Journal of Nuclear and Particle Physics 2021, 11(1): 15-26
DOI: 10.5923/j.jnpp.20211101.03

Sensitivity Analysis of the Kinetic Parameters to Physical Parameters Variation in VVER Reactor

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Abstract The effective delayed neutron fraction and the neutron generation time are the most important parameters of reactor kinetics. The main objective of this paper is to identify the influential physical parameters on kinetic parameters (sensitivity analysis). The influence of the control rod movement, temperature changes, fuel consumption, fuel enrichment, and burnable absorbers BAs on kinetic parameters is investigated. The calculations are performed using MCNP6 code together with (ENDF/B)-VII.1 library for VVER-1000. The study evidenced that fuel consumption, temperature increasing and control rod movement have the greatest influence on the effective delayed neutron fraction. The value of $ß_{eff}$ reduced by fuel combustion after 365 days and by rising temperature by 33.5% and 20.9% respectively. While increased to 12.11% with fully insertion of control rods. β_{eff} parameter is not influenced by the fuel enrichment. Also, the fuel enrichment and insertion of control rods have the greatest effect on the generation time. The influence of the BAs material on the dependence of the kinetic parameters on the BAs enrichment is presented.

Keywords Kinetic parameters, Effective delayed neutron fraction, Generation time, Power reactors, Monte Carlo code

1. Introduction

The determination of kinetic parameters is of major importance in reactor physics calculations because of its important role in the transitional reactivity analysis, safety and control of nuclear reactors. Kinetic parameters are the effective delayed neutron fraction, prompt neutron lifetime and neutron generation time.

The effective fraction of delayed neutrons is a key safety parameter in nuclear reactors as it plays a scale role in the reactivity value of control bars, vacuum fractions, Doppler effect, etc. [1]. It is crucial that nuclear reactors have delayed neutrons because they act to control the rate of increase in reactor power. Without delay neutrons, the reactor's power will increase in such a magnitude and in such a short time period that significant damage will result [2]. The effective delayed neutron fraction determines the time-dependent response of the reactor. A smaller value of β_{eff} indicates that a larger fraction of the fission neutrons appears as the prompt neutrons; therefore, the kinetic response of the reactor is quicker. Conversely, a larger value of β_{eff} indicates that a smaller fraction of the fission neutrons appears as the prompt neutrons and the core has a slower response [3].

The effective total delayed neutron fraction is designated as β_{eff} and is normally obtained from the following relationship [4]:

$$\boldsymbol{\beta_{eff}} = \sum_m \sum_i \overline{\gamma}_{d,i}^{(m)} \frac{\left\langle \left\langle \phi^+(r,E)\chi_{d,i}^{(m)}(E) \left\langle \Sigma_f^{(m)}(r,\acute{E})\phi(r,\acute{E}) \right\rangle_{\acute{E}} \right\rangle_E \right\rangle_r}{\sum_m \left\langle \left\langle \phi^+(r,E)\chi^{(m)}(E) \left\langle \gamma^{(m)}(\acute{E})\, \Sigma_f^{(m)}(r,\acute{E})\phi(r,\acute{E}) \right\rangle_{\acute{E}} \right\rangle_E \right\rangle_r} \quad (1)$$

Where 'm' is the fissile isotope index, 'i′ the delayed neutron family index, ′$\chi_{d,i}^{(m)}$′ is the delayed neutron spectrum for fissile isotope m and delayed neutron family i, ′$\chi^{(m)}$′ is the total neutron spectrum for fissile isotope m, ′$\overline{\gamma}_{d,i}^{(m)}$′ is the average value of delayed neutrons emitted from fissile isotope m and delayed neutron family i, for a given incident neutron spectrum, ′$\gamma^{(m)}$′ is the total neutron emitted from fissile isotope m, and ′$\Sigma_f^{(m)}$′ The macroscopic fission cross section of the fissile isotope m.

Another important kinetic parameter that characterizes the time behavior of neutron population is the prompt neutron lifetime. The prompt neutron lifetime (l_p) has an impact on the time scale of the reactor core response to reactivity changes. It is related to the neutron generation time and therefore is a measure of the time that it takes for changes in the core multiplication factor to affect the neutron population. In reactor kinetics, the prompt neutron lifetime is defined as the mean time for one neutron to be removed from the reactor i.e. it is the average time between the emission of a fission neutron and its final absorption in the active part of the reactor core. [5]

Also the prompt neutron generation time (Λ) called reproduction time. It is often used to determine the dynamic

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Received: Mar. 31, 2021; Accepted: Apr. 12, 2021; Published: Apr. 25, 2021
Published online at http://journal.sapub.org/jnpp

response of a nuclear reactor [6]. It is defined as mean time required for one generation of neutrons to produce, due to fission, another generation of prompt neutrons or precursors [7]. The neutron generation time is related to the prompt neutron lifetime by ($\Lambda = l_p/k_{eff}$) therefore is a measure of the time that it takes for changes in the core multiplication factor to affect the neutron population [8]. For a critical system (k ~ 1), the prompt neutron lifetime is equal to the mean generation time (Λ), I. e. The time of neutron removal is equal to the time for neutron creation. Consequently, in a subcritical system, the neutron lifetime is smaller than the generation time and vice versa in a supercritical system [1].

Also, it is a very important characteristic because of its own definition it is inversely proportional to macroscopic absorption cross section and consequently, to inverse ^{235}U atom density, this can be explained from its definition [9] as shown in equation 2:

$$\boldsymbol{\Lambda} \equiv \frac{\int \boldsymbol{\phi_0^+ \phi (1/v) dvdr}}{\int ((\boldsymbol{1-\beta})\boldsymbol{\chi} + \sum_i \boldsymbol{\beta_i \chi_i})\boldsymbol{\phi_0^+ v} \sum_f \boldsymbol{\phi dvdr}} \propto \frac{\mathbf{1}}{\boldsymbol{\Sigma_a}} \qquad (2)$$

The information about kinetic parameters is important in the safety analysis of nuclear reactors. When designing the nuclear reactor, evolution of kinetic parameters is very important on account of their unstable behavior [10]. A worthy design should assure the safe conditions of the reactor core in the life cycle period [11]. The neutronic and dynamic behaviors of the reactor core may be varied from its initial condition at the Beginning of Cycle (BOC) result of changes in many parameters as fuel composition, temperature, and control rod position, etc. The kinetic parameters depend on the time behavior of the reactor power transient after reactivity insertion. The variation of kinetic parameters is very important in nuclear power plant operation since they determine different kinds of safety procedures. It is very difficult to measure β_{eff} and Λ separately (only their ratio, β_{eff}/Λ, can easily be measured), hence these parameters are usually determined only by calculation.

In this paper, the primary goal is to identify the influential physical parameters on kinetic parameters (sensitivity analysis). The influence of several physical parameters on the kinetic parameters is studied and analyzed. These parameters are temperature changes, the position of the control rods, fuel consumption, enrichment of uranium fuel, and the presence of burnable absorbers as well the enrichment of BAs in the fuel. The calculations are performed using the Monte Carlo code MCNP6 [12] [13] together with the Evaluated Nuclear Data Files, part B (ENDF/B)-VII.1 [14]. This study is focused on PWRs that have hexagonal geometries. The Russian designed VVER is a pressurized water reactor that uses hexagonal fuel assemblies with triangularly pitched fuel rods and annular pellets. The reference power plant for this investigation is VVER-1000/V320 reactor [15] [16].

2. Brief Description of VVER-1000/V320 Reactor Core

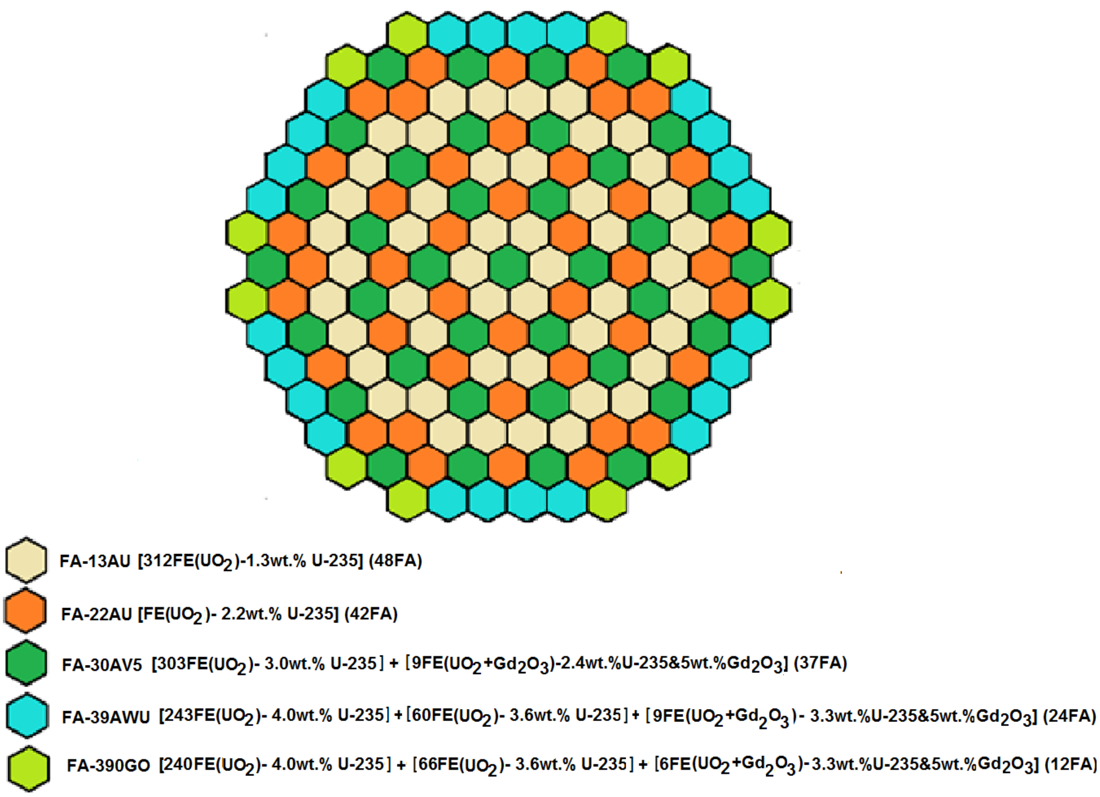

Figure 1. Core loading pattern for first cycle of VVER-1000/V320

VVER-1000/V320 [15] [16] reactor core is made up from 163 hexagonal fuel assemblies of the same geometry producing 3000 MWth at full operating power. Each fuel assembly consists of 312 fuel rods containing uranium dioxide (UO_2). The VVER-1000/V320 core loading pattern for the first fuel cycle consists of five fuel assembly type. The fuel assemblies' arrangements are shown in Figure 1.

Each fuel assembly has different enrichment, different numbers of fuel pins with different enrichment (radial profiling) as well as different pin numbers with burnable absorber and weight percentage of the burnable absorber Gd_2O_3. The enrichment of gadolinium oxide in U-Gd is 5.0%. The isotopic compositions of the fuel, cladding, central and guide tubes, absorber cladding, absorber rod, steel buffer, steel barrel and steel vessel are presented in the [15].

In fuel assembly (FA), there are 19 special channels. One of the channels is used to place neutron-measuring sensors of in-core instrumentation system. Eighteen channels are the guiding channels. The guiding channels are normally empty and light water flows through them. In some of the fuel assemblies Control Protection System (CPS) absorbing rods moves in them with the help of mechanical drives. Control Protect System Control Rods (CPS CRs) can be placed into the guiding channel of 121 non-periphery fuel assembly. 103 CPS CRs are required for reaching reactor sub-criticality even if there is no boron acid in the core. Burnable absorber serves for decreasing boric acid concentration at the beginning of the fuel cycle and for provision of negative coolant temperature coefficient of reactivity. They are used also for flattening the radial power distribution in the core. The absorber integrated with fuel (gadolinium in the form of oxide Gd_2O_3) with natural content of isotopes is used as the burnable absorber. The pin lattice layouts of the different FA types are shown in the figure 2. [15] In present work, MCNP6 code is used to simulate the full core of the VVER-1000/V320 reactor.

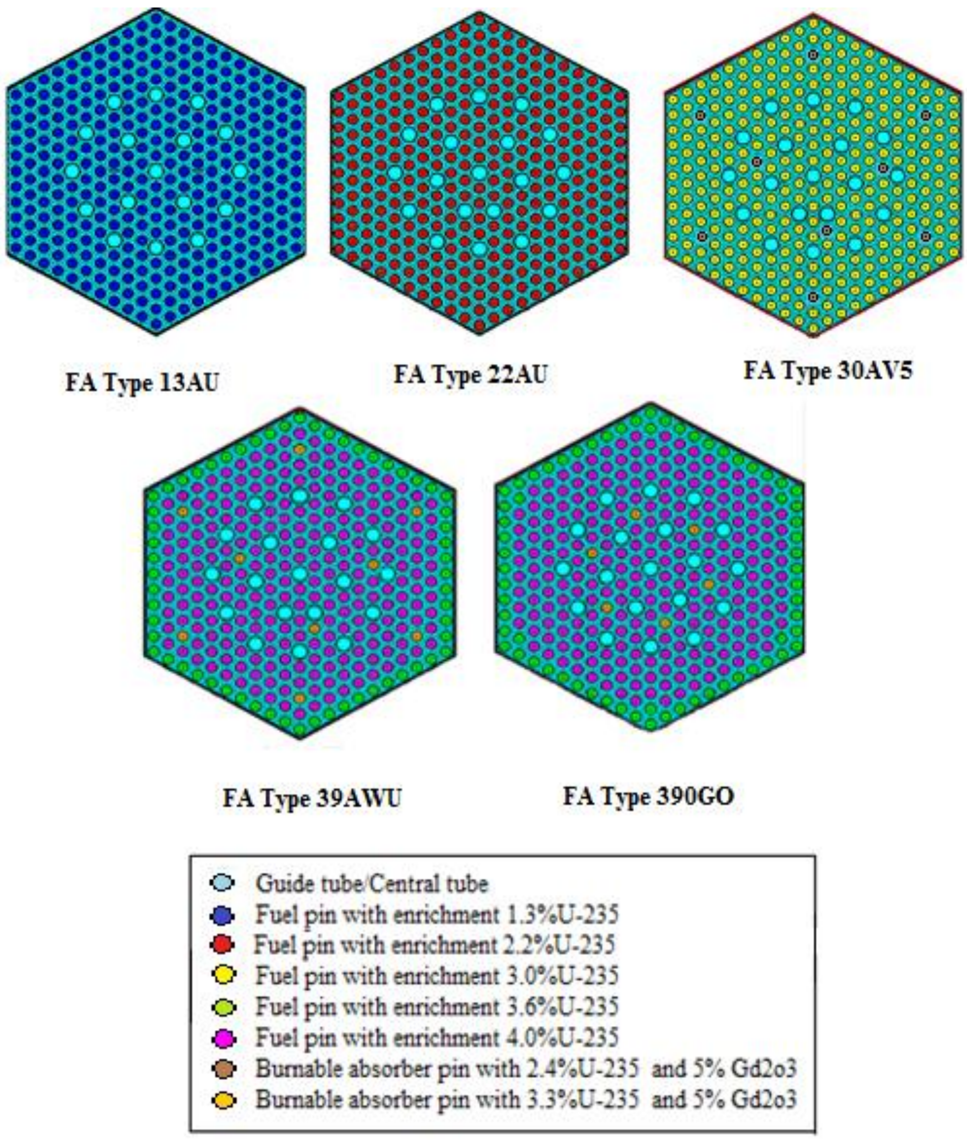

Figure 2. Pin layout of the FA types 13AU, 22AU, 30AV5 and 39AWU

3. Model and Calculation Procedures

This paper has examined and analyzed the influence of several physical parameters on kinetic parameters (the effective delayed neutron fraction (β_{eff}), and the prompt generation time (Λ)) for VVER-1000 reactor.

MCNP is a general-purpose, continuous-energy, generalized-geometry, time-dependent, Monte Carlo radiation-transport code designed to track many particle types over broad ranges of energies. MCNP6 represents the culmination of a multi-year effort to merge the MCNP5 and MCNPX codes into a single product comprising all features of both. The MCNP6 code contains numerous features; one of those is to determine the delayed neutron parameters. The accuracy of the calculated delayed neutron parameters affects the accuracy of transient or dynamic condition. The superiority of the MCNP6 code can be seen in the change of the prompt neutron life time parameter (l_p), that can't be obtained from the deterministic code so can be used in the sensitivity analysis of the delayed neutron parameter. Also, the code has been expanded to handle a multitude of particles and to include model physics options for energies above the cross-section table range, a material burnup feature, and delayed particle production.

The cross section for all materials (I.e. The fuel, cladding, moderator, burnable absorber material and structural) are taken from the ENDF/B-VII.1 library (ENDF71x). Figure 3 shows the full geometric model for the VVER-1000/V320 reactor core layout in MCNP Visual Editor (VisEd). Several models are carried out according to the position of the control rods, burnup level, U-235 loading on the core level, temperature changes, presence of BAs, BAs material which used and the enrichment of BAs in the fuel.

In MCNP code, both KCODE and KSRC cards are used to calculate k_{eff} at beginning of cycle by using both delayed and prompt neutrons. In this work, KCODE simulations were performed using 500 cycles with 1000,000 neutrons per cycle. The first 50 generations were skipped to obtain a well-distributed neutron source and are therefore the result of 500 million active neutron histories.

The effective delayed neutron fraction; β_{eff} is calculated by the MCNP transport code using prompt method [12] [17] which requires two calculations. The effective delayed neutron fraction is defined as shown in Eq.3 [17] [18].

$$\beta_{eff} = \frac{k_{eff} - k_p}{k_{eff}} \quad (3)$$

Where: k_{eff} is the effective multiplication factor for all neutrons (prompt and delayed neutrons). The k_{eff} was acquired in the straight calculation mode of MCNP calculation, using the data card TOTNU and KCODE. When the TOTNU card is used and has no entry after it, the total average number of neutrons from fission (ν) using both prompt and delayed neutrons is used and the total effective multiplication factor (k_{eff}) is calculated.

While k_p is the effective multiplication factor when only prompt neutrons are considered. The method for obtaining k_p in MCNP is rather simply by using the TOTNU card with entry NO while keeping the same KCODE parameters as before. A TOTNU card with NO as the entry causes ν_p to be used, and consequently k_p to be calculated, for all fissionable nuclides for which prompt values are available.

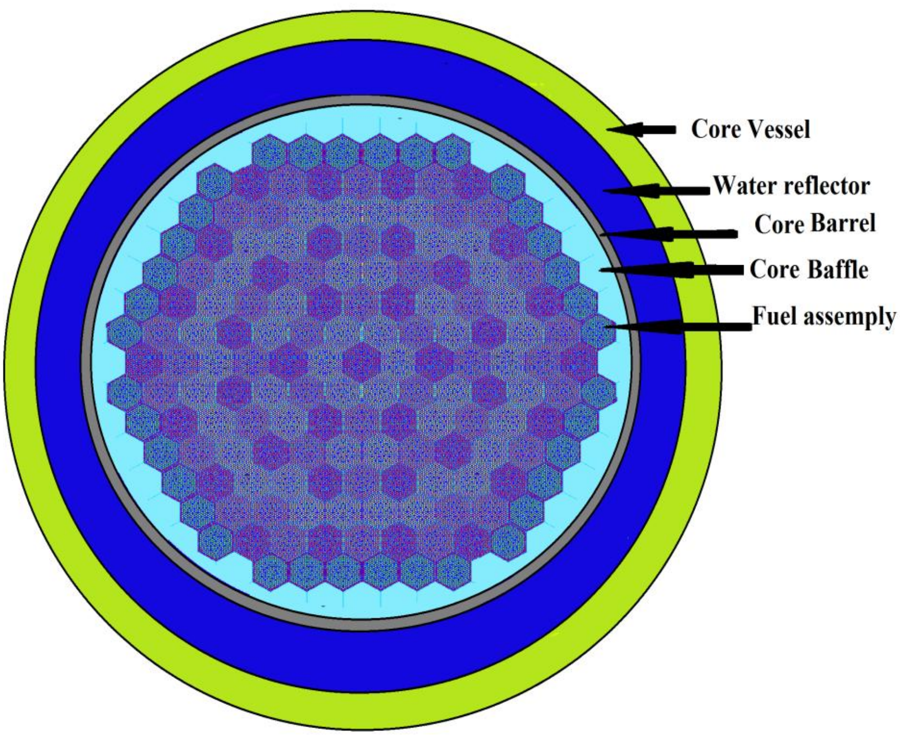

Figure 3. Full MCNP Core Geometry Model for VVER-1000/V320 reactor

The prompt neutron generation time Λ not given explicitly by MCNP code we can get it using Eq.4 [19]. Where l_p, is the prompt removal lifetime, it calculated normally by MCNP code with k_{eff}.

$$\Lambda = \frac{l_p}{k_{eff}} \quad (4)$$

In this paper, to validate, calculate and analyze the kinetic parameters, the calculations are performed in two stages as follows:

First stage: the accurate calculations of the reactor kinetic parameters are very important for the safe operation the reactor. Thus, in this work, after modeling the VVER core by using MCNP6 code, the validation of MCNP6 model is performed by comparing the effective delayed neutron fraction (β_{eff}) result of the MCNP code with the reference data in calculations [15]. The relative difference is obtained by the following equation.

$$\boldsymbol{Relative\ difference}\,\% = \left(\frac{\boldsymbol{MCNP6\ result - Reference\ result}}{\boldsymbol{Reference\ result}}\right) * \mathbf{100} \quad (5)$$

In this step, the calculations for this stage are performed at Beginning of Cycle (BOC), Hot Zero Power (HZP), no Xe-135, no Sm-149, all control rod groups (CRG) are withdrawn (0%) except the group10 it is inserted by 76%, moderator temperature is 280.4℃ (553.55K) and the boron concentration is 6.75g/kg.

Second stage, sensitivity studies are performed to investigate the influence of several physical parameters on the kinetic parameters. The main concern are fuel consumption, fuel enrichment, control rod movement, temperature changes, and the presence or absence of the burnable absorbers, BAs material used as well as their enrichment in the fuel elements. In this stage, all calculations are performed at BOC and Hot Full Power state except for the cases of temperature change. The studies are investigated as follow:

- Influence of the control rod movement on kinetic parameter is investigated. In this step, the calculations of kinetic parameters are carried out at different positions of control rods; when it fully withdrawn as well as when control rods are inserted by 10%, 30%, 50%, 70%, 100%.
- The influence of fuel consumption on the kinetic parameters is investigated. In this step, calculations of kinetic parameters were performed up to 365 days every 50 days.
- Influence of the temperature increases on kinetic parameter is investigated. The temperature gradually increases up to 1200k. The kinetic parameters are calculated at 1027k, 1050k, 1100k, 1150k, and 1200k.
- Influence of the fuel enrichment on kinetic parameter is investigated by comparing the kinetic parameters of the base core with the kinetic parameters of the enriched core. In this step, the calculations are performed by increasing the fuel enrichment of the base core. The fuel assemblies type AU13, which has 1.3% average enrichment of U-235, is replaced with UO_2 fuel assemblies with enrichment 2.0%, 2.5%, 3.0%, 3.5%, 4.0%, 4.5% and 5% w/o respectively.
- Influence of the neutron absorbers in the reactor on kinetic parameter is investigated. Neutron absorbers are placed inside fresh fuel assemblies as a solution in the moderator or Integral Burnable Absorbers (IBAs). Integral Burnable Absorbers are more effective because it controlling the neutron, which generates in the core without depending on the control rods or other control mechanisms, also it mitigates the increase in reactivity at the beginning of operation especially in the first third of assembly life. Present work deals with the IBAs. Two of the operational and industrial integral burnable absorber materials used in pressurized water reactors, including Gadolinium oxide (Gd_2O_3) and Erbium oxide (Er_2O_3) were studied. In this step, to study the effect of BAs on the kinetic parameters; the presence or absence of BAs and the material of BA that used, the VVER-1000 core was modeled without any neutron absorber rods, with gadolinium BA and with erbium BA. Then, the kinetic parameters are calculated for the core with and without neutron absorbers. The kinetic parameters were calculated at BOC, Hot Full Power state. For sensitivity analysis, the comparison between the kinetic parameters for the cases without BAs and with gadolinium BA as well erbium BA is performed. Also, the effect of the enrichment of BAs in the fuel on the kinetic parameters is studied. The kinetic parameters are calculated for the core with several enrichment ranges from 5-10 w/o%.

4. Results and Discussion

4.1. Validation of MCNP Model

The MCNP model is validated by comparing the results of the effective delayed neutron fraction computed by the MCNP6 code with the reference data in the calculations [15]. The effective delayed neutron fraction is calculated using Eq. 3. The MCNP6 results; k_{eff} and k_p as well calculated effective delayed neutron fraction are presented in table1. The standard deviation associated with criticality calculations in MCNP6 code is also presented. Moreover, the relative difference between the β_{eff} of MCNP6 code and the mentioned reference is calculated using Eq. 5 and shown in table 1.

Table 1. Calculated effective delayed neutron fraction compared with reference data

$k_{eff} \pm \sigma$	$k_p \pm \sigma$	β_{eff}		Relative Difference, %
		(MCNP)	(Reference)	
1.04930 ± 0.00017	1.04170 ± 0.00023	0.724	0.73	0.82

Table 1 illustrates that: The statistical uncertainty associated with criticality calculations in MCNP6 is approximately 17.0pcm and 23.0pcm for k_{eff} and k_p, respectively. Also, effective delayed neutron fraction of MCNP results is found to be in close agreement with the reference reported resulting in a very small relative difference (0.82%) is observed this confirms the ability and reliability of MCNP6 results.

4.2. Sensitivity Studies

The dependency of the kinetic parameter on the control rod movement, the temperature changes, the fuel consumption (burn up), the fuel enrichment and the integral burnable absorbers are investigated in this section. The statistical uncertainties (1 standard deviation) associated with criticality calculations in MCNP6 code were ranging from 0.00013 - 0.00025 while with prompt neutron lifetime were from 1.3E-08 - 9.6E-09. Kinetic parameters (the effective delayed neutron fraction and generation time) were calculated using Eq. 3 and Eq. 4 as mentioned previously. The dependency these parameters on the kinetic parameters are studied as follows:

- The influence of control rod movement on the kinetic parameter is investigated as shown in figure 4. This figure shows the variations in the effective delayed neutron fraction and the prompt neutron generation time relative to the control rods position% from the bottom of the reactor.

Figure 4 shows that, the effective delayed neutron fraction increases as the position of the control rod increases, while the prompt neutron generation time decreases. Whereas the insertion of the control rod in the core increases the average neutron velocity, the contribution of the fast fission in the reactor core increases and thermal fission decreases. Due to the increase in fast fissions in the core, the prompt neutron generation time decreased while the effective delayed neutron fraction increased due to increasing contribution of U^{238} in β_{eff}.

Also, in the current study, a higher value of β_{eff} parameter produces when the control rods are fully inserted in the core but the Λ parameter reduces. The value of the effective delayed neutron fraction increased by 12.11% the value of neutron generation time decreased by 14.6%.

- The influence of fuel consumption on kinetic parameters is investigated during 360 days operating time. Figure 5 shows the changes in the effective delayed neutron fraction and the prompt neutron generation during 360 days operating time.

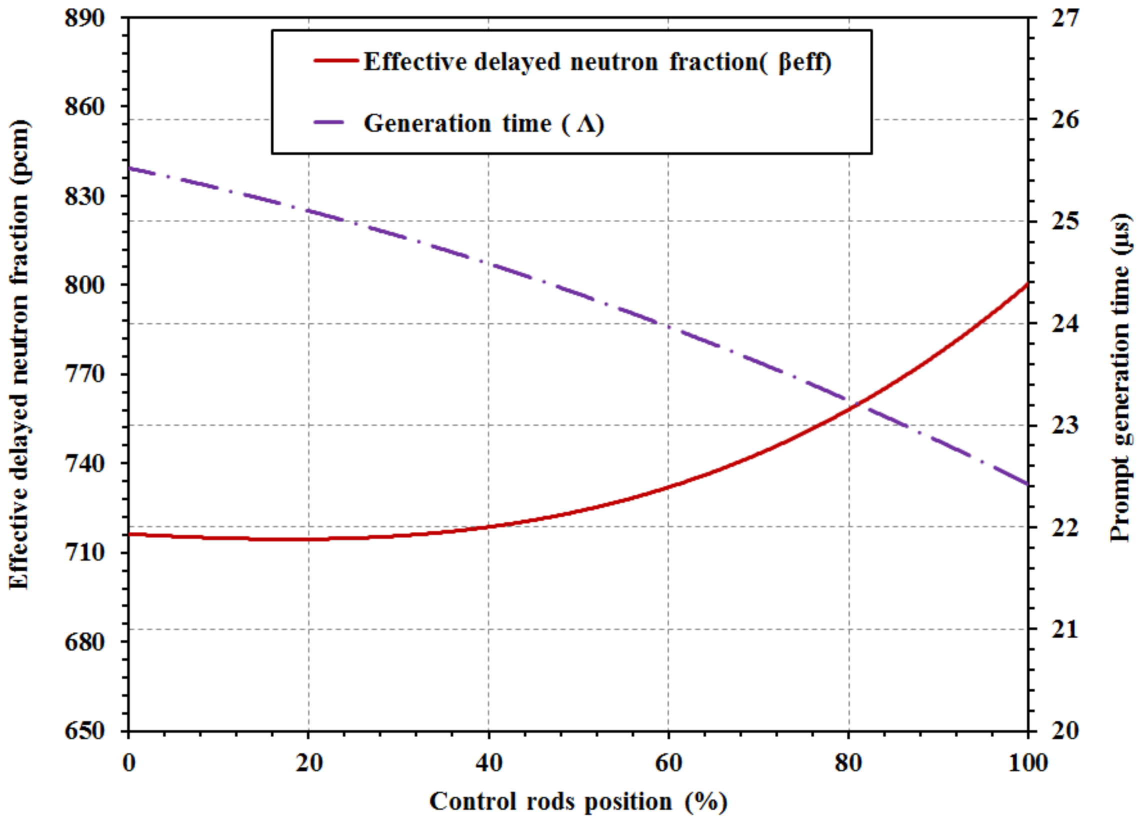

Figure 4. Variations in kinetic parameters versus control rods position%

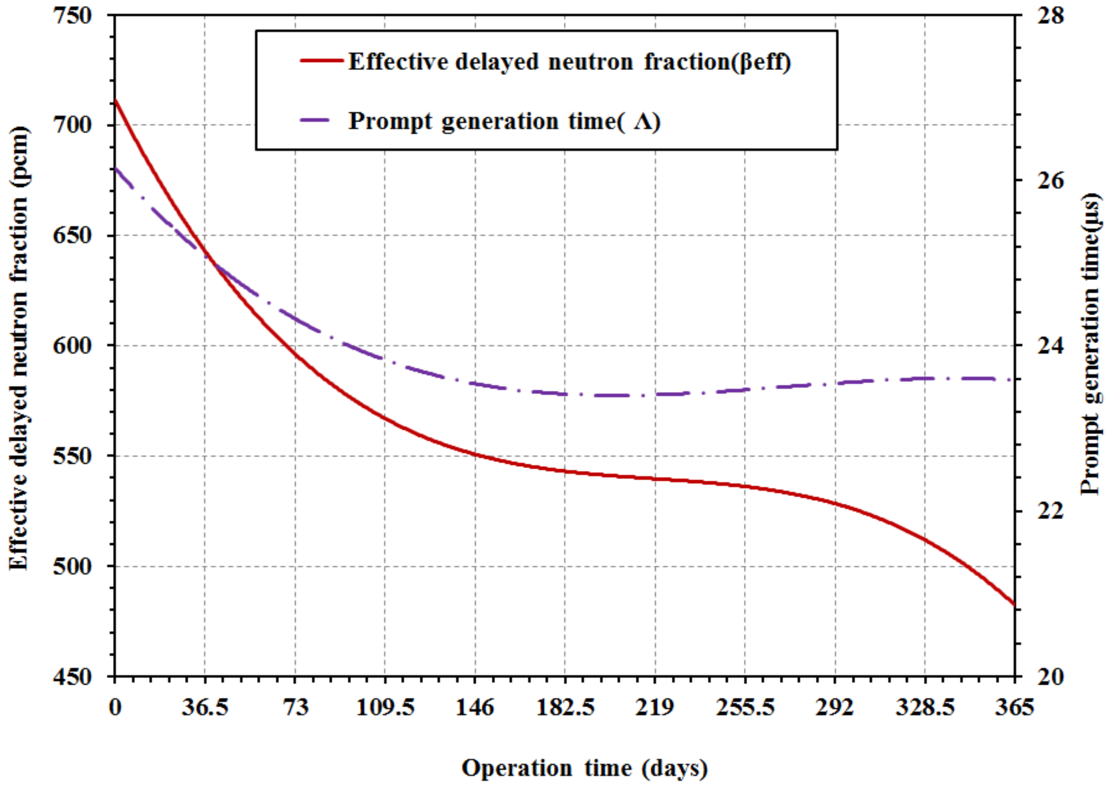

Figure 5. Variations in kinetic parameters versus the operating time

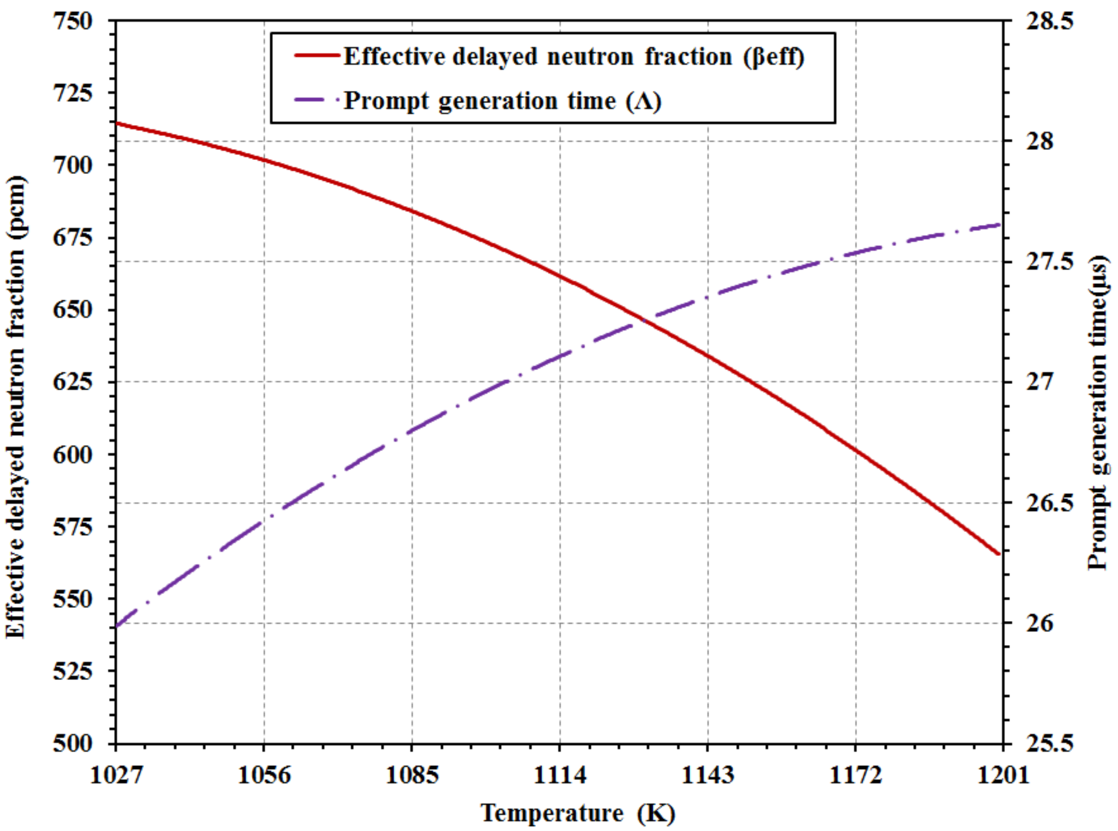

Figure 6. Variations in kinetic parameters versus temperature rising

As shown in figure 5, the β_{eff} reduced from 715pcm at BOC to 475pcm at EOC also; Λ is 26μs at BOC and reduced to 23.7μs at EOC, i.e. the values of β_{eff} and Λ becomes smaller as the burnup increases. This is because fission in lower burnup is caused only by U-235 while in a higher burn up is caused by U-235, Pu-239, Pu-240 and Pu-241 (as a result of plutonium buildup). Owing to, the fact that the Pu-239, Pu-240 and Pu-241 have delayed neutron fraction less than U-235, this leads to the softening of the neutron spectrum during the burnup. Consequently, the effect of delayed neutrons decreases and the value of β_{eff} decreases with fuel depletion. As well, the prompt neutrons decrease by increasing the fuel burnup in the VVER reactor core. Thus the prompt generation time is decreased. Fuel consumption leads to a reduction in the Λ and β_{eff} by 8.85% and 33.5% respectively.

- The influence of temperature increase on VVER kinetic parameters has been investigated. The variations in kinetic parameters with the temperature increase are illustrated in figure 6.

Figure 6 illustrates that, as a result of temperature rise in the VVER core, lower values of the effective delayed neutron fraction produce while higher values produce for prompt generation time parameter. The reason is that: the resonance cross-section increases, due to the increase in temperature, so the more neutrons capture in U-238 consequently, the number of moderated neutrons decreases and thus, the fission process decreased and the generated neutrons in the fuel decreased. Therefore, delay neutron precursors are reduced accordingly; $ß_{eff}$ decreased. The effective delayed fraction decreased by a higher temperature by 20.4%, while the rate of increase was seen for the generation time by 6.4%.

- The influence of fuel enrichment increases on the kinetic parameters has been studied. Figure 7 shows the variations in the β_{eff} and Λ values with the increasing UOX fuel enrichment.

From Figure 7, it can be observed that, the prompt generation time decreased with the increase in ^{235}U content, for the reason that the prompt neutron generation time is inversely proportional to the ^{235}U content. In terms of quantity of this parameter, the dropped percentage is 48% due to the increase in enrichment from 1.3% - 5%. While, doesn’t show any considerable change in the effective delayed neutron fraction by increasing enrichment of fuel. It means the β_{eff} parameter isn't influenced by the fuel enrichment.

- The influence of burnable absorbers on the VVER kinetic parameters is investigated. The variations of effective delayed neutron fraction and prompt neutron generation time for the cases without BAs and with gadolinium BA rods as well with erbium BA rods are shown in Figure 8.

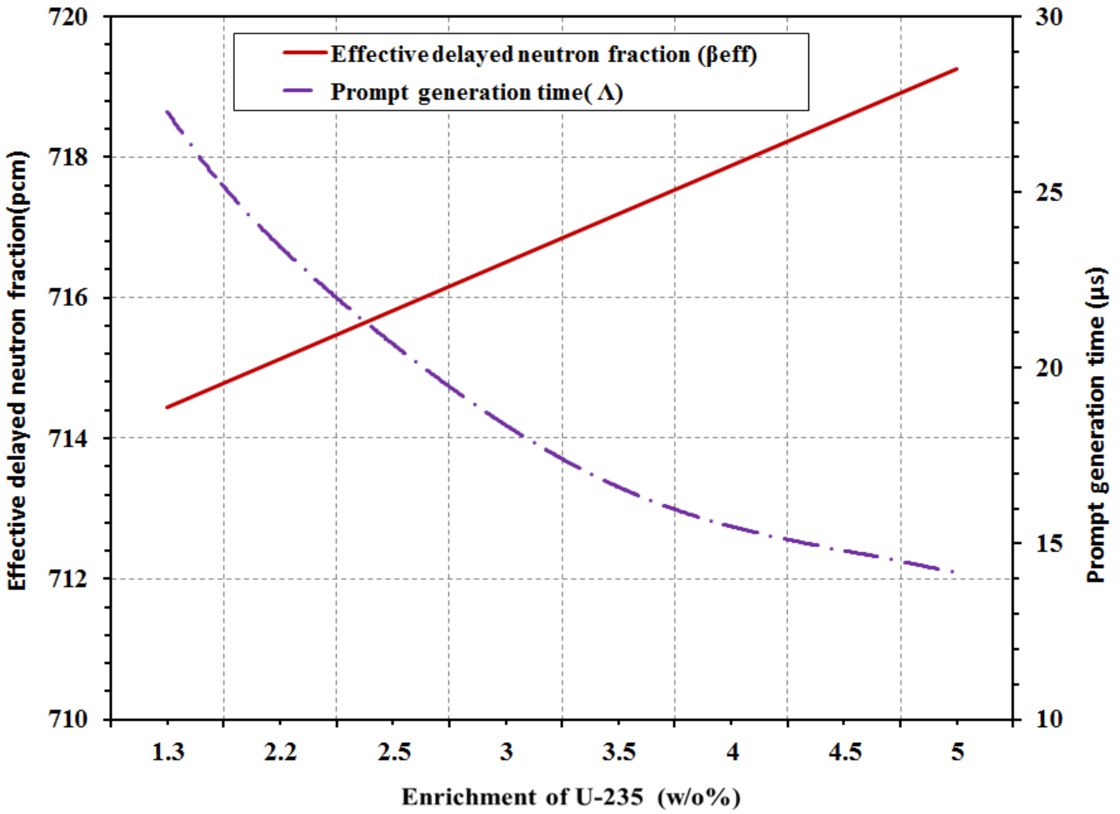

Figure 7. Variations in kinetic parameters versus increasing fuel enrichment

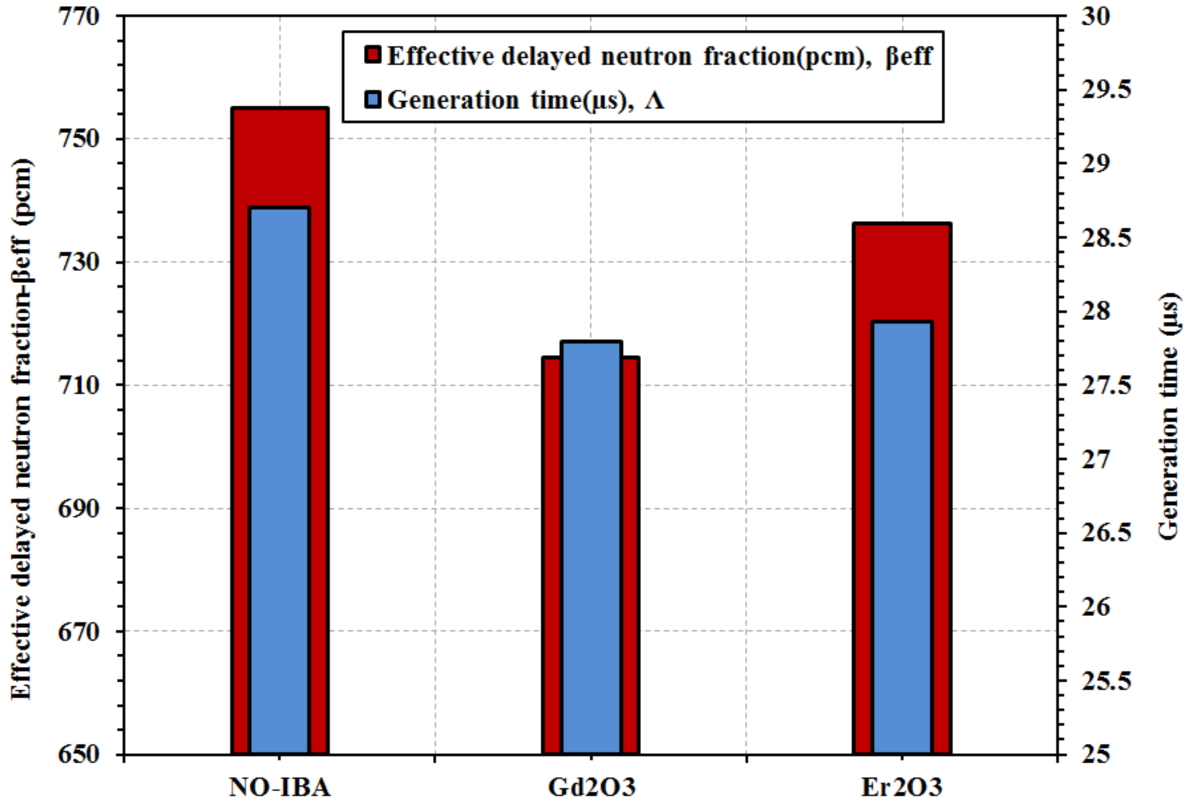

Figure 8. Variations of VVER kinetic parameters with and without IBAs

Figure 8 illustrates that: for the core without any BAs, the value of the effective delayed neutron fraction was much higher than with BAs owing to higher fission reactions. The neutron absorption cross sections increase due to presence of burnable absorbers in the core, and hence the leaking escape probabilities of neutrons increase. Therefore, the (β_{eff}) in the reactor without burnable absorbers becomes larger than in the reactor with burnable absorbers.

As well, the β_{eff} was 715pcm for the core with Gd_2O_3 rods while with Er_2O_3 was 736pcm; this indicates that the β_{eff} for the core with gadolinium is lower than with erbium. That's due to the presence of Gd-155 and Gd-157 that have extraordinarily high thermal neutron absorption cross-sections of 61,100 and 259,000 barns respectively, while the Erbium has thermal neutron absorption cross-sections of 9,100 barns and 312barns for Eu-151 and Eu-153 respectively, thus the effective delayed neutron fraction of the core with gadolinium will be lower than with erbium.

In addition, the generation time was larger without any BAs and smaller in the core with BAs. This due to larger thermal neutron absorption cross section of gadolinium BA and erbium BA compared to the fuel elements. As well, the generation time was slightly smaller for the core with gadolinium BA than with erbium BA. Owing to the fact that, the generation time is inversely proportional to the thermal neutron absorption cross sections (as shown in Eq.2), therefore the greater the BA absorption cross section the shorter prompt neutron generation.

The values of β_{eff} and Λ parameters are decreased due to present of IBA. Their reduction percentage with Gd_2O_3 are 5.4%, 9.32%, respectively, while with Er_2O_3 are 2.5% and 8.97% respectively.

Moreover, the effective delayed neutron fraction and generation time were calculated and analyzed with the increase of the BAs enrichment in the fuel element from the base case (5%) to 10.0%, as shown in figures 9 and 10 for gadolinium and erbium respectively.

Figure 9 shows that, As the BAs enrichment is increased from the base case the value of the β_{eff} parameter is reduced to a certain concentration, after which it increases. This because, at sufficient enrichments gadolinium becomes a self-shielded absorber, in that the neutron absorption event occurs very close the absorbing surface and the inner volume of the absorber sees little or no thermal neutron flux. This demonstrates that the increase in the BA enrichment over this enrichment in the reactor will not be effective. This stands for the fact that at some point, the concentration of burnable absorber atoms becomes negligible.

As shown in figure 10, the average neutron generation time (Λ) decreased with the increase in BAs enrichment. This results from a reduction in the prompt neutron lifetime due to the faster removal of thermal neutrons in the core with BA rods leading to the shorter average neutron generation time.

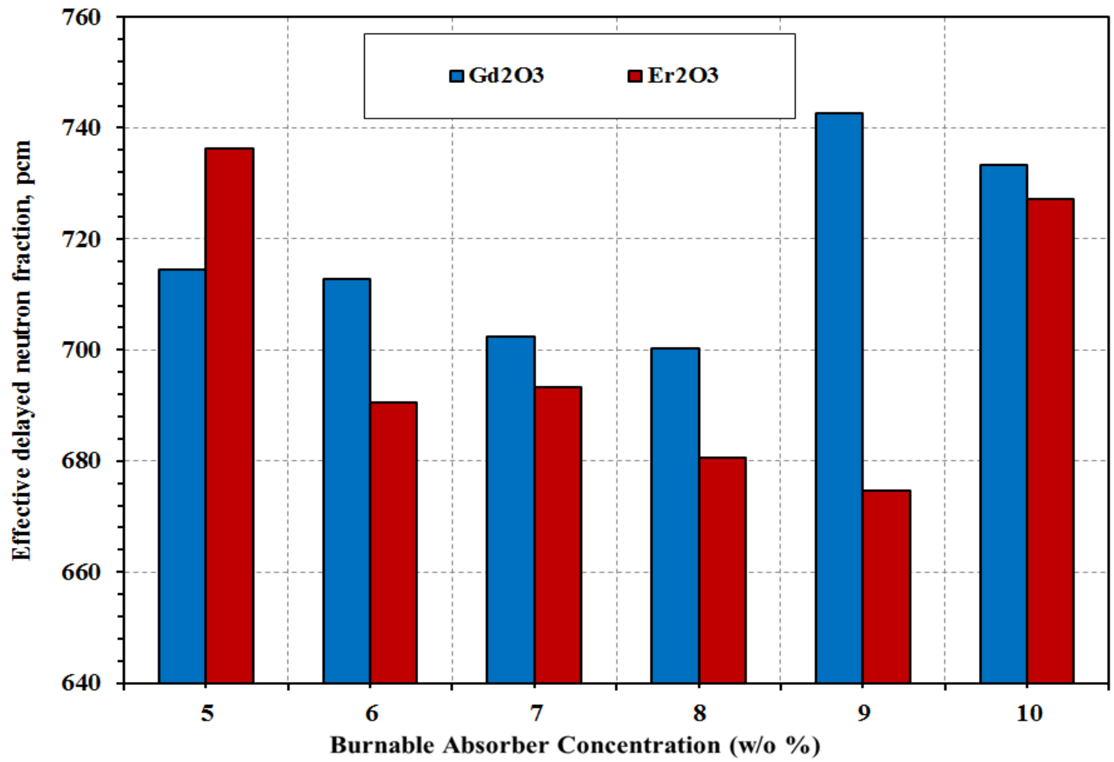

Figure 9. Variations in effective delayed neutron fraction versus increasing BA concentration

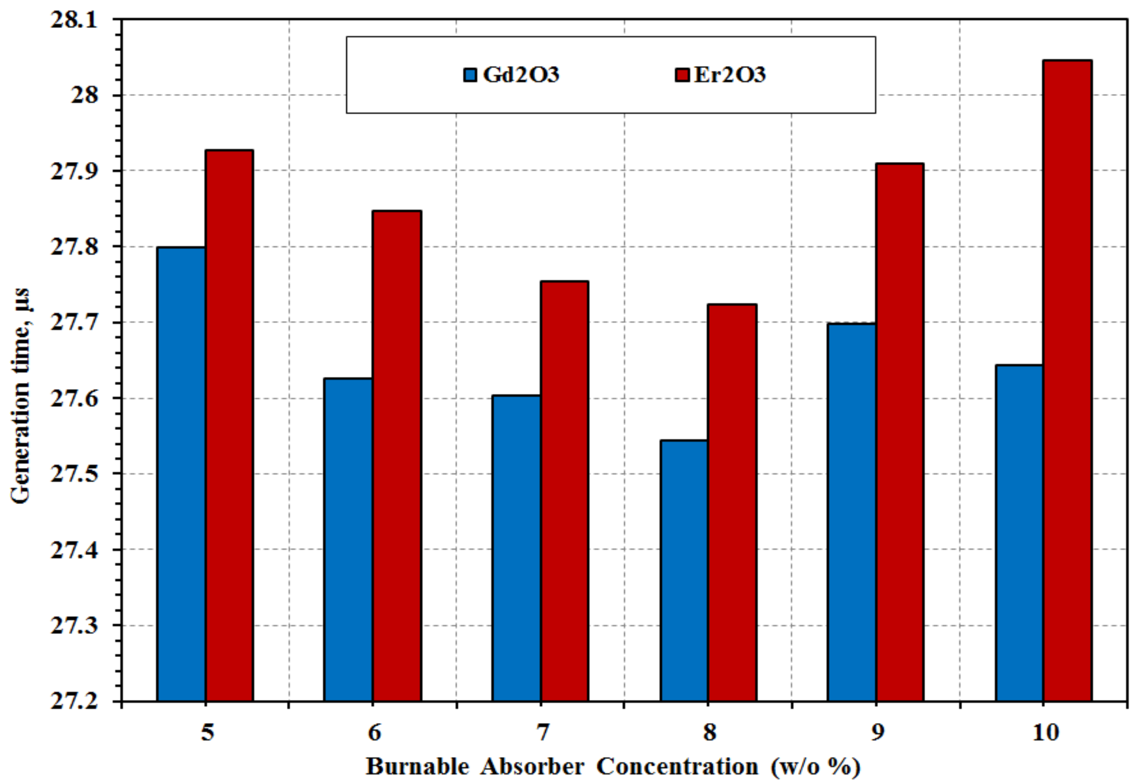

Figure 10. Variations in generation time versus increasing BA concentration

Finally, a reader can conclude that any change in the temperature, the fuel enrichment, the fuel consumption, the control rod movement, and the burnable absorber material how influence on the kinetic parameters which has a key role in analyzing the dynamics of nuclear reactor behavior.

5. Conclusions

Reactor kinetic parameters are very important for safety analysis in power reactors. The kinetic parameters are the effective delayed neutron fraction (β_{eff}), and prompt neutron generation time (Λ). The effects of change in temperature, burnp, the fuel enrichment, the control rod movement and burnable absorber rods (enrichment and absorber type which used) in VVER-1000 core have been investigated using Monte Carlo code MCNP6.

The sensitivity analysis evidenced that the greatest effect on the effective delayed neutron fraction was the fuel consumption, increasing temperature and control rod positions. While, lowest effect was for the fuel enrichment and the presence of BAs. The fuel enrichment and insertion of control rods have the greatest effect on the generation time while the fuel consumption, temperature changes and presence of BA have the lowest effect. The effect of changes in all parameters is detailed as follows:

- The value of prompt generation time parameter decreased by fully inserted of control rods in the core by 14.6%. While the value of the effective delayed neutron fraction has increased about 12.11%.
- Also, effective delayed neutron fraction, prompt neutron generation time becomes smaller as fuel consumed. The parameters have dropped up to 33.5% and 8.85% for β_{eff} and Λ parameters respectively.
- In addition, the raising of temperature produces a decrease of effective delayed neutron fraction of 20.9% and increase of generation time by 6.4%.
- The Uranium enrichment produces a decrease in the generation time. The prompt neutron generation time decreased by 48.0%, β_{eff} doesn't show any considerable change by increasing U-235 enrichment. It means the β_{eff} parameter is not influenced by the fuel enrichment.
- Furthermore, the effective delayed neutron fraction (β_{eff}) for the reactor without IBA is higher than for the reactor with IBAs. The Gd_2O_3 has smaller value for β_{eff} than Er_2O_3. The Burnable absorbers cause a decrease in the β_{eff} value by 5.4%, 2.5% for gadolinium and erbium respectively, and a decrease in the Λ value by 9.32% and 8.97% respectively.

From all observations we can conclude that, the changing the control rod position, temperature, and fuel burn-up strongly affects on the effective delayed neutron fraction (β_{eff}) and the prompt neutron generation time (Λ) which have a key role in analyzing the dynamics of nuclear reactor behavior.

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