuel cell.

Although they have different functions, the modelling of the central tube and guide tube is quite similar, the water fill in both tubes was placed with a radius of 0.4800 cm and 0.5450 cm, respectively. The claddings with thicknesses of 0.0826 cm for the central tube and 0.0873 cm for the guide tubes are also placed, followed by surrounding water outside these claddings marking up a fuel rod lattice with a hexagonal pitch of 1.2750 cm. The exact geometry modelled by MCNP6 for fuel, central tube and guide tube cells is depicted in Fig. 2.

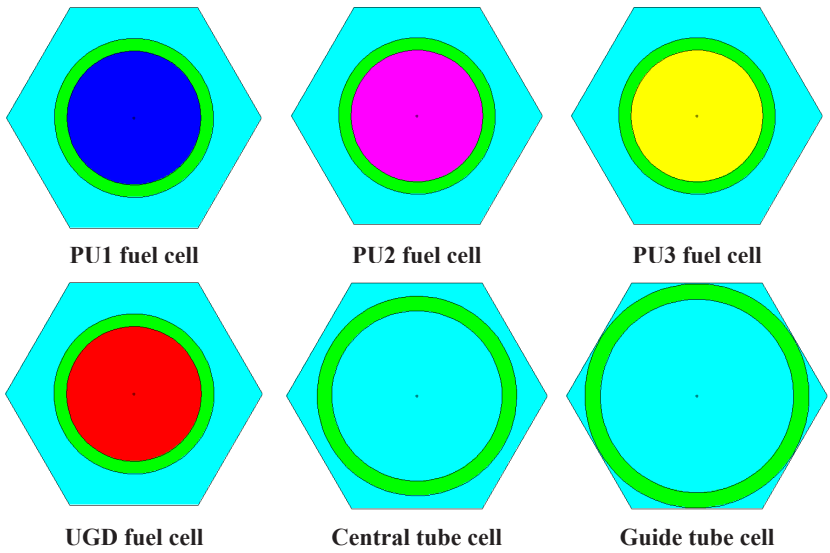


Fig. 2. MCNP6 model for fuel, central tube, and guide tube cells.

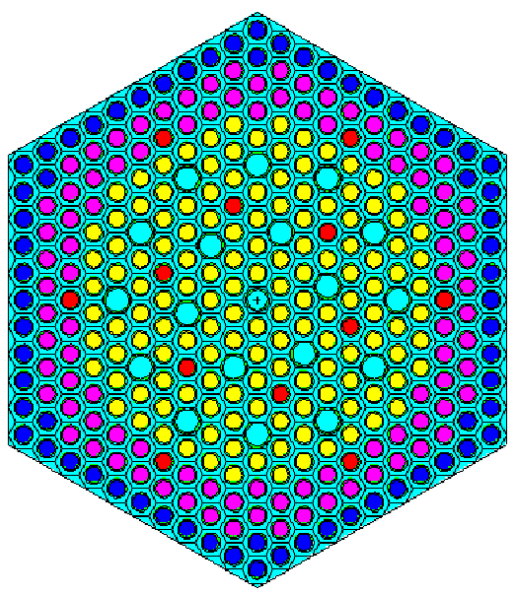


Fig. 3. MCNP6 model for VVER-1000 MOX assembly.

The VVER-1000 MOX fuel assembly model was constructed by making an array of fuel, guide tubes, and central tube cells in a hexagonal geometry. The water surrounding the whole fuel array is then making up the fuel assembly that has a pitch of 23.6 cm. All outer surfaces of the VVER-1000 MOX fuel assembly were assumed to be reflective surfaces. The exact geometry modelled by MCNP6 model for fuel assembly is depicted in Fig. 3. Detailed isotopic compositions of MOX fuel assemblies is given in Table 3.

Table 3. Isotopic Compositions of VVER-1000 MOX Assembly

PU1	MOX fuel with 2.0 wt% Pu fissile	^{235}U	4.2672E-5	^{239}Pu	4.2414E-4
		^{238}U	2.1025E-2	^{240}Pu	2.7250E-5
		^{16}O	4.3047E-2	^{241}Pu	4.5228E-6
PU2	MOX fuel with 3.0 wt% Pu fissile	^{235}U	4.2209E-5	^{239}Pu	6.3621E-4
		^{238}U	2.0797E-2	^{240}Pu	4.0875E-5
		^{16}O	4.3045E-2	^{241}Pu	6.7842E-6
PU3	MOX fuel with 4.2 wt% Pu fissile	^{235}U	4.1652E-5	^{239}Pu	8.9071E-4
		^{238}U	2.0522E-2	^{240}Pu	5.7225E-5
		^{16}O	4.3043E-2	^{241}Pu	9.4980E-6
UGD	UO_2 fuel with 3.6 wt% ^{235}U and 4 wt% Gd_2O_3	^{235}U	7.2875E-4	^{155}Gd	1.8541E-4
		^{238}U	1.9268E-2	^{156}Gd	2.5602E-4
		^{16}O	4.1854E-2	^{157}Gd	1.9480E-4
		^{152}Gd	2.5159E-6	^{158}Gd	3.0715E-4
		^{154}Gd	2.7303E-5	^{160}Gd	2.6706E-4

Table 4. Isotopic Compositions of VVER-1000 Thorium MOX Assembly

PT1	Thorium MOX fuel with 3 wt% Pu fissile	^{230}Th	4.3000E-6	^{239}Pu	6.3426E-4
		^{232}Th	2.1310E-2	^{240}Pu	4.1647E-5
		^{16}O	4.3994E-2	^{241}Pu	6.8274E-6
PT2	Thorium MOX fuel with 4.5 wt% Pu fissile	^{230}Th	4.2292E-6	^{239}Pu	9.5145E-4
		^{232}Th	2.0959E-2	^{240}Pu	6.2474E-5
		^{16}O	4.3975E-2	^{241}Pu	1.0242E-5
PT3	Thorium MOX fuel with 6.3 wt% Pu fissile	^{230}Th	4.1443E-6	^{239}Pu	1.3321E-3
		^{232}Th	2.0539E-2	^{240}Pu	8.7470E-5
		^{16}O	4.3953E-2	^{241}Pu	1.4339E-5
PT4	Thorium MOX fuel with 6 wt% Pu fissile	^{230}Th	4.1585E-6	^{239}Pu	1.2687E-3
		^{232}Th	2.0609E-2	^{240}Pu	8.3304E-5
		^{16}O	4.3957E-2	^{241}Pu	1.3656E-5
PT5	Thorium MOX fuel with 9 wt% Pu fissile	^{230}Th	4.0170E-6	^{239}Pu	1.9032E-3
		^{232}Th	1.9907E-2	^{240}Pu	1.2497E-4
		^{16}O	4.3920E-2	^{241}Pu	2.0487E-5
PT6	Thorium MOX fuel with 12.6 wt% Pu fissile	^{230}Th	3.8471E-6	^{239}Pu	2.6649E-3
		^{232}Th	1.9066E-2	^{240}Pu	1.7498E-4
		^{16}O	4.3876E-2	^{241}Pu	2.8686E-5

Table 5. Isotopic Compositions of Non-fuel Material in VVER-1000 Assembly

CL1	Zirconium alloy	^{93}Nb	4.2250E-4	^{174}Hf	1.0555E-8
		^{90}Zr	2.1913E-2	^{176}Hf	3.4700E-7
		^{91}Zr	4.7786E-3	^{177}Hf	1.2270E-6
		^{92}Zr	7.3042E-3	^{178}Hf	1.7997E-6
		^{94}Zr	7.4021E-3	^{179}Hf	8.9851E-7
		^{96}Zr	1.1925E-3	^{180}Hf	2.3142E-6
MOD1	Moderator, 0.6 g/kg of boron, T_m= 575K, ρ= 0.7235 g/cm^3	^{1}H	4.8430E-2	^{10}B	4.7940E-6
		^{16}O	2.4220E-2	^{11}B	1.9420E-5
MOD2	Moderator, without boron, T_m= 575K, ρ= 0.7235 g/cm^3	^{1}H	4.8430E-2	^{10}B	0
		^{16}O	2.4220E-2	^{11}B	0
MOD3	Moderator, without boron, T_m= 300K, ρ= 1.0033 g/cm^3	^{1}H	6.7170E-2	^{10}B	0
		^{16}O	3.3580E-2	^{11}B	0

This study investigates the neutronic performance of Thorium MOX fuel in the fuel assembly of the VVER-1000 reactor. Modelling the modified fuel assembly by Thorium MOX fuel was done in the same way as those of MOX assembly since it used an identical dimension and geometry. Thorium MOX fuel being modelled was modified as mentioned in the previous section: ThMOX1 with 3 wt% fissile plutonium (PT1), 4.5 wt% fissile plutonium (PT2), and 6.3 wt% (PT3), and ThMOX2 with 6 wt% fissile plutonium (PT4), 9 wt% fissile plutonium (PT5), and 12.6 wt% (PT6). Detailed isotopic compositions of Thorium MOX fuel assemblies are provided in Table 4, and the isotopic compositions of non-fuel materials in fuel assemblies are given in Table 5. This paper considers three different coolant states shown as MOD1, MOD2, and MOD3 representing different densities, temperatures, and boron concentrations in g Boron/kg water, used in the calculation. MOD1 stands for 575 K water with density of 0.7235 g/cm^3 and 600 ppm boron, MOD2 stands for 575 K water without soluble boron, and MOD3 stands for 300 K water with density of 1.0033 g/cm^3 also without soluble boron.

4. RESULTS AND DISCUSSION

The KCODE card was used in MCNP6 with 100,000 neutrons per cycle, 500 total cycles and the first 100 cycles skipped. The initial fission source defined by the KSRC card was positioned in the middle of a fuel assembly. The thermal scattering data S(α,β) for light water were used to consider thermal neutron interaction with water at the energy region below ~4 eV. Reflective boundary conditions were used on the outer surface of the fuel assembly to make sure that the neutrons were reflected back to the fuel assembly when reaching boundaries.

4.1. Model Validation

The benchmark problems are made up of five conditions or states, covering both cold and hot operation conditions of the VVER-1000 reactor as shown in Table 6. S1 is the operation condition while soluble boron exists within the coolant at 600 ppm,

and the burnup calculation was carried out in this condition. S2 was the same as S1 but it was calculated without ^{135}Xe and ^{149}Sm poisoning. S3 was a hot zero power condition with 575 K fuel and coolant temperature and 600 ppm boron concentration, while S4 was the same as S3 but without soluble boron. S5 was set to a cold zero power condition without soluble boron with fuel and coolant temperature of 300 K. These five reactor conditions were then used to estimate the reactivity coefficients of the VVER-1000 fuel assembly.

Table 6. Calculated Reactor Conditions

State	Description	Fuel temp. (K)	Non-fuel temp. (K)	^{135}Xe, ^{149}Sm	Moderator type	Boron (ppm)	Moderator density (g/cm^3)
S1	Operating poisoned state	1027	575	Equil.	MOD1	600	0.7235
S2	Operating non-poisoned state	1027	575	0	MOD1	600	0.7235
S3	Hot state	575	575	0	MOD1	600	0.7235
S4	Hot state without boron acid	575	575	0	MOD2	0	0.7235
S5	Cold state	300	300	0	MOD3	0	1.0033

Table 7. The k_{inf} of VVER-1000 MOX Assembly

State	MCNP6 (M)	SERPENT (S)	Δk (%) [(M-S)/S]
S2	1.20072 ±9E-05	1.19258 ±8.6E-05	0.683
S3	1.21201 ±9E-05	1.20919 ±8.4E-05	0.233
S4	1.24673 ±1E-04	1.24408 ±8.5E-05	0.213
S5	1.33015 ±9E-05	1.32487 ±7.6E-05	0.398

The k_{inf} results from MCNP6 calculations for VVER-1000 MOX assembly in the states S2-S5 in comparison with Serpent calculation from reference [30] are given in Table 7. All these calculations were conducted without burnup. It can be observed that k_{inf} values are in good agreement with SERPENT results. The small difference in k_{inf} of MCNP6 and SERPENT could be neglected and it could be stated that the model used in this calculation was quite consistent to the ones being used in SERPENT.

4.2. Thorium MOX Fuel

The k_{inf} result from the burnup calculation of VVER-1000 fuel assemblies using MOX and Thorium-MOX fuels is illustrated in Fig. 3. The burnup calculation was performed using the CINDER depletion module with the equilibrium ^{135}Xe and ^{149}Sm state was used at a thermal power density of 108 MW/m^3, with 1027 K fuel temperatures and 575 K on non-fuel as mentioned before (S1). The 20 burnup steps consist of 15 steps with intervals of 1 MWd/kgHM for 0-15 MWd/kgHM and 5 steps with intervals of 5 MWd/kgHM for 15–40 MWd/kgHM.

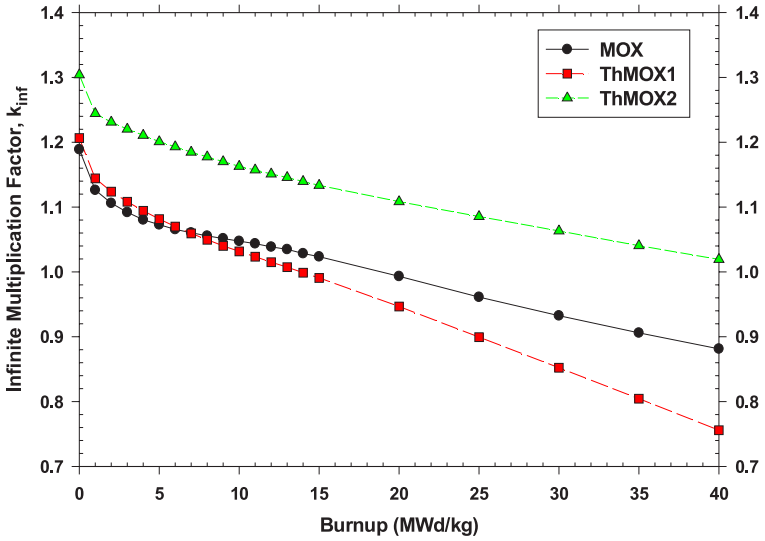


Fig. 3. K_{inf} as a function of burnup.

Figure 3 shows that at the beginning of cycle, the k_{inf} values are 1.18896 for MOX, 1.20649 for ThMOX1, and 1.30397 for ThMOX2 fuel assemblies, with a standard deviation below 10^{-4}. The MOX fuel shows a slightly sharper reduction in reactivity than the ThMOX fuel. At the beginning of cycle (BOC), ThMOX1 has almost the same k_{inf} as MOX fuel and ThMOX2 has higher k_{inf} since it uses a higher percentage of fissile plutonium as shown in Table 4. The MOX fuel assembly k_{inf} drops below unity when it reaches 20 MWd/kg, while the ThMOX1 fuel assembly can only keep criticality up to 14 MWd/kg. ThMOX2 demonstrates its ability to maintain criticality for up to 40 MWd/kg. This means that the ThMOX2 fuel could provide higher discharge reactivity than MOX fuel with its higher fissile plutonium content. It could improve the overall core cycle length but further consideration might be needed in terms of the production cost of plutonium fuel with higher fissile content and mixed with thorium.

Doppler and moderator temperature coefficients of reactivity are the two most dominant temperature coefficients in nuclear reactor systems. In reactor physics, the Doppler effect is due to Doppler broadening on resonance spectrum of nuclear reaction cross section of heavy metal isotopes, Th, U, Pu, etc. The Doppler temperature coefficient of reactivity (DTC) is then defined as the ratio of reactivity changes caused by fuel temperature increase. The moderator temperature coefficient of reactivity (MTC) is then defined as the change in reactivity caused by a change in moderator temperature. As the moderator increases in temperature, it becomes less dense and caused lower neutron moderation, leading to a hardened neutron spectrum which will decrease the core reactivity or lower reactivity. DTC is considered to have a greater effect than MTC because fuel temperature changes immediately followed by a change in reactor power.

The calculated temperature coefficient of reactivity for MOX and Thorium MOX fuel is listed in Table 8, and all MTC and DTC values are negative and take part as an inherent safety feature in the reactor physic aspect. The temperature coefficient of reactivity was computed at 0 MWd/kgHM, 20

MWd/kgHM, and 40 MWd/kgHM using the isotopic compositions from the burnup calculations on state S1. The Doppler coefficient of reactivity was simulated from the differences in k_{inf} for the state S2 and S3, where fuel temperature changed from 575 K to 1027 K and the non-fuel was constant at 575 K. The moderator temperature coefficient was estimated as differences in k_{inf} between the state S4 and S5 by switching the temperature of fuel and moderator from 575 K to 300 K.

Table 8. The Doppler Coefficient of Reactivity (DTC, $\Delta k/k\ K^{-1}$)

Burnup (MWd/kgHM)	MOX	ThMOX1	ThMOX2
0	-7.75793E-03	-1.01569E-02	-9.06375E-03
20	-8.82312E-03	-1.24533E-02	-9.80345E-03
40	-1.03861E-02	-1.65213E-02	-1.12742E-02

Table 9. The Moderator Coefficient of Reactivity (MTC, $\Delta k/k\ K^{-1}$)

Burnup (MWd/kgHM)	MOX	ThMOX1	ThMOX2
0	-5.03034E-02	-3.68157E-02	-3.98879E-02
20	-4.39760E-02	-4.00401E-02	-3.78422E-02
40	-4.12520E-02	-2.90968E-02	-4.55328E-02

From Table 8, it is evident that the Doppler reactivity value of the Thorium MOX assembly increases negatively with the burnup; contrary, the negative value of the moderator temperature coefficient decreases with the burnup. Compared to MOX fuel, Thorium MOX assembly has more negative Doppler reactivity due to thorium, in this case, ^{232}Th, absorbs larger neutrons than ^{238}U in higher fuel temperatures. The value of the moderator coefficient, as shown in Table 9, is found to be more negative than the Doppler coefficient because the fuel temperature was not kept at a constant as defined in conditions S4 and S5. However, these negative Doppler and moderator temperature coefficients are desirable from a safety point of view, as they help stabilize reactor power and avoid reactor excursions.

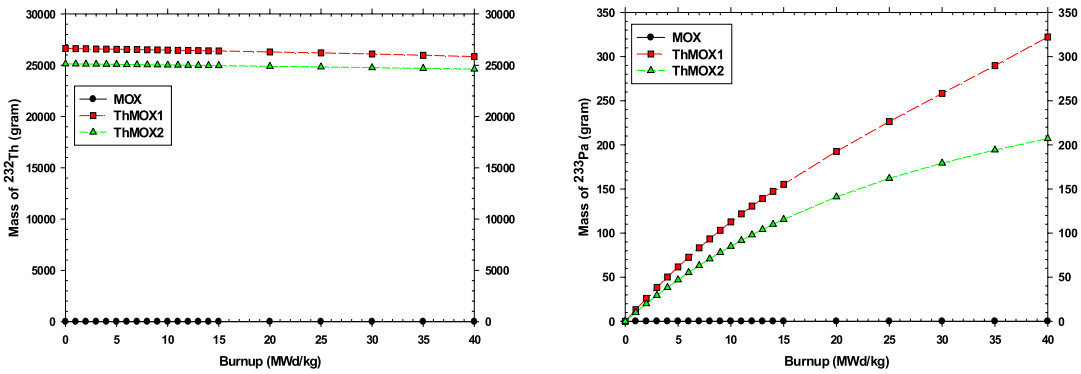


Fig. 4. Mass of ^{232}Th and ^{233}Pa as a function of burnup.

The fuel consumption and the production of some important isotopes in MOX and Thorium MOX fuel assembly are shown in Figs. 4–6. The curve in Figure 4

shows the mass of ^{232}Th being consumed and ^{233}Pa being produced. After 40 MWd/kg burnup, almost 790 g and 510 g of ^{232}Th isotope are being consumed from the 26,630 g and 25,130 g loaded in the first place of ThMOX1 and ThMOX2. There were 322.2 g and 207.1 g of ^{233}Pa being produced. They are lower than thorium being consumed since ^{233}Pa will decay into ^{233}U or transmute into other isotopes i.e., ^{234}Pa. It is straightforward that MOX fuel did not have thorium. Therefore, ^{232}Th and ^{233}Pa will be a flat line on zero. Also, ^{232}Th isotope production in MOX fuel assembly is very small and virtually non-existent since it will be produced by (n,2n) reaction and other neutron emission reactions without fission that have a small possibility to occur.

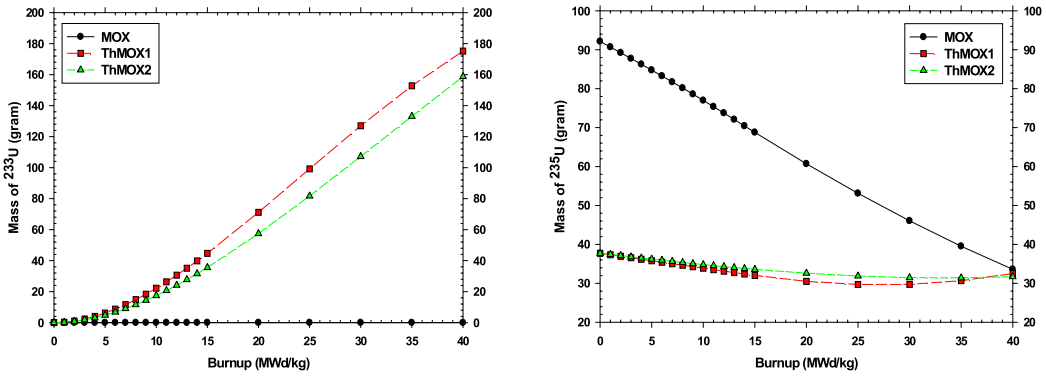


Fig. 5. Mass of ^{233}U and ^{235}U as a function of burnup.

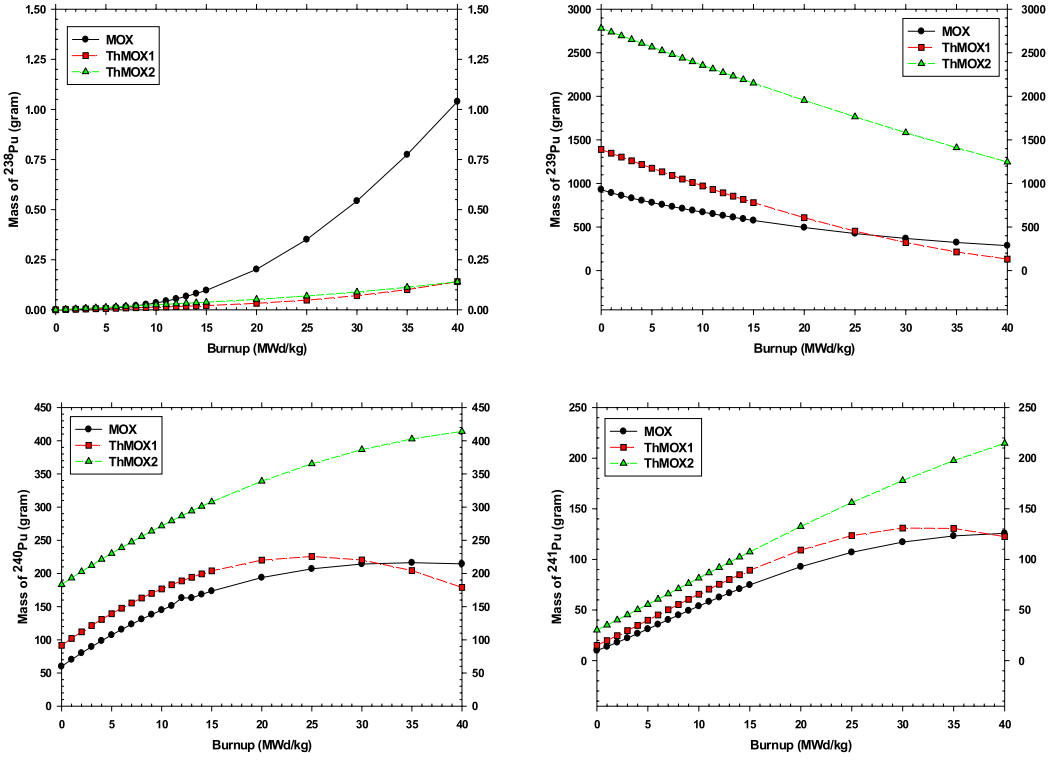


Fig. 6. Mass of ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Pu as a function of burnup.

Figure 5 shows the ^{233}U and ^{235}U mass change in both fuel elements. ^{233}U in Thorium MOX grows up to 175.2 g and 158.8 g after 40 MWd/kg burnup and is almost unnoticeable on MOX fuel even though ^{233}Pa is being produced in small quantities (1.034E-7 g). Using Thorium as a fuel option could increase the number of fissile isotopes within the fuel assembly since ^{233}U is fissile but with some drawbacks on the economy of neutrons within the fuel assembly since thorium will capture neutrons. As it is shown in Fig. 5, one can observe that the mass reduction of ^{235}U in MOX fuel is sharp from 92.14 g to 33.59 g or 63.54 % since ^{235}U is being consumed. On the another hand, Thorium MOX fuel is only 13.84 % and 15.91 % since they only have a small quantity in the first place, which came from 12 burnable fuel pins (GD1). There is also some tendency for ^{235}U in Thorium MOX fuel to increase after 40 MWd/kg burnup since enough lighter heavy metals, i.e., Pa and U are produced, and they could capture more neutrons and become ^{235}U. However, it is also noticeable that an increase of ^{233}U in Thorium MOX fuel for almost the same amount as the decrease of ^{235}U in MOX fuel does not increase fuel reactivity (k-inf) since plutonium fissile isotopes are dominating the source of fuel reactivity.

Figure 6 shows the changes in some plutonium isotopes, ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Pu. ^{238}Pu mass is less produced both in ThMOX1 (0.1404 g) and ThMOX2 fuel (0.1403 g) in comparison with MOX fuel (1.039 g) since Thorium MOX fuel has a lower amount of uranium isotopes. In general, ^{238}Pu came from ^{238}Np that undergoes beta decay, or from ^{238}Am emits a positron. On the other hand, the fissile isotope ^{239}Pu is produced from ^{238}Pu that captures a neutron becoming ^{239}Pu, or from ^{238}U that captures a neutron and is followed by beta decay twice. ^{239}Pu is the second most used nuclear fuel in nuclear reactors after ^{235}U since it is dominantly produced by ^{238}U, which is abundant inside the reactor core. From Fig. 6, it can be seen that ^{239}Pu is higher in Thorium MOX fuel in comparison with MOX fuel because plutonium enrichment inside both ThMOX1 and ThMOX2 fuel was higher (1.5 and 3 times) than one being used inside MOX fuel. Even though Thorium MOX reduces more ^{239}Pu, it has higher initial mass so its reduction fraction is similar.

The same as other isotopes, ^{239}Pu could capture neutrons and become a heavier isotope, becoming ^{240}Pu, capturing more neutrons, becoming ^{241}Pu, and so on. Another isotope of plutonium that has an odd mass is fissile, i.e., ^{241}Pu and isotopes with even mass are fertile and have a low capture reaction cross section. Therefore, they tend to accumulate inside nuclear reactors, especially ones dominated by thermal neutrons, as mostly designed in today's nuclear power plants. Like ^{239}Pu at the beginning of cycle, ^{240}Pu mass in ThMOX1 (91.71 g) and ThMOX2 fuel (183.4 g) is almost 1½ and 3 times greater than that in MOX fuel (60.0 g). Figure 6 shows that ^{241}Pu mass in ThMOX1 and ThMOX2 fuel increased by up to 8 and 7, less than MOX fuel reached 12 times. Table 10 summarises the change of plutonium from the beginning until its k_{inf} reaches 1, and it can be seen that adding thorium can increase plutonium being consumed (fraction) within the fuel assembly with some drawback on k_{inf} which leads to smaller core operating time if its Pu content only increases to 1.5 times as ThMOX1 or the VVER core can be made up of various fuel assemblies that use a lot higher Pu content, i.e., 3 times as ThMOX2.

Table 10. Plutonium Mass (g) at BOC and Critical Condition

Isotope	BOC (0 MWd/kg)			Critical condition (k_{inf} = 1)		
	MOX	ThMOX1	ThMOX2	MOX (20 MWd/kg)	ThMOX1 (14 MWd/kg)	ThMOX2 (>40 MWd/kg)
^{238}Pu	0.000E+00	0.000E+00	0.000E+00	2.019E-01	1.943E-02	1.403E-01
^{239}Pu	9.300E+02	1.391E+03	2.782E+03	4.945E+02	8.169E+02	1.247E+03
^{240}Pu	6.000E+01	9.171E+01	1.834E+02	1.938E+02	1.993E+02	4.141E+02
^{241}Pu	1.000E+01	1.510E+01	3.020E+01	9.282E+01	8.484E+01	2.147E+02
^{242}Pu	0.000E+00	0.000E+00	0.000E+00	1.406E+01	7.026E+00	2.669E+01
Total	1.000E+03	1.498E+03	2.996E+03	7.954E+02	1.108E+03	1.903E+03
Reduced total Pu (g) [mass at critical – mass at BOC]				-2.046E+02	-3.900E+02	-1.093E+03
Consumption rate [(Reduced total Pu/ mass at BOC) × 100 %]				-25.72 %	-35.20 %	-57.44 %

5. CONCLUSION

The neutronic investigation on Thorium MOX fuel in the VVER-1000 reactor assembly was conducted. A series of calculations were done with the MCNP6 code and the ENDF/B-VII library. The calculation results show that ThMOX1 has almost the same k_{inf} as MOX fuel and ThMOX2 has higher k_{inf} since it uses a higher percentage of fissile plutonium. Compared to MOX fuel, Thorium MOX assembly has more negative Doppler reactivity due to thorium. In this case, ^{232}Th, absorbs larger neutrons than ^{238}U in higher fuel temperatures. The value of the moderator coefficient was found to be more negative than the Doppler coefficient in this configuration. It can be concluded that replacing uranium with thorium can reduce the amount of plutonium produced while increasing plutonium consumption.

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