The Effect of burnable absorbers on neutronic parameters of VVER-1200 reactor

Noura Hafez¹, Hesham Shahbunder ²,3, Esmat Amin ⁴, S. U. El-Kamessy ³, S. A. Elfiki ⁵ and Ahmed Latef ⁵

¹ Nuclear Power Stations Engineering Department, Faculty of Engineering, Egyptian Russian University, Cairo, Egypt.
² Department of Physics, College of Sciences and Humanities in Al-Kharj, Prince Sattam bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia.
³ Physics Department, Faculty of Science, Ain Shams University, Cairo 11566, Egypt.
⁴ Nuclear and Radiation Regulatory Authority (NRRA), Cairo, Egypt.
⁵ Faculty of Engineering, Fayoum University, Cairo, Egypt.

E-mail: noura.physics@hotmail.com

Abstract. The presence of burnable absorbers play an important role in the safety of nuclear reactors. So, seeking their influences on the reactor core behaviour is a crucial issue in both reactor core design and operation. Therefore, the aim of the present work is to study the effect of the gadolinium oxide burnable absorbers on one of the significant safety parameters of VVER-1200/V392M core which is the neutron flux distribution. A full-scale three-dimensional model of the VVER-1200/V392M core was performed using MCNP5/MCNPX transport code with ENDF/B-VII.0 nuclear data library. The calculations were performed in the normal operation state for the first fuel cycle. Besides the neutron flux in both radial and axial distributions, the comparison between the fuel assemblies contained gadolinium oxide and that without gadolinium oxide is also discussed. Also, the effect of gadolinium oxide on the produced major actinides is investigated.

1. Introduction

The specification of the reactor core, that depends on its nuclear characteristics, is an essential aspect in nuclear safety and economic evaluation. These nuclear characteristics influence on the neutron behaviour and hence, the power distribution and fuel cycle which have to be extended to the improvement of fuel economics [1]. The improvement of fuel economics lead to increase fuel enrichment and also the need to improve the neutron flux distribution and reactivity control. These improvements in neutron flux distribution required the integration of the burnable absorbers in the fuel matrix. Burable absorbers (BA) or burnable poisons (BP) are materials such as gadolinium, dysprosium, boron, erbium and hafnium, which in their non-radiated state have a high neutron absorption cross-section. These materials are converted into materials of relatively low absorption cross-section as a result of neutron absorption.

Analysis studies on the performance of different burnable absorbers were carried out which mostly focused on the boiling water reactors [2, 3, 4]. Fewer studies had faced the pressurized water reactors...
[5, 6, 7]. Consequently, the present study is focused on studying the performance of burnable absorbers on PWRs especially that have hexagonal geometries.

The aim of the present work is studying and analyzing the influence of gadolinium oxide on the neutronic safety parameters such as neutron flux distribution including both fast and thermal distributions for the full core. Moreover, to investigate the effect of gadolinium oxide on the produced actinides in particularly the major actinides. Despite the importance of power distribution calculations among the whole core, the present work has focused on the neutron flux distributions to overcome the difficulty of power distributions due to the different materials utilized in the core.

The analysis of the present study is important not only for the safety of reactor operation, but also for enhancement of reactor core design.

2. VVER-1200 core description

In the present work, the VVER-1200 reactor core is selected as a case study that is one of the pressurized water reactors in which the borated water is utilized as coolant and moderator. The core is composed of hexagonal 163 fuel assemblies which are located on 13 hexagonal grids.

Each fuel assembly contains 331 rods that classified into three groups of 312 fuel rods, 1 instrumentation channel, and 18 guide channels in which the control rods are inserted. There are two types of fuel assemblies into the core corresponding to two different types of the fuel elements, which are uranium dioxide UO$_2$ and mixture of uranium dioxide and gadolinium oxide UO$_2$ + Gd$_2$O$_3$ as shown in Fig. 1. Fig. 2 shows a horizontal cross-section MCNP5 model of VVER-1200 core including the different types of fuel assemblies with different enrichment of fuel elements and their distributions around the core. A detailed parameters of the VVER-1200 core geometry and materials used are described in Table 1[8, 9].

The regulation of reactor power and suppression of fission chain reaction is carried out by two systems adjusting reactivity. The first one is the control and protection system (cps), in which 121 control rods divided into 12 groups are used for changing reactivity and for reactor shutdown in normal and emergency operation conditions. The second is the boron regulation system that is used for small changes in reactivity by changing boric acid concentration in the water primary circuit [8, 10].

![Fig. 1. Radial view of the two fuel assembly types.](image)
3. Computational tools

In the present study, the three dimensional model of VVER-1200 core were executed by Monte Carlo N Transport Code MCNP5 [11, 12] with ENDF/B-VII.0 nuclear data library [13] to calculate the neutronic safety parameters of VVER-1200 including the effective multiplication factor $k_{\text{eff}}$, the total, thermal and fast neutron flux for both axial and radial distributions, in addition to the burn-up calculations that were executed using MCNPX 2.7.0 code [14] with the same nuclear data library. The total number of histories employed in the eigenvalue calculations was $35 \times 10^6$ including the tracking of 100000 neutrons per time step with 250 active cycles and the standard deviation was less than 0.00015 in one $\sigma$, for all calculations.

The total integrated flux was typically calculated using FMESH:n superimposed mesh tally card with EMESH energy card to identify the thermal and fast energy regions. Since the obtained results from MCNP are normalized to one source neutron, so the obtained results from MCNP5 have to be scaled to the steady-state thermal power level of the critical state system as follows.

\[
\varphi_{\text{normalized}} \left( \frac{\text{neutrons}}{\text{cm}^2 \cdot \text{s}} \right) = \nu \left( \frac{\text{neutrons}}{\text{fission}} \right) \times \frac{3200 \times 10^6 (W)}{1.6022 \times 10^{-13} (f \times \frac{MeV}{MeV}) \times \epsilon_f (\text{MeV})} \times \varphi_{\text{MCNP}} \left( \frac{1}{\text{cm}^2} \right)
\]
Table 1

The VVER-1200 core description [8],[9]

| Parameter                                            | Value                                      |
|------------------------------------------------------|--------------------------------------------|
| Thermal power                                        | 3200 MW                                    |
| Electrical power                                     | 1200 MW                                    |
| Coolant, Moderator                                   | Purified water + boric acid                |
| Boric acid concentration in water                    | 1.0-16.0 g - BH$_3$O$_3$/Kg - H$_2$O       |
| **Fuel Assembly (FA)**                               |                                            |
| FA "Turnkey" size                                    |                                            |
| Maximum                                              | 23.51 cm                                   |
| Nominal                                              | 23.42 cm                                   |
| FA height                                            | 457 cm                                     |
| Gap between fuel assemblies                          | 34 cm                                      |
| **Fuel Element (FE)**                                |                                            |
| Fuel Type                                            | UO$_2$                                     |
|                                                      | UO$_2$ + Gd$_2$O$_3$                       |
| Enrichment                                           | 1.3 to 4.5 wt% U-235                       |
| Mass fraction of Gd2O3 in fuel                       | 5.0 to 8.0 wt% Gd$_2$O$_3$                 |
| Shape of FE                                          | Rod                                        |
| Fuel height                                          | 373 cm                                     |
| Fuel pellet diameter                                 | 0.76 cm                                    |
| Central hole diameter                                | 0.12 cm                                    |
| Clad material                                        | E-110 alloy                                |
| Clad density                                         | 6.515 g/cm$^3$                            |
| Clad height                                          | 393 cm                                     |
| Outer diameter of clad                               | 0.91 cm                                    |
| Inner diameter of clad                               | 0.773 cm                                   |
| **Control rod**                                     |                                            |
| Outer diameter of guide channel                      | 1.29 cm                                    |
| Inner diameter of guide channel                      | 1.09 cm                                    |
| Clad material                                        | SS alloy 12H18N10T                         |
| Clad density                                         | 7.85 g/cm$^3$                             |
| Absorber materials                                   | Boron Carbide (B$_4$C)                     |
|                                                      | Dysprosium titanate (Dy$_2$O$_3$TiO$_2$)   |
| Absorber materials density                           | 1.8 g/cm$^3$ (B$_4$C)                      |
|                                                      | 4.85 g/cm$^3$(Dy$_2$O$_3$TiO$_2$)          |
| **Instrumentation channel (IC)**                     |                                            |
| Outer diameter of IC                                 | 1.29 cm                                    |
| Inner diameter of IC                                 | 1.09 cm                                    |
| Clad material                                        | Zr alloy E-635                             |
| **Spacer grid**                                      |                                            |
| Spacer grid material                                 | SS 12H18N10T                               |
| Spacer grid density                                  | 7.85 g/cm$^3$                             |
4. Results and discussion

4.1. Mode of operation

The neutronic parameters calculations of VVER-1200 reactor core were accomplished for the normal operation state, where the criticality \( k_{\text{eff}} = 1.00018 \pm 0.00012 \) achieved under the following conditions shown in Table 2.

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Average coolant temperature| 586 K                  |
| Average fuel temperature   | 1073 K                 |
| Boric acid concentration   | 7.44 g/kg − H\(_2\)O  |
| Inserted control rods      | Group no. 12 (inserted by 20 %) |

4.2. Neutron flux distribution

4.2.1. Radial neutron flux distribution.

The radial total, thermal and fast flux distributions along x-axis for VVER-1200 core in normal operation state in case of the presence of gadolinium rods are shown in Fig. 3. As shown in Fig. 3, the total flux distribution along x-axis has a central down curvature in the region from \( x = -50 \text{ cm} \) to \( x = 50 \text{ cm} \), in addition to slightly depression in sides regions from \( x = -100 \text{ cm} \) to \( x = -75 \text{ cm} \) and from \( x = 75 \text{ cm} \) to \( x = 100 \text{ cm} \). By comparing the total, thermal and fast neutron flux distributions, one can observe that both the thermal and fast neutron flux distributions have central down curvature in the same region as in the total distribution and only the fast neutron distribution has the slight decrease in the same sides regions as the total flux distribution. This is due to the contribution of the fuel assemblies (FAG) that contain to the gadolinium oxide (gadolinia) rods, where 24 FAGs of the type FAG-Z33Z9 and 13 FAGs of type FAG-Z33Z2 are distributed uni-formally from the center of the core and in the core corner. Besides 24 FAGs of type Z44B2 that are located in the outside border of the hexagonal core.

To study the effect of gadolinium rods on the neutron flux distribution, the VVER-1200 core was modeled without any gadolinium rods (clean core). The comparison between the radial total, thermal and fast neutron flux distributions along x-axis for both cases without and with gadolinium rods is shown in Fig. 4, Fig. 5 and Fig. 6 respectively. In case of the core without Gd\(_2\)O\(_3\) rods, both the total, fast neutron flux distributions have a very slight depression in the core center from \( x = -5 \text{ cm} \) to \( x = 5 \text{ cm} \) which doesn’t appear in the thermal flux distribution. In addition to all the neutron flux distributions have the two down curvature at \( x = -75 \text{ cm} \) and \( x = 75 \text{ cm} \).

From the comparison between all neutron flux distributions in both cases with and without Gd\(_2\)O\(_3\) rods, it is clear that the gadolinium is a good neutron burnable poison. This is due to the high absorption cross-section at thermal energy especially for the two isotopes \(^{157}\text{Gd}\) and \(^{155}\text{Gd}\) as shown in Fig. 7. Moreover, it forms daughter products as a result of neutron absorption as Sm and Eu isotopes with relatively low absorption cross-sections of 5670 b and 4565 b respectively. The central slight depression in the region from \( x = -5 \text{ cm} \) to \( x = 5 \text{ cm} \) in case of the core without gadolinia and also the two down curvature in the sides regions in both cases of core are formed due to the insertion of the control rods of group 12 by 20 %, where the inserted part is made of Dysprosium titanate (Dy\(_2\)O\(_3\)TiO\(_2\)) that has absorption cross-section at thermal energy of 940 b.
Due to the symmetry of the core, the radial total, fast and thermal flux distributions along $y$-axis are approximately similar to those along $x$-axis.

Fig. 3. the radial total, thermal and fast flux distributions along $x$-axis of VVER-1200 core

Fig. 4. The comparison between total radial flux distributions along $x$-axis in case of with and without Gd rods
Fig. 5. The comparison between thermal radial flux distributions along x-axis in case of with and without Gd rods

Fig. 6. The comparison between fast radial flux distributions along x-axis in case of with and without Gd rods
Fig. 7. The comparison between cross-sections of the Gd isotopes for (n,γ) reaction

4.2.2. Axial neutron flux distribution.

In case of presence of gadolinium rods, the axial neutron flux for the whole VVER-1200 core, including the total, thermal and fast distributions, is shown in Fig. 8. From Fig. 8, one can observe that all distributions are generally symmetric around the center of the core. This is as a result of the symmetry in fuel distributions among the whole core. But by comparison between total, thermal and fast neutron distributions for the core without any gadolinium rods and with the presence of gadolinium rods as shown in Fig. 9, Fig. 10 and Fig. 11, respectively, it was noticed that despite the central down curvature that observed in radial distribution, all distributions (total, thermal, and fast) are approximately the same.

The calculations of axial and radial power distributions along the whole are complicated processes because the power distribution results from the integration of several physical parameters related to the flux distribution. So the neutron flux distribution is considered as an indicator for the power distribution along the core that is one of the important safety operation parameters.
Fig. 8. The axial total, thermal and fast flux distribution of VVER-1200 core

Fig. 9. The comparison between total axial flux distributions along z-axis in case of with and without Gd rods
Fig. 10. The comparison between thermal axial flux distributions along z-axis in case of with and without Gd rods

Fig. 11. The comparison between fast axial flux distributions along z-axis in case of with and without Gd rods
4.3. Burnup

4.3.1. Actinide isotopes.

The produced major actinides including plutonium and uranium isotopes from the three different types of fuel assemblies, where one doesn’t contain gadolinium and the others containing gadolinium with different numbers of rods, after burning of 600 days operation cycle are presented in Table 3. By comparing the mass variation of produced actinides among the different fuel assembly types, one can observe that the FAs don’t containing gadolinium fuel rods yield large amount of actinides than the second type containing gadolinium fuel rods except $^{239}\text{Pu}$ which produced in larger amount from FAs containing gadolinium fuel rod. This is as a result of the presence of gadolinium leads to increasing the absorption probability of fast neutrons by $^{238}\text{U}$, hence increasing the amount of $^{239}\text{Pu}$.

The analysis of plutonium isotopes are essential where they contribute the fission reaction process and determine the spent fuel proliferation level.

Table 3
Mass of actinide isotopes.

| Isotope  | Mass (g) | Z24   | Z33Z9 | Z33Z2 |
|----------|----------|-------|-------|-------|
| $^{235}\text{U}$ | $3.1 \times 10^4$ | $5.8 \times 10^3$ | $5.8 \times 10^3$ |
| $^{238}\text{U}$ | $4.4 \times 10^5$ | $4.4 \times 10^5$ | $4.4 \times 10^5$ |
| $^{238}\text{Pu}$ | $3.4 \times 10^4$ | $3.2 \times 10^3$ | $3.2 \times 10^3$ |
| $^{239}\text{Pu}$ | $2.9 \times 10^3$ | $3.2 \times 10^3$ | $3.2 \times 10^3$ |
| $^{240}\text{Pu}$ | $8.9 \times 10^2$ | $7.8 \times 10^2$ | $7.8 \times 10^2$ |
| $^{241}\text{Pu}$ | $5.6 \times 10^2$ | $5.3 \times 10^2$ | $5.4 \times 10^2$ |
| $^{242}\text{Pu}$ | $1.6 \times 10^2$ | $1.1 \times 10^2$ | $1.1 \times 10^2$ |

5. Conclusion

The effect of burnable absorbers including gadolinium and dysprosium titanate in the first cycle of the VVER-1200 reactor was studied using MCNP5/MCNPX codes.

The presence of gadolinium oxide plays a significant role in the safety of reactor, where it makes the neutron flux much flattened, and hence minimizes the power peaking specially at the center of the core. Also, dysprosium titanate is found to be good control rods where it increases the safety of operation by the relatively high absorption cross-section.

From the present study, it was noticed that the amount of produced plutonium isotopes, except $^{239}\text{Pu}$, from the fuel assemblies that don’t contain gadolinium oxide, are higher than that of contain gadolinium. This is because of the shielding effect of fissile isotopes as a result of presence of gadolinium oxide. The analysis of produced actinides in particularly the major actinides is important in the reactor operation as it determines the spent fuel proliferation level.

Further study of other burnable poisons in different core configurations with additional analysis is required to obtain the optimum reactor core designs.

Acknowledgment

The authors would like to gratefully thank Rosatom Technical Academy [15] members for providing some required information for this work.
References

[1] IAEA 1996 Safe core management with burnable absorbers in WWERs Tech. Rep. IAEA-TECDOC-858 Nuclear Power Technology Development Section Vienna, Austria

[2] Tung W H and Lee T T 2020 Annals of Nuclear Energy 138 107204 URL https://doi.org/10.1016/j.anucene.2019.107204

[3] Radaideh M I, Price D, O’Grady D and Kozlowski T 2019 Progress in Nuclear Energy 113 230–246 URL https://doi.org/10.1016/j.pnucene.2019.01.010

[4] Galahom A, IIBashter and Moustafa Aziz 2015 Annals of Nuclear Energy 76 461–468 URL https://doi.org/10.1016/j.anucene.2014.10.025

[5] Mustafa S and Amin E 2020 Radiation Physics and Chemistry 171 108724 URL https://doi.org/10.1016/j.radphyschem.2020.108724

[6] Tran H, Hung Hoang and Peng Hong Liem 2017 Energy Procedia 131 29–36 URL https://doi.org/10.1016/j.egypro.2017.09.442

[7] Galahom A A 2016 Annals of Nuclear Energy 94 22–31 URL https://doi.org/10.1016/j.anucene.2016.02.025

[8] Dien L D and Diep D N 2017 World Journal of Engineering and Technology 05 507–519 URL https://doi.org/10.4236/wjet.2017.53043

[9] IAEA 1995 In-core fuel management code package validation for WWERs Tech. Report IAEA-TECDOC-847 International Atomic Energy Agency Vienna URL https://inis.iaea.org/search/search.aspx?orig_q=RN:28026025

[10] IAEA 2003 WWER-1000 reactor simulator (Training Course no 21) (Vienna: International Atomic Energy Agency) URL https://www.iaea.org/publications/6686/wwer-1000-reactor-simulator

[11] Brown F, Kiedrowski B and Bull J 2010 MCNP5-1.60 release notes Tech. Report LA-UR-10-06235 LosAlamos National Laboratory (LANL) New Mexico, U.S. URL https://mcnp.lanl.gov/pdf_files/la-ur-10-06235.pdf

[12] X5 Monte Carlo Team 2003 MCNP – A general Monte Carlo N-Particle Transport code, version 5 Tech.Report LA-CP-03-0245 Los Alamos National Laboratory (LANL) New Mexico, U.S. (Revised 2/1/2008) URL https://mcnp.lanl.gov/pdf_files/la-cp-03-0245.pdf

[13] Chadwick M B, et. al. 2006 Nuclear Data Sheets 107 2931–3060 URL http://dx.doi.org/10.1016/j.nds.2006.11.001

[14] Pelowitz B 2011 MCNPX User’s Manual Tech. Rep. LA-CP-11-00438 Los Alamos National Laboratory (LANL)

[15] Rosatom 2020 Rosatom Technical Academy Ulitsa Kurchatova, 21, Obninsk, Kaluga Oblast, Russia, 249031(Accessed: January 13, 2020) URL http://rosatomtech.com