Effect of gadolinium absorber radial profiling in fuel pins on VVER-1000 assembly neutron-physical characteristics

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Abstract. The paper raises the problem of non-optimal use of resources. The purpose is to extend the fuel campaign. An alternative task is to increase the duration of the reactor campaign to increase the flexibility of decision-making during the operation of a nuclear reactor. The paper presents calculations of the profiling of a burnable absorber in fuel assemblies for VVER-1000 reactors. A quantitative assessment of the effect of alternative placement of gadolinium in fuel elements is made. Changes in the burnup of fuel elements in fuel assemblies are noted, as well as an advantage expressed in a change in the $k_{inf}$. The results showed a strong dependence of the isotopic composition of the peripheral layer on the neutron flux density and a weak dependence of the isotopic composition of the central fuel element with gadolinium layers on the neutron flux density. The burnup when using the iterative process turned out to be impossible to align along the radius presumably due to the production of plutonium. A significant advantage of profiling a fuel cell with gadolinium is expressed in the period before the first overload, with each subsequent overload the efficiency of the technology decreases. However, $k_{inf}$ of the profiled assembly throughout the entire fuel campaign exceeds the $k_{inf}$ of the standard assembly, which indicates the efficient use of a burnable absorber.

1. Introduction

Burnable absorbers are widely used in connection with the need to compensate for excess fuel reactivity for safety reasons. At the same time, alternative options for more efficient use of burnable absorber are still possible, allowing to extend the fuel campaign for a longer period. The issue of influence on campaign parameters is quite interesting and has been considered in a number of works [1-13].

One of the possibilities for prolonging the campaign is to use the burnable absorbers to release the reactivity during its combustion, during which an increasing number of U-235 fissions occur in the deeper layers of the fuel rod by the time when the reactivity margin of the fuel elements becomes sufficiently small, and this leads to a relative increase in the multiplication factor. However, due to uneven fuel burnup, the fuel assembly must be replaced before all the reactivity stored in the fuel is released, thus, the potential for using burnable absorbers also decreases; therefore, the urgent task of this work is radial fuel profiling in order to extend the campaign.
2. Description of solution

2.1. A program of calculations
The calculations were carried out using the SERPENT-2 software package, which implements the Monte Carlo method and allows high-precision calculations of various characteristics of the system, taking into account the continuous energy dependence of neutron cross sections [14].

In the SERPENT software package, two- or three-dimensional geometry is used to create computational models, consisting of cells bounded by elementary surfaces and their derivatives. The calculation of \( k_{inf} \) using the SERPENT software is based on solving the transport equation of neutron transport, during which the interactions of neutrons with the medium (fission, scattering, absorption, etc.) are simulated by the stochastic method.

2.2. A model
A VVER-1000 fuel assembly was chosen as a working model. The model is shown in figure 1. Eleven hexagonal rings can be distinguished, which were numbered from the periphery to the center (1-11). The standard version has 300 fuel elements with UO2, 18 guide channels, 12 fuel rods in rings 3 and 7 with VP (UO\(_2\) + Gd\(_2\)O\(_3\)) and 1 measuring channel. Fuel element enrichment 4.45%, fuel element enrichment 4.95%. This model of fuel assemblies was chosen to determine the dependence of the burnup of the profiled fuel rod layers on the neutron flux density.

2.3. A method
Each fuel element with 8% gadolinium oxide content was divided along the radius into 10 layers of equal thickness, the central layer was assigned the number 1, the peripheral layer – 10. The concentrations of fuel with burnable absorber in the fuel elements of the standard assembly were set the same. After each iteration, the concentrations were double normalized: by the average fuel burnup by 40 MWt\(\cdot\)day/kg and by the total gadolinium content in the fuel assembly, which should remain

![Figure 1. Model of the design fuel assembly.](image-url)
constant and equal to the initial one. Thus, it was supposed to achieve equalization of the burn-up depth without a quantitative change in the gadolinium content, but only due to its redistribution over the fuel elements of the fuel assemblies.

The change in the concentration of gadolinium oxide in each layer was performed in accordance with the ratio of the actual value of the burnup depth to the average value at the time of reaching 40 c. The condition for stopping the iterative process was the achievement of the largest value of the neutron multiplication factor $k_{inf}$ at the mean burnup value of 40 MWt·day/kg, followed by a steady decrease in it beyond the error limits.

3. Results and discussion

To solve the problem, we used the iterative process of normalizing the gadolinium concentrations by fuel burnup along the fuel rod radius.

As a result, a discrete solution was obtained containing the optimal concentrations for each layer of the outer and inner rings of fuel elements.

The concentration values and their ratio for the rings are shown in table 1.

| $r$   | $N$ (out ring) | $N$ (in ring) | $N$ (or) / $N$ (ir) | $N$ (standard) |
|------|----------------|---------------|---------------------|----------------|
| 0.0386 | 0.000005249    | 0.000003278   | 1.60                | 0.000521139    |
| 0.0772 | 0.000005254    | 0.000003380   | 1.55                | 0.000521139    |
| 0.1158 | 0.000005637    | 0.000003684   | 1.53                | 0.000521139    |
| 0.1544 | 0.000006369    | 0.000004065   | 1.57                | 0.000521139    |
| 0.1930 | 0.000007561    | 0.000004877   | 1.55                | 0.000521139    |
| 0.2316 | 0.000009739    | 0.000006312   | 1.54                | 0.000521139    |
| 0.2702 | 0.000013608    | 0.000009013   | 1.51                | 0.000521139    |
| 0.3088 | 0.000022122    | 0.000014988   | 1.48                | 0.000521139    |
| 0.3474 | 0.000056690    | 0.000041560   | 1.36                | 0.000521139    |
| 0.3860 | 0.002651180    | 0.002678500   | 0.99                | 0.000521139    |

3.1. The burnup depth

For layers 1-9 of both the outer and inner rings, a regularity in the change in concentrations is observed, which is well approximated by a polynomial law of the fourth degree. The deviation is observed in the 10th, peripheral layer of the fuel rod, where the gadolinium concentration remains high throughout the entire iterative process. In figure 2 graphically reflects the change in concentrations over the layers of the fuel elements of the outer and inner rings.
As a result of the work, it was possible to achieve equalization of burnup over the layers of fuel elements for micro-campaigns with standard and increased ones (up to 21 MWt·day/kg). With regard to the complete fuel cycle, the equalization of burnup on the inner and peripheral layers is practically impossible due to the production of excess plutonium during the combustion of gadolinium at the edges of the fuel rod. As a result, due to the shielding of a part of the fuel, the fuel element burnup remains to be uneven.

The burnup depth for fuel element layers is shown in figure 3 and figure 4.

Figure 2. Concentrations over the layers of the fuel elements of the outer and inner rings.

Figure 3. The depth of burnup in the layers of peripheral fuel rods with different average burnup values 17 MWt·day/kg, 21 MWt·day/kg, 40 MWt·day/kg.
Figure 4. The depth of burnup in the layers of central fuel rods with different average burnup values 17 MWt∙day/kg, 21 MWt∙day/kg, 40 MWt∙day/kg.

3.2. *Effect of profiling on $k_{inf}$*

$k_{inf}$ values were tracked at each iteration throughout the entire fuel cycle. In the profiled version of the assembly at the end of the reactor campaign – $k_{inf}$ is higher than in the standard version, on the basis of which we can talk about the prospects of this version in terms of extending the fuel campaign.

The change in $k_{inf}$ upon reaching the burnup depth of 17, 21, 40 MWt∙day/kg is shown in Table 2 and figure 5.

| Burnup depth, MWt∙day/kg | $k_{inf}$ of standart fuel element with Gd$_2$O$_3$ | $k_{inf}$ of profiled fuel element with Gd$_2$O$_3$ | $\Delta k_{inf}$ |
|--------------------------|---------------------------------|---------------------------------|---------------|
| 17                       | 0.963968                        | 0.98138                         | 0.017412      |
| 21                       | 0.948563                        | 0.963017                        | 0.014454      |
| 40                       | 0.880353                        | 0.882207                        | 0.001854      |

It can be seen that $k_{inf}$ of the profiled version exceeds $k_{inf}$ of the standard one by a value significant for a given burnup depth.

With a burnup of 13 MWt∙day/kg, the efficiency of using the profiled version of fuel elements in fuel assemblies on the own neutron spectrum is 99.15 eff. days relative to the standard version (to determine the amount of gain $k_{inf}$ in eff. 40 MWt∙day/kg – linear extrapolation), 17 MWt∙day/kg give a gain of 94.82 eff. days, 21 MWt∙day/kg – 71.89 eff.days; with a burnup depth of 40 MWt∙day/kg, the time increment will be 13.71 eff. days.
4. Conclusion

Consideration of the possibility of increasing the reactor campaign is more promising due to the presence of a strong $k_{inf}$ differentiation between the profiled and standard types of fuel in the range from 10 to 21 MWt·day/kg. A clear advantage of using the profiled version of the fuel element is the great flexibility in operating the reactor plant in the time intervals before refueling.

References

[1] Abu Sondos M A, Demin V M and Savander V I 2019 The effect of burnable absorber (Gd and Eu) on the neutron-physics characteristic of fuel assemblies of VVER-1000 reactor IOP Conf. Series: Jour. of Ph.: Conf. Series 1189 012003 DOI: 10.1088/1742-6596/1189/1/012003

[2] Abu Sondos M A Demin V M and Savander V I Decrease the Volume of Boric Regulation of the Reactivity when Using the Burnable Absorber on the Basis of (GD2O3) in the Fuel Reactor WWER-1200 Gl. Nucl. Saf. 14(2) pp 56-65 DOI: 10.26583/gns-2019-03-06

[3] Abu Sondos M A Demin V M and Smirnov A Comparative Analysis of Neutrons Properties of Nuclear Fuel Produced by Westinghouse and Fuel Element for WWE R Reactors by code SERPENT Gl. Nucl. Saf. 14(2) pp 103-09 DOI: 10.26583/gns-2019-02-12

[4] Al'davakhra S, Savander V I and Belousov I N 2006 Computational method for and analysis of the application of granular absorbers in VVER reactors At. En. 100(1) pp 8-13

[5] Al'davakhra S 2006 Use of burnable absorbers in VVER reactors Dissertation of the candidate of technical sciences, Moscow: MEPhI p 143

[6] Bergelson B R, Belonog V V, Gerasimov A S and Tikhomirov G V 2010 Burnup of nuclear fuel VVER with different absorbers At. En. 109(4) pp 194-97

[7] Baranov V G, Ternovykh M Y, Tikhomirov G V and Khlunov A V 2008 Simulation of nuclear-physical processes in the surface layer of a fuel kernel with a consumable absorber At. En. 105 (6) 391-96

[8] Frybortova L 2019 Recommended strategy and limitations of burnable absorbers used in VVER
fuel assemblies Nucl. Sc. & Tech. 30(8) p 14 DOI: 10.1007/s41365-019-0651-x

[9] Khoshahval, F, Foroutan S S, Zolfaghari A and Minuchehr H 2016 Evaluation of burnable absorber rods effect on neutronic performance in fuel assembly of WWER-1000 reactor Ann. of Nucl. En. 87 pp 648–658 DOI:10.1016/j.anucene.2015.10.012

[10] Saad H M, Refaat R, Aziz M and Mansour H 2019 Effect of Axial Distribution of Gadolinium Burnable Poison in Advanced Pressurized Water Reactor Assembly Nucl. & Rad. Saf. Foll. jour. 84(4) pp 46-53 DOI: 10.32918/nrs.2019.4(84).06

[11] Tran H N, Hoang V K, Liem P H and Hoang H T P 2019 Neutronics design of VVER-1000 fuel assembly with burnable poison particles Nucl. Eng. & Tech.51(7) pp 1729–1737

[12] Turner J Middleburgh S C and Abram T J 2019 A high density composite fuel with integrated burnable absorber: U3Si2-UB2 Jour. of Nuc. Mat. 529:151891 p 5 DOI: 10.1016/j.jnucmat.2019.151891

[13] Vnukov R A, Karpovich G V and Kolesov V V 2020 Issledovanie primenimosti neuprugogo rassejaniya v ramkah reshenija sistemy integro-diffreencial'nogo uravnenija perenosu nejtronov i differencial'nyh uravnenij izmenenija izotopnogo sostava Fut. of Nuc. P. – AF 2019: XV Int. s. & pr. conf. 1 pp 67–68

[14] Leppänen J 2012 PSG2 / Serpent – a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code. User’s Manual p 163