THE EFFECT OF BURNABLE ABSORBERS ON CRITICALITY AND REACTIVITY COEFFICIENT OF VVER-1000 ASSEMBLY

by

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Burnable absorbers play an important role in nuclear reactor safety and exploring their effect on the reactor core behavior is an important issue in the design and operation of the reactor core. The aim of the present work was to discover the effect of burnable absorbers on criticality and reactivity coefficient of VVER-1000 assembly. The calculations were conducted with a 3-D Monte Carlo transport code MCNP6 and ENDF/B-VII.1 nuclear library. The Gd_2O_3 content varying from 0 wt.% to 8 wt.% was considered to complete the inter-comparison analysis between the criticality and the reactivity coefficients for three UO_2+Gd_2O_3 fuel configurations. At the beginning of the cycle, there is a significant difference between the criticality (kinf) of assembly with and without Gd_2O_3, however, at the middle of the cycle those differences become very small and almost the same at the end of the cycle. The Doppler temperature coefficient values are always sufficiently negative and demonstrate a more negative trend with increasing gadolinium concentrations and fuel burnup. At beginning of the cycle, the moderator temperature coefficient value increases negatively as gadolinium concentration increases but, at middle of the cycle this trend does not occur. The fuel composition is predicted to be the reason behind this situation. At the end of cycle, there is no clear trend in the moderator temperature coefficient values with respect to Gd_2O_3 concentration. The absorbing effect of Gd_2O_3 appears to have diminished significantly. Overall, this research provides insights into the influence of the burnable absorbers on the neutronic parameters of the VVER-1000 assembly and its contribution to reactor safety.

Key words: burnable absorber, UO_2 + Gd_2O_3 configuration, criticality, reactivity coefficient, VVER-1000 assembly

INTRODUCTION

Burnable absorbers play an important role in nuclear reactor safety and exploring their effect on the reactor core behavior is an important issue in the design and operation of the reactor core. Burnable absorbers are known as materials with a high neutron absorption cross-section, which, as a result of radiation capture, are converted into isotopes with a relatively low neutron absorption cross-section. They are widely used to compensate for the initial excess reactivity at the beginning of the cycle by absorbing neutrons and thereby lowering the reaction rate of uranium fuel. The negative reactivity of the burnable absorbers decreases during the reactor campaign due to a reduction in its concentration. In the ideal case, it should decrease at the same rate as the reserve of reactivity with burnable of the fuel decreases. Burnable absorbers benefit almost all reactor designs by providing reactivity control for extended fuel cycles, burning of long-lived radionuclides, and reactor safety [1, 2].

The VVER [3] is a pressurized water reactor (PWR), using light water as a coolant and moderator with 3000 MW thermal power. The feature of VVER that distinguished it from other PWR is its hexagonal fuel geometry. As the source of clean energy in the form of a nuclear power plant (NPP), the VVER-1000 [4] with its large electricity generation capacity, also incorporates safety features within its design. The VVER-1000 with 31 units in operation, which accumulated for about 500 reactor years of operation became the most common VVER design worldwide.

With technological improvements and economic improvements, the VVER-1000 design balances the combination of passive and active safety systems to manage the beyond-design basis accident (BDBA). Based on the significant experience gained with the well-established VVER-1000, a number of VVER- 1000 were in operation and under construction at present time in Novovoronezh, Kalinin,

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Balakovo, and Rostov Russia, South Ukraine, Rovno, Zaporozhe, and Khmelnitski Ukraine, Kazloduy Bulgaria, Temelin the Czech Republic, Tianwan China, Kudankulam India, Bushehr Iran, and Rooppur Bangladesh. The two units of VVER- 1200/523 generating 2.4 GW electric power are planned to be operational later in 2024 [5].

In general, a typical VVER-1000 reactor consists of 163 fuel assemblies with triangular (hexagonal) fuel rods pattern with various configurations of different ^{235}U enrichment and gadolinia. In the VVER-1000 reactor, the burnable absorber of gadolinium oxide (Gd_2O_3) is mixed homogeneously with low-enriched uranium oxide (UO_2) fuel. The fuel rods containing gadolinium are carefully distributed in the fuel assemblies to flatten out the neutron flux distribution and core power during operation. Each fuel assembly includes 300 UO_2 fuel rods, 12 UO_2 + Gd_2O_3 fuel rods, 18 guide tubes, and one central tube for instrumentation. In this paper, the UO_2 + Gd_2O_3 fuel rods have been placed in a reference configuration called configuration I. Two other configurations, configuration II and III, with the same amount of UO_2 + Gd_2O_3 pins, but different in position are considered.

The aim of the present work was to observe the effect of burnable absorbers on criticality and reactivity coefficient of VVER-1000 assembly. The VVER-1000 low enriched uranium (LEU) fuel assembly proposed in the OECD Benchmark was selected as a calculation model [6]. The calculations were conducted with a 3-D Monte Carlo transport code MCNP6 [7] and ENDF/B-VII.1 [8] continuous energy nuclear data library. The CINDER90 [9] module within the MCNP6 was utilized to perform the burnup and depletion calculation of fuel with a thermal power of 18 MW thermal per fuel assembly (3000 MW thermal from total of 163 fuel assembly), from fresh fuel up to 40 MWd/kgHM (Mega Watts day per kg heavy metal). The Gd_2O_3 content varying from 0 wt.% to 8 wt.% was considered to complete the inter-comparison analysis between the criticality and the reactivity coefficients for three UO_2 + Gd_2O_3 fuel configurations of VVER-1000 assembly. This range of Gd_2O_3concentration was chosen since VVER 1000 uses a 4 % concentration and increases it up to twice as much, which was considered since the previous study [10, 11] shows some increase in core effective multiplication factor but with some drawback on fuel thermal conductivity.

THE VVER-1000 ASSEMBLY

The VVER-1000 assembly has a hexagonal geometry with a total of 331 rods, categorized into 312 fuel rods, 18 guide tubes, and one central tube. In this model of study, 312 fuel rods consist of 300 UO_2 rods with 3.7 wt.% ^{235}U and 12 UO_2+ Gd_2O_3rods containing a homogeneous mixture of UO_2 with 3.6 wt.% ^{235}U and $Gd_2O_3$with concentration of 4.0 wt.%. The gadolinium oxide content in the fuel rod is useful in controlling excess reactivity at the beginning of the cycle and it also takes part in controlling core reactivity since it is only equipped with 18 control rod assembly made of B_4C absorber material.

The fuel-cladding and structural materials are mainly composed of Zr-Nb-Hf alloy. Fuel-cladding prevents direct contact of fuel to coolant and prevents the release of fission products into the coolant. The fuel assembly structure supports the whole geometry and fuel grid, ensuring the correct placement between each fuel rod. The guide tube provides a channel for inserting control rod and the central tube provides a measuring channel for obtaining information of control neutron population and temperature. The configuration and the design parameters of the assembly are given in fig. 1 and tab. 1.

CALCULATION MODEL

In the present work, a series of numerical calculations were conducted using the MCNP6 code and ENDF/B-VII.1 nuclear data library to study the effect of UO_2 + Gd_2O_3 fuel configuration on the criticality and reactivity coefficient of VVER-1000 reactor assembly. The MCNP6 was a successor of its previous version of MCNP which integrates the features of MCNP5 [12] and improves the fuel depletion capabili-

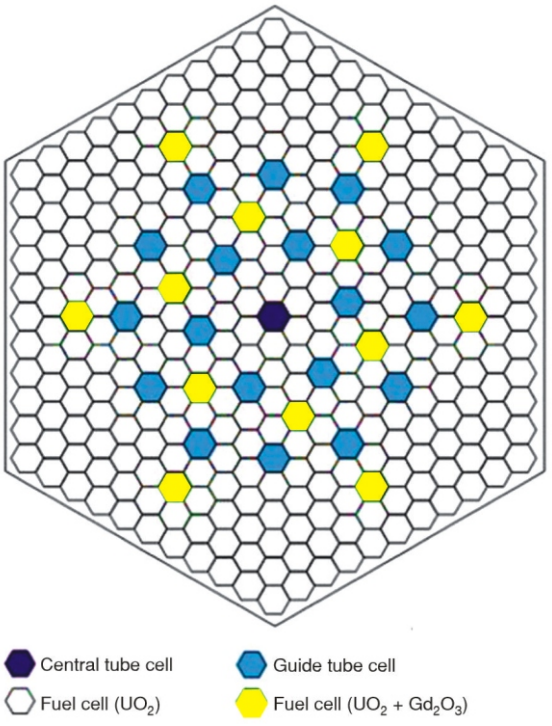

Figure 1. Configuration of the VVER-1000 fuel assembly [13]

Table 1. Design parameters of the VVER-1000 fuel assembly

Number of UO_2 fuel cell	300
Number of UO_2 + $Gd2O_3$ fuel cell	12
Number of guide tube	18
Number of central tube	1
Inner/outer radius of fuel cell [cm]	0.3860 / 0.4582
Inner/outer radius of guide tube [cm]	0.5450 / 0.6323
Inner/outer radius of central tube [cm]	0.4800 / 0.5626
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.%]	3.7
Density of Gd_2O_3 [gcm^{-3}]	7.4

ties of MCNPX [14]. The MCNP was a particle transport calculation code for neutrons, photons, and electrons developed by the Los Alamos National Laboratory. The code with its powerful capabilities has been demonstrated extensively in modeling and simulating the core physics parameters and fuel depletion through various types of reactors [15-31].

Three steps were undertaken to model the geometry of the VVER-1000 assembly. The first step of MCNP6 calculation was to model the UO_2 fuel rod and the UO_2 + Gd_2O_3 fuel rod. These annular pellets have the same radius of 0.3860 cm. The zircaloy-4 cladding was modeled surrounding the fuel rod with an inner and outer radius of 0.3860 cm and 0.4582 cm, respectively. Water is used surrounding fuel cladding to create a fuel cell in a simple hexagonal (SH) lattice. The Gd_2O_3 content in the UO_2 + Gd_2O_3 fuel rod was adjusted to vary from 0 wt.% to 8 wt.%. The burnable poison mixture consists of six stable isotopes of gadolinium, such as ^{152}Gd, ^{154}Gd, ^{155}Gd, ^{156}Gd, ^{157}Gd, ^{158}Gd, and ^{160}Gd with the natural abundance of 0.2 %, 2.18 %, 14.8 %, 20.47 %, 15,67 %, 24.84 %, and 21.86 %, respectively.

The second step is to model the guide tube and central tube in a similar manner as the fuel rod. The fuel pellet was replaced with water and the cladding was modeled to have an inner and outer radius of 0.3860 cm and 0.4582 cm for the control rod guide tube and 0.4800 cm and 0.5626 cm for the central tube, respectively. The cladding was also surrounded with water in an SH lattice. Each UO_2 and UO_2 + Gd_2O_3 fuel cell, guide tube cell, and central tube cell was then defined as a universe with1.2750 cm lattice pitch to form a fuel assembly.

The VVER-1000 LEU fuel assembly with an assembly pitch of 23.6 cm was constructed to follow the exact geometry dimensions of VVER reactor components. By constraining the number of UO_2 + Gd_2O_3 fuel pins within the fuel assembly and recreating 2 other fuel pin configurations that are fairly distributed, we calculate fuel performance as a part of the sensitivity analysis of burnable poison fuel pin position within the fuel assembly. The MCNP6 model for each lattice cell and fuel assembly for the UO_2 + Gd_2O_3 fuel pin are illustrated in figs. 2 and 3, respectively. Also, the isotopic compositions for fuel and non-fuel material in VVER-1000 assemblies (in atoms per barn per cm) are presented in tabs. 2 and 3, respectively.

The total number of 50 million neutron histories being used for most of the infinite multiplication calculation, using 100 000 neutrons for a total of 750 cycles and 250 skipped, while only 2 million neutron histories were used for burnup calculation, 10 000 neutrons with a total of 250 cycles and 50 skipped. As a typical Monte Carlo calculation, skipped cycles were used to find fission source distributions. The fission source was placed in the center of some fuel rods. The standard deviation was less than 0.00010 for all k_{inf} calculations. The thermal neutron scattering data $S(\alpha, \beta)$ was applied to consider the inelastic interaction of thermal neutrons with hydrogen within light water below 4 eV.

Fuel depletion (burnup) calculation was being carried out in MCNP6 using CINDER90 at a constant power of 18 MW for 355 cm fuel height being modelled, with both ^{135}Xe and ^{149}Sm under equilibrium state. The fuel burned to 40 MWd/kgHM with 20 burnup steps consisting of 15 steps of 1 MWd/kgHM from 0-15 MWd/kgHM and five steps of 5 MWd/kgHM from 15-40 MWd/kgHM. These burnup steps were chosen to present the selected burnup degree for this study.

Three different moderator conditions represented in the calculations are categorized as MOD1/MOD2/MOD3 with a density of 0.7235/0.7235/1.0033 gcm^{-3} and a boron concentration of 600/0/0 ppm, respectively. The 1200 K temperatures were used to approximate the fuel temperature of 1027 K and 600 K for the non-fuel temperature of 575 K because data for those specific temperatures does not exist in the MCNP library. Reflective boundary condition was used in this fuel assembly level calculation.

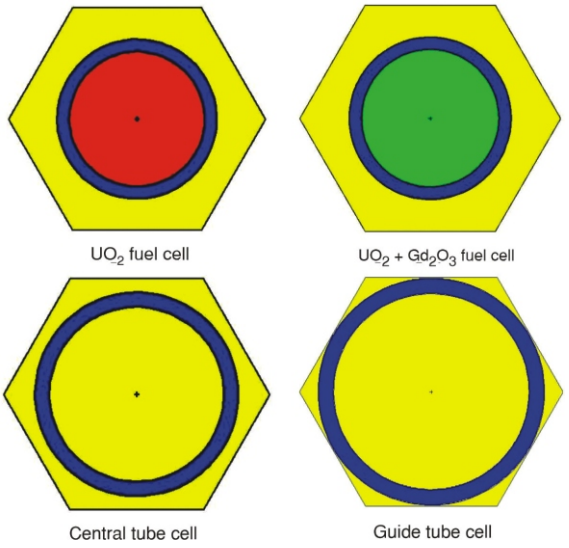

Figure 2. The MCNP6 model for each lattice cell

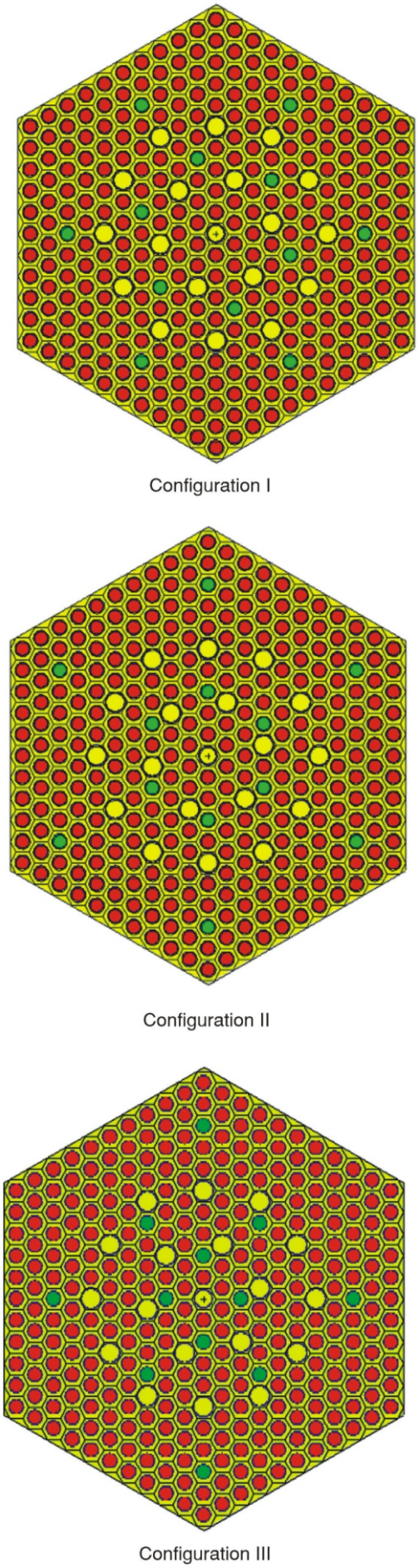

Figure 3. The MCNP6 model for VVER-1000 assembly

RESULTS AND DISCUSSION

In the operation of a nuclear reactor, as criticality is the state in which a fuel can sustain a nuclear chain reaction by itself, maintaining adequate criticality but also safety in the operation of the reactor, is an important priority. The criticality of a finite reactor core can be expressed as an effective multiplication factor (k_{inf}) while in this study, a fuel assembly with a reflective boundary condition represents an infinite reactor in which no neutrons leak from the fuel assembly geometry, leading to the term of infinite multiplication factor (k_{inf}).

Since k_{inf} is analog to the potential of the fuel element to produce fission neutrons during operation, the higher value of k_{inf} is analog to a higher potential of fuel to undergo fission followed by a higher number of fission neutrons produced. Presenting an absorber such as gadolinium into the fuel element could lower the fission potential for this fuel since this study uses a fraction of the burnable absorber to its fuel mixture which will lead to a lower fuel concentration. Adding a burnable absorber lowers the fission potential of fuel at the beginning, so the neutron population in the fuel element needs to increase to compensate for the additional absorption from gadolinium, leading to a higher fission rate in order to produce the same amount of power in each fuel assembly.

Since the neutron absorber will be consumed through the transmutation process induced by the neutrons, the amount of neutron absorber decreases but, the fuel itself also decreases since it is the source of fission neutrons at the beginning. Figure 4 shows the kinf of fuel assembly using various Gd_2O_3 concentrations as fuel depletes. Fuel without gadolinium on each fuel configuration decreases sharply with fuel burnup due to fissile material within fuel consumed during fuel burnup to achieve power generation as user input. At the beginning of the cycle (BOC), there is a significant difference between the k_{inf} of assembly with and without Gd_2O_3. As we already knew, the higher the Gd_2O_3 concentration within the fuel, the lower the k_{inf} value became.

The k_{inf} of assembly with 2 wt.% Gd_2O_3 for all fuel configurations decreases in the period from 0 to 1 MWd/kgHM because of the two predominant Gd isotopes, ^{155}Gd and ^{157}Gd. As Gd_2O_3 absorbs neutrons and slowly depletes, k_{inf} increases significantly with fuel burnup to a maximum at 4 MWd/kgHM at the point where the gadolinium is almost completely depleted. After that, it decreases as burnup increase at the same rate as fuel assembly without gadolinium, down to the end of the cycle (EOC). Similarly, the k_{inf} of fuel assembly with 4 wt.%, 6 wt.%, and 8 wt.% Gd_2O_3 decrease in the period from 0 to 3, 4, and 6 MWd/kgHM and increases significantly as the fuel burnup proceeds to reach a maximum of 7, 9, and 11 MWd/kgHM respectively, and then decreases again to achieve a subcritical at EOC. For all UO_2 + Gd_2O_3 fuel configurations, the curve of k_{inf} on the burnup has a similar profile and values.

Table 2. Isotopic concentration of fuel material in VVER-1000 assembly (in atoms per barn per cm)

UO_2 fuel with 3.7 wt.% ^{235}U	^{235}U		^{238}U	^{16}O	
	$8.6264\ 10^{-4}$		$2.2169\ 10^{-2}$	$4.6063\ 10^{-2}$	
UO_2 fuel with 3.6 wt.% ^{235}U	^{235}U		^{238}U	^{16}O	
	$7.5912\ 10^{-4}$		$2.0071\ 10^{-2}$	$4.1660\ 10^{-2}$	
UO_2 fuel with 3.6 wt.% ^{235}U and 2 wt.% Gd_2O_3	^{235}U	^{238}U	^{16}O	^{152}Gd	^{154}Gd
	$7.4394\ 10^{-4}$	$1.9669\ 10^{-2}$	$4.1757\ 10^{-2}$	$1.2580\ 10^{-6}$	$1.3652\ 10^{-5}$
	^{155}Gd	^{156}Gd	^{157}Gd	^{158}Gd	^{160}Gd
	$9.2705\ 10^{-5}$	$1.2801\ 10^{-4}$	$9.7400\ 10^{-5}$	$1.5358\ 10^{-4}$	$1.3353\ 10^{-4}$
UO_2 fuel with 3.6 wt.% ^{235}U and 4 wt.% Gd_2O_3	^{235}U	^{238}U	^{16}O	^{152}Gd	^{154}Gd
	$7.2875\ 10^{-4}$	$1.9268\ 10^{-2}$	$4.1854\ 10^{-2}$	$2.5159\ 10^{-6}$	$2.7303\ 10^{-5}$
	^{155}Gd	^{156}Gd	^{157}Gd	^{158}Gd	^{160}Gd
	$1.8541\ 10^{-4}$	$2.560\ 10^{-4}$	$1.9480\ 10^{-4}$	$3.0715\ 10^{-4}$	$2.6706\ 10^{-4}$
UO_2 fuel with 3.6 wt.% ^{235}U and 6 wt.% Gd_2O_3	^{235}U	^{238}U	^{16}O	^{152}Gd	^{154}Gd
	$7.1357\ 10^{-4}$	$1.8867\ 10^{-2}$	$4.1951\ 10^{-2}$	$3.7739\ 10^{-6}$	$4.0955\ 10^{-5}$
	^{155}Gd	^{156}Gd	^{157}Gd	^{158}Gd	^{160}Gd
	$2.7812\ 10^{-4}$	$3.8403\ 10^{-4}$	$2.9220\ 10^{-4}$	$4.6073\ 10^{-4}$	$4.0059\ 10^{-4}$
UO_2 fuel with 3.6 wt.% ^{235}U and 8 wt.% Gd_2O_3	^{235}U	^{238}U	^{16}O	^{152}Gd	^{154}Gd
	$6.9839\ 10^{-4}$	$1.8465\ 10^{-2}$	$4.2048\ 10^{-2}$	$5.0318\ 10^{-6}$	$5.4606\ 10^{-5}$
	^{155}Gd	^{156}Gd	^{157}Gd	^{158}Gd	^{160}Gd
	$3.7082\ 10^{-4}$	$5.1204\ 10^{-4}$	$3.8960\ 10^{-4}$	$6.1430\ 10^{-4}$	$5.3412\ 10^{-4}$

Table 3. Isotopic concentration of non-fuel material in VVER-1000 assembly (in atoms per barn per cm)

Zirconium alloy	^{90}Zr	^{91}Zr	^{92}Zr	^{94}Zr
	$2.1913\ 10^{-2}$	$4.7786\ 10^{-3}$	$7.3042\ 10^{-3}$	$7.4021\ 10^{-3}$
	^{96}Zr	^{93}Nb	^{174}Hf	^{176}Hf
	$1.1925\ 10^{-3}$	$4.2250\ 10^{-4}$	$1.0555\ 10^{-8}$	$3.4700\ 10^{-7}$
	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf
	$1.2270\ 10^{-6}$	$1.7997\ 10^{-6}$	$8.9851\ 10^{-7}$	$2.3142\ 10^{-6}$
MOD1: moderator, 0.6 g per kg of boron, T_m = 575 K, ρ = 0.7235 gcm^{-3}	^{1}H	^{16}O	^{10}B	^{11}B
	$4.843\ 10^{-2}$	$2.422\ 10^{-2}$	$4.794\ 10^{-6}$	$1.942\ 10^{-5}$
MOD2: moderator, without boron, T_m = 575 K, ρ = 0.7235 gcm^{-3}	^{1}H		^{16}O	
	$4.843\ 10^{-2}$		$2.422\ 10^{-2}$	
MOD3: moderator, without boron, T_m = 300 K, ρ = 1.0033 gcm^{-3}	^{1}H		^{16}O	
	$6.717\ 10^{-2}$		$3.358\ 10^{-2}$	

It can be said that the increase and decrease in k_{inf} value just shows how fuel element potential to fission changes during each burn time, and at the end, it almost converges to the same position on fuel burnup degree (MWd/kgHM) of fuel element without burnable absorber. It could also be known that with higher burnable poison, then it will need more time to deplete all absorber isotopes so its effect could be neglected, and it could be seen in fig. 4 that a higher concentration of burnable poison absorber needs a lot longer time to deplete.

Table 4 presents the k_{inf} of fuel assembly derived from fig. 4 with its comparison in the same configuration, Gd_2O_3 concentration and burnup level. It could be seen from the table, that the deviation fraction of k_{inf} between the assembly with 0 wt.% Gd_2O_3 and 4 wt.% Gd_2O_3 as a standard burnable poison used in VVER-1000 is ~9.71 %, while the assembly with 2 wt.%, 6 wt.%, and 8 wt.% Gd_2O_3 is ~1.25 %, ~ –0.69 %, and ~ –1.21 %, respectively. However, at the middle of the cycle (MOC), those deviations become very small (0.08 %, –0.03 %, –0.05 %) and very small also (–0.05 %, –0.13 %, 0.03 %) at the end of the cycle (EOC). This is caused by burnable poison that is depleted during the burnup process leaving fissile material to be burned as it was before.

In the reactor design, the Doppler temperature coefficient (DTC) and the moderator temperature coefficient (MTC) are also considered basic safety parameters. To ensure the safety of reactor operation, generally, a negative DTC and MTC are considered. DTC is caused by an increase in fuel temperature which influences the Doppler broadening of nuclear material in the resonance energy region. In this study, the DTC was calculated by using the following equation

$$DTC \quad \frac{k_2 \quad k_1}{k_2 \quad k_1} \frac{1}{T} \tag{1}$$

where k_1 was calculated while both moderator and fuel temperatures were at 575 K, k_2 was calculated while

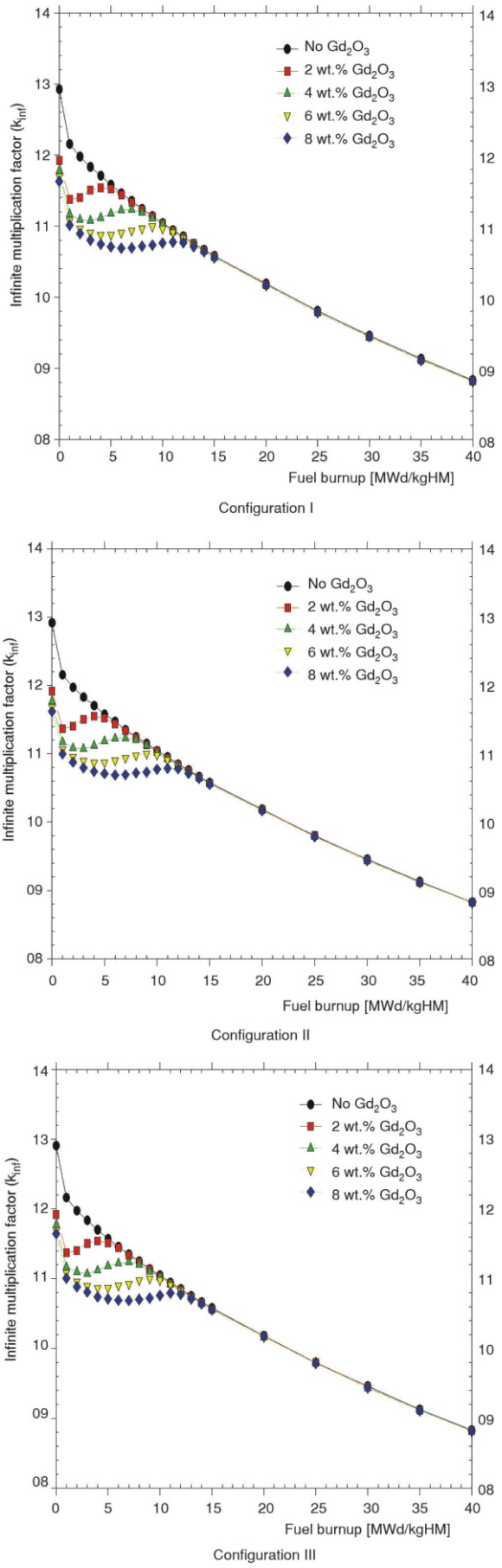

Figure 4. Infinite neutron multiplication factor (k_{inf})

moderator temperature was at 575 K and fuel at 1027 K, and T = 452 K.

Table 5 presents the results of DTC for each combination of gadolinium concentration and UO_2 + Gd_2O_3 fuel configurations. It can be seen from the table that, the DTC values even without burnable poison were negative and increased their negativity as fuel burned. As the gadolinium concentration increases, the amount of UO_2 decreases, and the effect of Doppler broadening on fertile material tends to increase caused by slightly lower fissile material density, increasing the capture-to-fission ratio. The DTC being observed does not reflect any significant difference between all three UO_2 + Gd_2O_3 fuel configurations.

The calculation of MTC was carried out by the following eq.

$$MTC \quad \frac{k_1 \quad k_3}{k_1 \quad k_3} \frac{1}{T} \tag{2}$$

where k_3 was calculated while the moderator temperature was at 300 K and fuel was at 575 K. The k_1 was calculated while both moderator and fuel temperatures were at 575 K, so that T = 275 K.

Generally, MTC was affected by the fuel-to-moderator ratio. A decrease in moderator density, due to an increase in light water temperature, will lead to an increase in the fuel-to-moderator ratio. This could lead to a decrease in neutron moderation and a decrease in the multiplication factor of an under-moderated fuel assembly since we lose the moderation capabilities of the fuel assembly. Since light water density decreases with increasing its temperatures from 1.0033 gcm^{-3} at 300 K to 0.7235 gcm^{-3} at 575 K, with less moderation, the MTC could become negative on a properly designed fuel assembly.

Table 6 presents the results of MTC for each combination of gadolinium concentration and the three configurations being considered. From the table, it is found that the MTC values are all negative and more negative than previously observed DTC. At BOC, as gadolinium concentration increases, the MTC value increases negatively. At MOC, this trend does not repeat except only at 2 wt.% Gd_2O_3 concentration on configurations II and III. Same as without burnable poison, the MTC value becomes more negative as fuel was burned but mostly, the trend was as burnable poison concentrations increased, the MTC shows less negative value. It can be rooted in both fuel-to-moderator ratio and additional neutron absorption from gadolinium itself.

As gadolinium concentrations increase, the fuel concentration decreased slightly in the fuel assembly since the burnable absorber pin only covers 12 of 312 fuel pins in the fuel assembly. It will slightly move the moderation efficiency of fuel assembly since a slightly lower fuel-to-moderator ratio could increase moderation efficiency slightly and lead to a slightly positive MTC. But this phenomenon was not seen at the beginning of the cycle when the burnable absorber itself still

Table 4. Infinite multiplication factor (k_{inf})

Gd_2O_3 concentration	Burnup [MWd/kgHM]	Configuration I	Configuration II	Configuration III
0%	0	1.29236 0.00008	1.29180 0.00008	1.29103 0.00008
	20	1.01925 0.00008	1.01888 0.00008	1.01824 0.00008
	40	0.88342 0.00008	0.88277 0.00008	0.88302 0.00008
2 %	0	1.19234 0.00008	1.19171 0.00008	1.19224 0.00008
	20	1.01784 0.00008	1.01832 0.00008	1.01814 0.00008
	40	0.88234 0.00008	0.88269 0.00008	0.88235 0.00008
4 %	0	1.17802 0.00008	1.17692 0.00008	1.17727 0.00008
	20	1.01754 0.00008	1.01772 0.00008	1.01674 0.00008
	40	0.88185 0.00008	0.88202 0.00008	0.88243 0.00008
6 %	0	1.16992 0.00008	1.16840 0.00008	1.16966 0.00008
	20	1.01738 0.00008	1.01714 0.00008	1.01671 0.00008
	40	0.88072 0.00008	0.88118 0.00008	0.88083 0.00008
8 %	0	1.16298 0.00008	1.16192 0.00008	1.16464 0.00008
	20	1.01647 0.00008	1.01649 0.00008	1.01762 0.00008
	40	0.88215 0.00008	0.88287 0.00008	0.88220 0.00008

Table 5. Doppler temperature coefficient (DTC, k/k K^{-1})

Gd_2O_3 concentration	Burnup [MWd/kgHM]	Configuration I	Configuration II	Configuration III
0 %	0	$-1.28048\ 10^{-5}$	$-1.28434\ 10^{-5}$	$-1.29346\ 10^{-5}$
	20	$-1.91902\ 10^{-5}$	$-1.90895\ 10^{-5}$	$-1.93802\ 10^{-5}$
	40	$-2.34848\ 10^{-5}$	$-2.36240\ 10^{-5}$	$-2.25021\ 10^{-5}$
2 %	0	$-1.48388\ 10^{-5}$	$-1.45178\ 10^{-5}$	$-1.47981\ 10^{-5}$
	20	$-1.95301\ 10^{-5}$	$-1.91609\ 10^{-5}$	$-1.93893\ 10^{-5}$
	40	$-2.31323\ 10^{-5}$	$-2.35763\ 10^{-5}$	$-2.31349\ 10^{-5}$
4 %	0	$-1.49506\ 10^{-5}$	$-1.52112\ 10^{-5}$	$-1.50382\ 10^{-5}$
	20	$-1.95393\ 10^{-5}$	$-1.95387\ 10^{-5}$	$-1.98293\ 10^{-5}$
	40	$-2.28316\ 10^{-5}$	$-2.24023\ 10^{-5}$	$-2.24501\ 10^{-5}$
6 %	0	$-1.51995\ 10^{-5}$	$-1.52619\ 10^{-5}$	$-1.50738\ 10^{-5}$
	20	$-1.96978\ 10^{-5}$	$-1.97663\ 10^{-5}$	$-1.99563\ 10^{-5}$
	40	$-2.35366\ 10^{-5}$	$-2.36138\ 10^{-5}$	$-2.38197\ 10^{-5}$
8 %	0	$-1.53941\ 10^{-5}$	$-1.54832\ 10^{-5}$	$-1.51739\ 10^{-5}$
	20	$-1.99379\ 10^{-5}$	$-1.99229\ 10^{-5}$	$-1.99669\ 10^{-5}$
	40	$-2.32972\ 10^{-5}$	$-2.30733\ 10^{-5}$	$-2.37535\ 10^{-5}$

exists a lot on the fuel element and still dominates the absorption to fission ratio. When fuel was burned, followed by a burnable absorber reduced in fuel elements, the slight increase in moderation efficiency takes over and could be observed as a slight increase in MTC value. This phenomenon was observed clearly when gadolinium concentrations were more than 4 wt.% when the effect of the fuel-to-moderator ratio was dominant enough rather than at 2 wt.% concentration.

CONCLUSION

Study on the effect of burnable absorbers on criticality and reactivity coefficient of VVER-1000 assembly has been conducted with a 3-D Monte Carlo transport code MCNP6 and ENDF/B-VII.1 nuclear library. The Gd_2O_3 content varying from 0 wt.% to 8 wt.% was taken into account to complete the inter-comparison analysis between the results for three fuel configurations. At BOC, there was a significant difference in criticality between assemblies with and without Gd_2O_3. However, this difference became very small at MOC and almost the same at EOC. The DTC values were always quite negative and tended to become more negative with increasing gadolinium concentration and fuel burnup. At BOC, the MTC values became more negative with increasing gadolinium concentration. However, this trend did not occur at MOC, possibly due to the fuel composition. At EOC, no clear trend in the MTC values with respect to Gd_2O_3 concentration is predicted because the Gd_2O_3 absorbing effect has been significantly reduced. The results concluded that the addition of Gd_2O_3 enhances negative reactivity coefficients (DTC and MTC) at the beginning of

Table 6. Moderator temperature coefficient (MTC, k/k K^{-1})

Gd_2O_3 concentration	Burnup [MWd/kgHM]	Configuration I	Configuration II	Configuration III
0 %	0	$-9.33246\ 10^{-5}$	$-9.38223\ 10^{-5}$	$-9.35157\ 10^{-5}$
	20	$-1.35930\ 10^{-4}$	$-1.35259\ 10^{-4}$	$-1.35792\ 10^{-4}$
	40	$-1.17803\ 10^{-4}$	$-1.17776\ 10^{-4}$	$-1.17253\ 10^{-4}$
2 %	0	$-1.25352\ 10^{-4}$	$-1.24852\ 10^{-4}$	$-1.23595\ 10^{-4}$
	20	$-1.35266\ 10^{-4}$	$-1.35591\ 10^{-4}$	$-1.35988\ 10^{-4}$
	40	$-1.18540\ 10^{-4}$	$-1.16942\ 10^{-4}$	$-1.17863\ 10^{-4}$
4 %	0	$-1.41288\ 10^{-4}$	$-1.41341\ 0^{-4}$	$-1.38966\ 10^{-4}$
	20	$-1.35389\ 10^{-4}$	$-1.34998\ 10^{-4}$	$-1.34805\ 10^{-4}$
	40	$-1.17873\ 10^{-4}$	$-1.12758\ 10^{-4}$	$-1.17603\ 10^{-4}$
6 %	0	$-1.50742\ 10^{-4}$	$-1.50318\ 10^{-4}$	$-1.47548\ 10^{-4}$
	20	$-1.34929\ 10^{-4}$	$-1.34603\ 10^{-4}$	$-1.34304\ 10^{-4}$
	40	$-1.17326\ 10^{-4}$	$-1.17906\ 10^{-4}$	$-1.18504\ 10^{-4}$
8 %	0	$-1.56543\ 10^{-4}$	$-1.56325\ 10^{-4}$	$-1.53128\ 10^{-4}$
	20	$-1.34918\ 10^{-4}$	$-1.34500\ 10^{-4}$	$-1.34468\ 10^{-4}$
	40	$-1.17815\ 10^{-4}$	$-1.17453\ 10^{-4}$	$-1.17314\ 10^{-4}$

the cycle, which is an important safety feature. However, these effects become less significant with increasing fuel burnup as the Gd_2O_3 is depleted.

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Zuhair: conceptualization, formal analysis, methodology, software, writing – original draft, writing – review and editing. W. Luthfi: writing – original draft, software, formal analysis. M. D. Isnaini: writing – review and editing, methodology. Sriyono: writing – review and editing, Suwoto: methodology, writing – review and editing, supervision.

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УТИЦАЈ САГОРИВИХ АПСОРБЕРА НА КОЕФИЦИЈЕНТЕ КРИТИЧНОСТИ И РЕАКТИВНОСТИ АНСАМБЛА РЕАКТОРА VVER-1000

Сагориви апсорбери играју важну улогу у сигурности нуклеарног реактора и истраживање њиховог утицаја на понашање језгра реактора важно је питање у дизајну и раду језгра реактора. Циљ овог рада је да се открије утицај сагоривих апсорбера на критичност и коефицијент реактивности склопа реактора VVER-1000. Прорачуни су спроведени помоћу 3-D Монте Карло транспортног кода MCNP6 и нуклеарне библиотеке ENDF/B-VII.1. Садржај Gd_2O_3 вариран је од 0 до 8 тежинских процената да би се извршила анализа међусобног поређења између коефицијената критичности и реактивности за три конфигурације горива UO_2 + Gd_2O_3. На почетку циклуса постоји значајна разлика између критичности ансамбла са и без Gd_2O_3, међутим, на средини циклуса, те разлике постају веома мале и скоро исте на крају циклуса. Вредности Доплеровог температурног коефицијента су увек довољно негативне и показују негативнији тренд са повећањем концентрације гадолинијума и сагоревања горива. На почетку циклуса, вредност температурног коефицијента модератора расте негативно како се концентрација гадолинијума повећава, али на средини циклуса овај тренд се не јавља. Претпоставља се да је састав горива разлог за ову околност. На крају циклуса не постоји јасан тренд вредности температурног коефицијента модератора у односу на концентрацију Gd_2O_3. Чини се да се апсорбујући ефекат Gd_2O_3 значајно смањио. У целини, ово истраживање пружа увид у утицај сагоривих апсорбера на неутронске параметре склопа реактора VVER-1000 и њихове доприносе сигурности реактора.

Кључне речи: сагориви апсорбер, конфигурација UO_2+Gd_2O_3, критичност, коефицијент реактивности, склоп VVER-1000